



Bernese GNSS Software Version 5.2

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Edited by

Rolf Dach, Simon Lutz,
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User manual of the *Bernese GNSS Software*, Version 5.2

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Bernese GNSS Software

Version 5.2

Astronomical Institute, University of Bern

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1. Introduction and Overview

The *Bernese GNSS Software* is a scientific software package meeting highest quality standards for geodetic and further applications based on Global Navigation Satellite Systems (GNSS). Both of the currently fully operational GNSS are supported: the American Global Positioning System (GPS) and the Russian Глобальная навигационная спутниковая система: Global Navigation Satellite System (GLONASS). The analysis of dual-frequency data for the upcoming new systems, like European Galileo, Chinese BeiDou, or Japanese Quasi-Zenith Satellite System (QZSS), is prepared but not yet fully developed for an operational processing.

This documentation is intended to give insight into theoretical aspects of GNSS data processing, working principles and concepts of the *Bernese GNSS Software*, and the practical use of the package for a reader who already has a basic knowledge of GNSS data processing. Despite the large number of pages not all topics related to GNSS data processing can be thoroughly covered by this document. The reader may, however, get a good insight into analysis strategies which promise to meet the accuracy requirements for his particular applications.

1.1. From Version 3 to Version 5

In March 1988, the *Bernese GNSS Software* Version 3.0, a tool based on its predecessor *Bernese Second Generation GPS Software*, was completed. Between 1988 and 1995 five major releases could be issued in order to take into account the rapid development in the field of high accuracy applications of the GPS: release 3.1 was issued in December 1988, release 3.2 in April 1990, 3.3 in May 1991, 3.4 (Rothacher et al. 1993) in May 1993, and release 3.5 in February 1995.

In September 1996, the Version 4.0 of the *Bernese GNSS Software* (Rothacher and Mervart 1996) was released with a first version of program ADDNEQ to combine normal equations for efficiently computing multi-session and multi-campaign solutions. Version 4.0 contained a first *Bernese Processing Engine* developed together with C. Rocken and J. Johnson from University Corporation for Atmospheric Research (UCAR), which was particularly well suited to process data from permanent GPS networks in a completely automatic and very efficient way.

Since Version 4.2 of the *Bernese GNSS Software* (released in November 1999, Hugentobler et al. 2001) the capability to process GLONASS observations (also together with GPS observations) as well as SLR measurements to GNSS satellites is available. Furthermore, for the first time Fortran 90 features were used for a test release of the new ADDNEQ2 program as the successor of ADDNEQ.

A big step was the release of version 5.0 in April 2004 (Dach et al. 2007). For the first time, the *Bernese GNSS Software* features a user-friendly Graphical User Interface (GUI) based on the Qt-library, built-in html-based help system, a new front-end for automatization

(Bernese Processing Engine, BPE), and Perl as the BPE script language. It was also the first released version with the capability of precise orbit determination not only for GNSS but also for LEO.

The following years were used for numerous developments focusing on multi-GNSS capability (as described, e.g., in Meindl et al. 2009). Finally, not all of the developments were included in the current release Version 5.2. The most important enhancements with respect to Version 5.0 are:

- New processing capabilities:
 - FODITS: Find Outliers and Discontinuities in Time Series, a new program of the *Bernese GNSS Software* (see PhD thesis, Ostini 2012)
 - GLONASS ambiguity resolution
 - 1/4-cycle shift for *L2C* is considered in ambiguity resolution
 - improved constraining of zero- and single-difference reference ambiguities
 - GLONASS clock estimation and PPP
 - GNSS-specific estimation of receiver antenna corrections
 - support of individually calibrated receiver antennas including the corresponding check of the RINEX header information
 - stochastic pulses may be estimated when fitting orbits in ORBGEN
 - accelerations due to solid Earth tides are considered for orbit integration in ORBGEN
 - solve for Helmert-parameters when combining solutions in ADDNEQ2
 - improved Solution INdependent EXchange format (SINEX) import capabilities
 - automated adaption of pre-processing options in MAUPRP according to the baseline length
 - possibility to exclude specific receiver types when selecting baselines
 - acceleration parameters for LEO orbit determination
- New observation and processing models:
 - troposphere: GMF/GPT and VMF1 for GNSS; Mendes-Pavlis for SLR
 - ionosphere: higher order terms (2nd and 3rd order and ray bending) including scaling factors
 - geophysical deformation models can be introduced as grids and validated by estimating scaling factors
 - center of mass corrections for ocean and atmospheric tidal loading
 - Latest IERS 2010 conventions compliance
- Technical improvements:
 - use Makefile to compile the Fortran source code
 - dynamic memory allocation for the most important variables in GPSEST
 - option to compute no solution in GPSEST and ADDNEQ2 and only generate a resulting normal equation file
 - CPU usage statistics for each program run and for the BPE
- Menu/BPE related improvements:
 - upgrade to Qt 4
 - reprocessing mode: automatically create campaigns for each session in case of a multi-session BPE
 - flexible suspension of Process Control Files (PCFs) to optimize the usage of computer resources
 - “remote mode” for slow data connections

Version 5.2 of the *Bernese GNSS Software* is delivered including ready-to-use BPE examples: precise point positioning, baseline-wise processing, double-difference network processing (RINEX-to-SINEX), clock estimation, LEO orbit determination, and SLR orbit validation.

1.2. Main Objectives and General Characteristics

The *Bernese GNSS Software* Version 5.2, continues the tradition of a high performance, high accuracy, and highly flexible GPS/GLONASS (GNSS) post-processing package for many applications. State-of-the-art modeling, detailed control over all relevant processing options, powerful tools for automatization, the adherence to up-to-date, internationally adopted standards, and the inherent flexibility due to a highly modular design are characteristics of the *Bernese GNSS Software*.

Typical users are:

- scientists for research and education
- survey agencies responsible for high-accuracy GNSS surveys (e.g., first order networks)
- agencies responsible to maintain arrays of permanent GNSS receivers
- commercial users with complex applications demanding high accuracy, reliability, and high productivity

At the time of the release of this document about 600 institutions and universities on all continents were users of the *Bernese GNSS Software* for a vast variety of applications.

The *Bernese GNSS Software* is particularly well suited for:

- efficient processing of local to global scale networks using single- or dual-frequency GNSS measurements
- automatic processing of permanent networks
- any type of post-processing from near-real time to reprocessing years of GNSS data
- processing of data from a large number of receivers
- combined processing of GPS and GLONASS observations
- analysis of real kinematic receivers (even on airplanes)
- ionosphere and troposphere monitoring
- clock estimation and time transfer
- orbit determination for GNSS and LEO satellites together with related parameters (e.g., Earth orientation parameters)
- SLR orbit validation

General features of the software are designed to meet highest accuracy requirements:

- All principal observables recorded by high precision geodetic receivers (i.e., code and phase data on both carriers) may be processed. DCBs for satellites and receivers are taken into account for applications involving code observations. Capability to process SLR observations to GNSS and LEO satellites.
- Single and dual frequency data may be processed in the same estimation step. The use of ionosphere models minimizes the impact of ionospheric biases on station coordinates and other estimated parameters.

Table 1.1.: Parameter types implemented in the *Bernese GNSS Software* Version 5.2 .

Parameter	Description	available in		Main Reference
		GPSEST	ADDNEQ2	
Station-related parameters				
Station coordinates	Rectangular coordinates X, Y, Z in the ITRF (at present the ITRF 2008 is used). The program output also provides the results in the (user defined) geodetic datum (λ, β, h) .	Yes	Yes	Ch. 10
Station velocities	In program ADDNEQ2, station velocities may be set up if a long time series of NEQ systems containing the same stations is available.	No	Yes	Ch. 10
Epoch specific station coordinates	A set of station coordinates is assigned to each epoch (for kinematic surveys).	Yes	No	Ch. 10
Scaling factors	Scaling factors for up to three crustal deformation models provided in global grid files can be estimated to validate the model and/or to investigate the impact of the model on GNSS-derived parameters.	(Yes) ^a	Yes	Ch. 10
HELMERT-parameters	Transformation parameters (translation, rotation, scale) between the coordinate parameters from different normal equations can be estimated.	No	Yes	Ch. 9
Clock and bias parameters				
Receiver clock corrections	Estimation using code and phase zero-difference data (e.g., for time transfer) relative to a reference clock.	Yes	No	Ch. 15
Satellite clock corrections	Estimation using code and phase zero-difference data.	Yes	No	Ch. 15
Differential code biases	P1–P2 and P1–C1 code biases for receivers and satellites. Multipliers may also be estimated to verify the tracking technology of a receiver.	Yes	Yes	Ch. 14
GLONASS inter-frequency bias	inter-frequency biases (IFBs) due to the different frequencies of the GLONASS signals from different satellites are estimated when processing GLONASS zero-difference data.	Yes	Yes	Ch. 15
<i>continued on next page</i>				

^aParameter is in GPSEST available but it makes only sense in a long-term solution by program ADDNEQ2.

<i>continued from previous page</i>				
Parameter	Description	available in		Main Reference
		GPSEST	ADDNEQ2	
Antenna calibration related parameters				
Satellite antenna phase center offsets	Such offsets may be assigned to different types of spacecraft (e.g., GPS Block IIA, Block IIR, or GLONASS satellites).	Yes	Yes	Ch. 18
Satellite antenna phase center variations	Phase patterns may be assigned to each individual satellite or according to the different types of spacecraft.	Yes	Yes	Ch. 18
Receiver antenna phase center offsets	May be estimated for antenna calibration experiments if site coordinates are accurately known.	Yes	No	Ch. 18
Receiver antenna phase center variations	Antenna phase center variations may be modeled using different techniques. Model parameters may be determined.	Yes	No	Ch. 18
GNSS-specific parameters	Biases for station coordinates and vertical troposphere among observations from different GNSS may indicate deficiencies in the GNSS-specific receiver antenna calibration.	Yes	Yes	Ch. 14
Atmosphere related parameters				
Station-specific troposphere parameters	Time- and station-specific zenith delay and gradient parameters may be introduced or solved for. High temporal resolution is possible, as well as reducing the number of parameters in ADDNEQ2.	Yes	Yes	Ch. 12
Ionosphere maps	Regional or global ionosphere single-layer maps may be determined. The electron density in the layer is described by spherical harmonics.	Yes	Yes	Ch. 13
Scaling factors for higher order ionosphere terms	Scaling factors for each component of the higher order ionosphere terms (second, third order and ray bending) can be estimated to validate the input data for the HOI corrections and/or to investigate the influence of the corrections on GNSS-derived parameters.	(Yes) ^a	Yes	Ch. 13
Stochastic ionosphere parameters	Epoch- and satellite-specific ionosphere parameters may be introduced (together with a priori weights) to support ambiguity resolution.	Yes	No	Ch. 13
<i>continued on next page</i>				

<i>continued from previous page</i>				
Parameter	Description	available in		Main Reference
		GPSEST	ADDNEQ2	
Orbit related parameters				
Orbital elements	Osculating orbital elements at initial time t_0 of arc: semimajor axis a , eccentricity e , inclination i , right ascension of ascending node Ω , argument of perigee ω , and argument of latitude u_0 at time t_0 .	Yes	Yes	Ch. 16
Radiation pressure parameters	Radiation pressure parameters: A total of <i>nine</i> parameters per satellite and arc may be introduced, three in each of three orthogonal directions (direction sun–satellite, solar panel axis, and normal to the first two). Constant and periodic once–per–revolution terms may be introduced.	Yes	Yes	Ch. 16
Pseudo–stochastic orbit parameters	Velocity changes in pre–determined directions at user–defined epochs may be introduced for each satellite. Up to three directions (e.g., radial, along–track, out–of–plane) may be defined per epoch.	Yes	Yes	Ch. 16
Earth orientation parameters	Polar motion (x and y components), UT1–UTC, nutation in obliquity and in longitude may be modeled. Only drifts may be estimated for the latter three parameter types. High time resolution is possible.	Yes	Yes	Ch. 16
Center of mass	The center of mass of the Earth may be estimated (for global analyses).	Yes	Yes	Ch. 16
Technique specific parameters				
Phase ambiguities	One initial phase ambiguity parameter has to be assigned to each (linearly independent) double difference. Resolved ambiguities may be introduced in subsequent program runs.	Yes	No	Ch. 8
SLR range biases	SLR range biases can be introduced or estimated: one bias per station/satellite/group of satellites.	Yes	Yes	Ch. 19

- The rigorous combined processing of data from GPS, GLONASS, and GPS/GLONASS receivers is possible.
Processing of Galileo-measurements is supported on an experimental stage, only.
- Data can either be processed in double-difference mode or in zero-difference mode (in particular for time transfer and precise point positioning).
- Different linear combinations of L_1 and L_2 may be used: ionosphere-free, geometry-free, wide-lane, and Melbourne-Wübbena.
- Simultaneous solution for a large number of different parameter types.
- The parameter estimation programs may be used for baseline/session/campaign/multiple-campaign processing. Many different complex solutions (e.g., annual coordinate and Earth rotation parameter (ERP) solutions) using (e.g., daily) normal equation systems can be produced without reprocessing the observations.
- Processing and combination of data from various receiver types in the same processing step due to a fully integrated handling of:
 - code biases (DCB — due to different code tracking technologies used by the different receivers) and
 - 1/4-cycle (as the result of the simultaneous processing of GPS L2C and L2P data for certain receiver types).
- Different ambiguity resolution strategies allow fixing of phase ambiguities on up to very long (several thousand kilometers) baselines — available for GPS and GLONASS.
- The processing programs support the simultaneous estimation of a large number of different parameter types (see Table 1.1).
- The software allows to process data from all static and many kinematic GNSS applications, including the kinematic and reduced-dynamic precise orbit determination for LEOs.
- Geophysical deformation models can be introduced as grids and validated by estimating scaling factors.
- Station motions due to plate motions, tides, and ocean tidal loading are modeled, conforming to latest International Earth Rotation and Reference Systems Service (IERS) standards.
- Different troposphere mapping functions are available. The estimation of troposphere gradient parameters is implemented.
- Higher order ionosphere corrections (2nd and 3rd order and ray bending) including the estimation of scaling factors.
- Allows applying and estimating antenna phase patterns for receiver (GNSS-specific) and for satellite antennas. Supports the ANTenna EXchange format (ANTEX).
- Modeling of all time-dependent parameters uses a piecewise linear, continuous representation, in particular for troposphere zenith delay and gradient parameters, Earth orientation parameters, and global ionosphere models.
- The normal equation stacker (ADDNEQ2) offers sophisticated options for pre-elimination of parameters, parameter transformations, and for the definition of the geodetic datum, including minimum constraint network conditions.
- Setup and manipulation of normal equations without inversion.
- International input/output formats are supported: RINEX with LEO extension (observations may even be extracted from RINEX version 3 files), SP3c, SINEX, IONEX, Clock RINEX, Troposphere SINEX, ANTEX, and IERS ERP.
- A sophisticated observation simulation tool is available.
- The menu reflects the program structure to guide the user through the processing steps.

- A graphical user interface with clear input panels supports the user by managing the numerous program options. An extended html-based online help is available for all options.
- The Bernese Processing Engine (BPE) allows to tailor automated processing sequences. It includes options supporting, in particular, the efficient reprocessing of GNSS data from several years.

Technically the *Bernese GNSS Software* Version 5.2 may be characterized as follows:

- platform independent: supports UNIX/Linux, Mac, and MS-Windows Operating Systems with the same source code
- Perl supported as cross-platform scripting language
- use of Fortran 90 (structures, dynamic memory allocation)
- platform independent Graphical User Interface (GUI) written in C++ using the Qt4 library
- “remote mode” for the GUI in case of slow data connections
- clear directory structure in program-, user- and data area
- user friendly installation script on Unix/Linux and Mac, setup wizard on Windows
- use of a Makefile to compile the Fortran source code
- executables and libraries from different compilers may be used in parallel
- results from several compilers on a set of Linux distributions and Windows
- systems have been compared and they are equivalent

1.3. Program Structure

The *Bernese GNSS Software* consists of more than 450 000 lines of source code in about 1 500 modules. The menu program acts as user interface for most of the more than 100 programs (listed in Table 1.2). These programs are activated through pull-down menus that reflect the main parts of the software in a logical way as illustrated in Figure 1.1:

Transfer Part — "Menu>RINEX": The *Transfer Part* includes all programs related to the transfer of RINEX files (observations, navigation messages, meteorological files, clock files) into Bernese format or vice versa, and to the manipulation of RINEX files such as cutting to a specific time window or concatenation of files. RINEX tools allow to extract header information, generate statistical information, or preprocess observations at the RINEX level.

Conversion Part — "Menu>Conversion": The *Conversion Part* collects programs to convert binary files into ASCII format and vice versa. Additional programs allow to convert SINEX files into normal equation files or to manipulate troposphere SINEX files. The program to convert ANTEX files to the Bernese format may be found here as well.

Note that some conversion programs specific to certain applications (e.g., LEO- or SLR- processing) are located in the related submenus of the "Menu>Service" section.

Orbit Part — "Menu>Orbits/EOP": The *Orbit Part* contains all programs related to satellite orbits and Earth orientation parameter (EOP). This includes the generation of an internal orbit representation (so-called standard orbit) starting from precise ephemerides or broadcast information, the update of orbit information, the creation

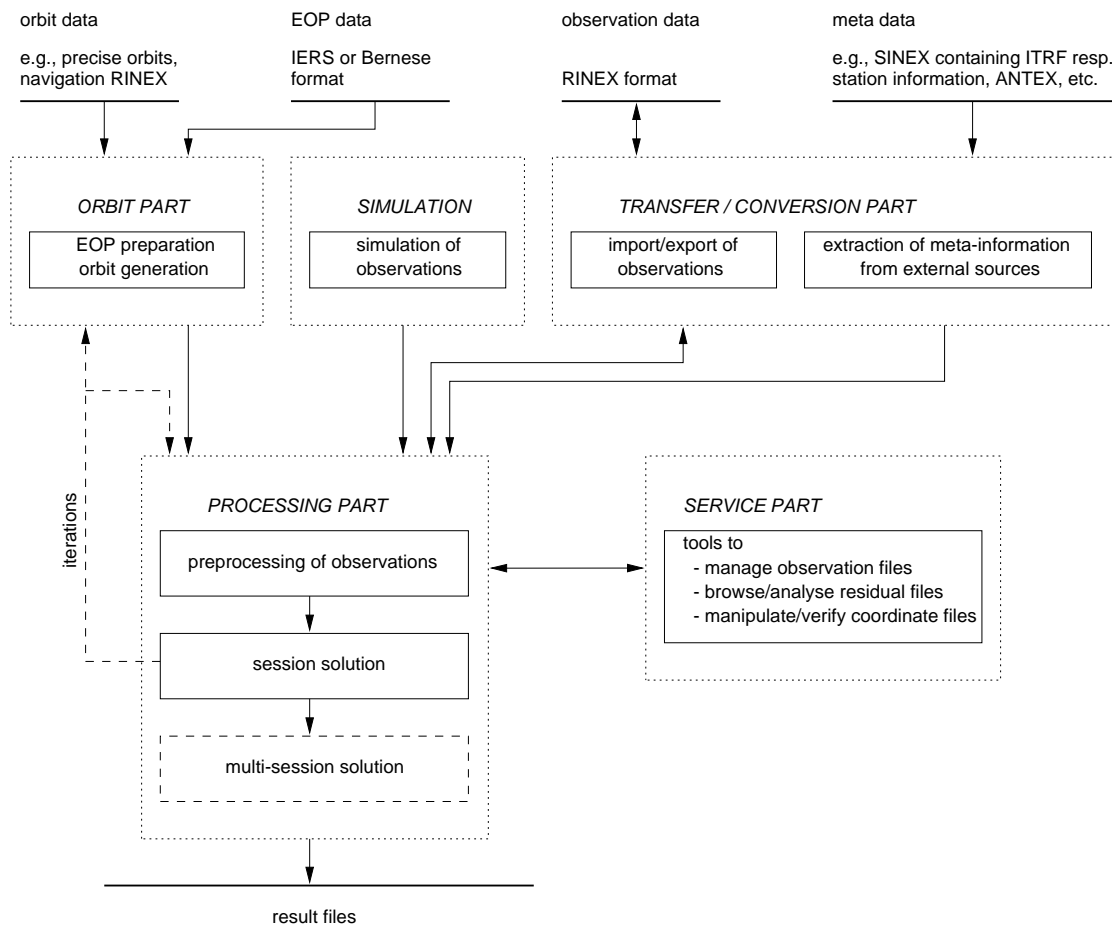


Figure 1.1.: Functional flow diagram of a standard processing in *Bernese GNSS Software Version 5.2* .

of precise orbit files, the concatenation of precise orbit files, the comparison of orbits, the conversion of EOP information from IERS format to Bernese format, and the extraction of pole information.

Processing Part — "Menu>Processing": The *Processing Part* contains the main processing programs. This includes code pre-processing and receiver synchronization, generation of baseline files, single or dual frequency phase pre-processing. The main parameter estimation based on GPS and/or GLONASS or SLR observations (program GPSEST) and on the superposition of normal equation systems (program ADDNEQ2) build the core of this part and of the software package as a whole.

Simulation Part — "Menu>Service>Generate simulated observation data": The *simulation part* consists only of one program to generate simulated GPS and GLONASS observations (code and/or phase, L1 or L1/L2) based on statistical information (root mean squares (RMS) of observations, biases, cycle slips).

Service Part — "Menu>Service": The *Service Part* is a collection of useful tools to handle station information files, edit/browse/manipulate binary observation files, check residuals, compare and manipulate coordinates, and for automated processing. In addition, clock and ionosphere tools as well as SLR and LEO utilities may be found here as well. It also provides the possibility to browse program output and error message files.

The *Bernese Processing Engine* ("Menu>BPE") is a tool operating on top of these programs and is ideally suited to set up automated processing procedures, e.g., the processing of data stemming from a permanent network. The processing strategy is set up once and for all from the RINEX files to the final results with all necessary programs. It is even possible to set up a parallel processing on different machines. A number of supporting tools ("Menu>Service>Automated processing") and a collection of scripts ($\backslash\{\text{BPE}\}/\text{bpe_utils.pm}$) are available for easy building of complex processing chains.

Table 1.2 gives an overview and a short description of the individual program units of the different parts of the software. All programs included in the menu are accompanied by an extended html-based online help.

To run programs which are not included in the menu system (section "Programs which are not directly accessible through the menu system" in Table 1.2), you may use the `RUNGPS` command (see Section 21.9). In this case the menu system will start up displaying the input file of the program you have specified.

In the section "Miscellaneous programs" at the end of Table 1.2, tools serving as menu interface and BPE programs are listed. These programs are called either automatically by the menu (`MENUAUX`, see Section 21.10.6) or by the BPE and the corresponding BPE scripts (see Chapter 22).

1.4. About this Document

This document is structured in two parts. The first part focuses on theory, models, the use of the programs for data import and preparation as well as for the estimation of the various parameter types. The second part emphasizes the technical aspects of the use of the *Bernese GNSS Software* (e.g., the menu system and the Bernese Processing Engine). In addition, it contains a description of several processing examples demonstrating the use of the software for different applications.

The introduction is followed by Chapter 2 ("Fundamentals", page 19) giving a short technical introduction to GNSS (Section 2.1: "Global Navigation Satellite Systems — A Short Review", page 19), an overview of celestial mechanics (Section 2.2: "GNSS Satellite Orbits", page 32), and a short development of the observation equations and the linear combinations used in the *Bernese GNSS Software* (Section 2.3: "Observation Equations", page 47). Chapter 3 ("Directory Structure and Campaign Setup", page 57), Chapter 4 ("Import and Export of External File Formats", page 73), and Chapter 5 ("Preparation of Earth Orientation, GNSS Orbit, and Satellite Clock Information", page 107) describe the preparation of a campaign for the processing, where to get input information and how to import them into the *Bernese GNSS Software*, and how to prepare the orbit information for the processing. In Chapter 6: "Data Preprocessing" (page 127) the preprocessing programs are introduced.

The basics of the two main programs of the *Bernese GNSS Software*, `GPSEST` and `ADDNEQ2` are given in Chapter 7: "Parameter Estimation" (page 169) and Chapter 9: "Combination of Solutions" (page 209), respectively. Information on phase ambiguity resolution is provided in Chapter 8: "Initial Phase Ambiguities and Ambiguity Resolution" (page 191). Depending on your particular interests, the following chapters might be more or less central for your work: Chapter 10: "Station Coordinates and Velocities" (page 241), Chapter 12: "Troposphere Modeling and Estimation" (page 295), Chapter 13: "Ionosphere Modeling and Estimation" (page 311), Chapter 14: "GNSS Related Biases" (page 339),

Table 1.2.: List of main programs in the *Bernese GNSS Software* Version 5.2 .

Name	Purpose Location in menu system
Transfer part:	
RXOBV3	Transfer RINEX code / phase data into Bernese files "Menu>RINEX>Import RINEX to Bernese format>Observation files"
RXNBV3	Transfer RINEX broadcast data into Bernese files "Menu>RINEX>Import RINEX to Bernese format>Navigation files"
RXMBV3	Transfer RINEX meteo data into Bernese files "Menu>RINEX>Import RINEX to Bernese format>Meteo files"
RXNPRES	Transfer GPS / GLONASS broadcast files into precise format "Menu>RINEX>Import RINEX to Bernese format>Navigation files to SP3"
BV3RXO	Transfer Bernese code / phase data into RINEX files "Menu>RINEX>Export RINEX from Bernese format>Observation files"
BV3RXN	Transfer Bernese broadcast data into RINEX files "Menu>RINEX>Export RINEX from Bernese format>Navigation files"
CCRINEXO	Cut / concatenate GNSS RINEX observation files "Menu>RINEX>Cut/concatenate RINEX files>Observation files"
CCRINEXN	Cut / concatenate GPS RINEX navigation files "Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GPS)"
CCRINEXG	Cut / concatenate GLONASS RINEX navigation files "Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GLONASS)"
RNXGRA	Pseudo-graphics of RINEX observation files "Menu>RINEX>RINEX utilities>Create observation statistics"
RNXSMT	Clean RINEX data and smooth the code observations "Menu>RINEX>RINEX utilities>Clean/smooth observation files"
RNXCLK	Extract satellite clock from clock RINEX files "Menu>RINEX>RINEX utilities>Extract satellite clock"
Orbit part:	
BRDTST	Check broadcast files "Menu>Orbits/EOP>Broadcast orbits>Check broadcast orbits"
BRDTAB	Transform broadcast orbits into tabular orbits "Menu>Orbits/EOP>Broadcast orbits>Create tabular orbits"
SATCLK	Extract satellite clock information from broadcast files "Menu>Orbits/EOP>Broadcast orbits>Extract satellite clocks"
PRETAB	Transform precise orbits into tabular orbits "Menu>Orbits/EOP>Create tabular orbits"
ORBGEN	Generate / update standard orbits "Menu>Orbits/EOP>Create/update standard orbits"
DEFXTR	Extraction summary of ORBGEN program output "Menu>Orbits/EOP>Extract ORBGEN program output"
STDPRES	Produce precise ephemeris format from standard orbit "Menu>Orbits/EOP>Convert standard to precise orbits"
PREWEI	Change accuracy codes of precise orbit files "Menu>Orbits/EOP>Set accuracy codes in precise orbits"
CCPREORB	Cut / concatenate precise orbit files "Menu>Orbits/EOP>Concatenate/merge precise orbit files"
<i>continued on next page</i>	

<i>continued from previous page</i>	
Name	Purpose Location in menu system
STDDIF	Display differences between two standard orbits "Menu>Orbits/EOP>Compare orbits>Standard orbits"
ORBCMP	Helmert transformation between different precise orbits "Menu>Orbits/EOP>Compare orbits>Precise orbits"
STDELE	Comparison of osculating elements "Menu>Orbits/EOP>Compare orbits>Osculating elements"
POLUPD	Reformat and update pole files "Menu>Orbits/EOP>Handle EOP files>Convert IERS to Bernese Format"
POLXTR	Compose continuous pole file from a series of pole files "Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files"
Processing part:	
CODSPP	Single point positioning/clock synchronization using code observations "Menu>Processing>Code-based clock synchronization"
SNGDIF	Form single-difference observation files for code and phase "Menu>Processing>Create baseline files"
MAUPRP	Automatic phase preprocessing (cycle slip detection and correction, outlier detection, update of the ambiguity list) "Menu>Processing>Phase preprocessing"
GPSEST	Main parameter estimation program "Menu>Processing>Parameter estimation"
ADDNEQ2	Combination of solutions based on normal equations "Menu>Processing>Combine normal equation systems"
CODXTR	Extraction summary from CODSPP program output "Menu>Processing>Program output extraction>Code-based clock synchronization"
MPRXTR	Extraction summary from MAUPRP program output "Menu>Processing>Program output extraction>Phase preprocessing"
GPSXTR	Extraction summaries from GPSEST/ADDNEQ2 program output "Menu>Processing>Program output extraction>Parameter estimation/stacking"
Simulation part:	
GPSSIM	Simulation of GPS / GLONASS code / phase observations "Menu>Service>Generate simulated observation data"
Service part:	
STA2STA	Convert station information files "Menu>Service>Station information files>Convert station information files"
STAMERGE	Merge station information files "Menu>Service>Station information files>Merge station information files"
RNX2STA	Extract station information from RINEX files "Menu>Service>Station information files>Extract information from RINEX"
SNX2STA	Extract station information from a SINEX file "Menu>Service>Station information files>Extract information from SINEX"
<i>continued on next page</i>	

<i>continued from previous page</i>	
Name	Purpose Location in menu system
CHGHED	Change header information of Bernese observation files "Menu>Service>Bernese observation files>Change header"
SATMRK	Mark / reset flags in Bernese observation files "Menu>Service>Bernese observation files>Mark/delete observations"
OBSSPL	Split Bernese observation files "Menu>Service>Bernese observation files>Split observation files"
SATGRA	Pseudo-graphical display of Bernese observation files "Menu>Service>Bernese observation files>Create pseudo-graphics"
REDISP	Display binary residual files "Menu>Service>Residual files>Display residual file"
RESRMS	Check residuals for outliers, residuals statistics "Menu>Service>Residual files>Create residual statistics"
FODITS	Analysis of time series "Menu>Service>Coordinate tools>Analysis of time series"
HELMR1	Helmert transformation between two coordinate files "Menu>Service>Coordinate tools>Helmert transformation"
COMPAR	Comparison of several coordinate sets, repeatabilities "Menu>Service>Coordinate tools>Coordinate comparison"
VELDIF	Compare station velocities "Menu>Service>Coordinate tools>Velocity comparison"
NUVELO	Compute NUVEL1 or NUVEL1A velocities "Menu>Service>Coordinate tools>Compute NUVEL velocities"
COOVEL	Propagate coordinates with a given velocity field "Menu>Service>Coordinate tools>Extrapolate coordinates"
COOSYS	Apply Helmert parameters to a coordinate set "Menu>Service>Coordinate tools>Coordinate transformation"
ETRS89	Transform coordinates given in ITRFxx into ETRS89 "Menu>Service>Coordinate tools>Transform to ETRS89"
CRDMERGE	Merge coordinate and velocity files "Menu>Service>Coordinate tools>Merge coordinate/velocity files"
GRDS1S2	Extract atmospheric tidal loading coefficients "Menu>Service>Coordinate tools>Extract atmospheric tidal loading coefficients"
CCRNXC	Combine / concatenate / manipulate clock data "Menu>Service>Clock tools>Combine/manipulate clock RINEX files"
CLKEST	Generate high rate clock corrections "Menu>Service>Clock tools>Epoch-wise clock interpolation"
IONEST	Estimation of ionosphere models "Menu>Service>Ionosphere tools>Local ionosphere model estimation"
BASLST	Create list of baselines "Menu>Service>Automated processing>Select baselines"
MKCLUS	Form clusters of observation files "Menu>Service>Automated processing>Form clusters"
RESCHK	Detect misbehaving stations / satellites "Menu>Service>Automated processing>Detect misbehaving stations/satellites"

continued on next page

<i>continued from previous page</i>	
Name	Purpose Location in menu system
LEOAUX	Extract auxiliary (e.g., attitude) information for LEO processing "Menu>Service>LEO utilities>Prepare LEO auxiliary information"
KINPRE	Convert kinematic positions (KIN) to SP3c-format "Menu>Service>LEO utilities>Convert kinematic pos. to precise orbits"
IRV2STV	Convert IRV or PRE files to state vectors "Menu>Service>SLR utilities>Convert IRV/PRE to state vectors"
CPFSP3	Convert CPF to precise orbit files "Menu>Service>SLR utilities>Convert CPF to precise orbit files"
SP3CPF	Convert precise orbits to CPF files "Menu>Service>SLR utilities>Convert precise orbits to CPF files"
SNX2SLR	Prepare SLR data handling file "Menu>Service>SLR utilities>Prepare SLR data handling file"
QLRINEXO	Convert SLR Quick-look format to RINEX "Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX"
CRD2RN XO	Convert SLR CRD format to RINEX "Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX"
QLRSUM	Create SLR quick-look residual statistics "Menu>Service>SLR utilities>Create quick-look residual statistics"
Conversion part:	
SNX2NQ0	Convert SINEX files (V0.05, V1.00) into Bernese normal equation files for ADDNEQ2 and creation of coordinate- and velocity-files. "Menu>Conversion>SINEX to normal equations"
TROTRO	Manipulation of troposphere SINEX files "Menu>Conversion>Manipulate troposphere SINEX files"
ATX2PCV	Convert antenna phase center corrections into the Bernese format "Menu>Conversion>ANTEX to Bernese format"
OBSFMT	Convert binary header- and observation-files into ASCII "Menu>Conversion>Observation files>Binary to ASCII"
FMT OBS	Convert ASCII into binary header- and observation-files "Menu>Conversion>Observation files>ASCII to binary"
RESFMT	Convert binary residual files into ASCII "Menu>Conversion>Residual files>Binary to ASCII"
FMTRES	Convert ASCII residual files into binary "Menu>Conversion>Residual files>ASCII to binary"
STDFMT	Convert standard orbit and radiation pressure coefficient files into ASCII "Menu>Conversion>Orbit files>Binary to ASCII"
FMTSTD	Convert ASCII into standard orbit and radiation pressure coefficient files "Menu>Conversion>Orbit files>ASCII to binary"
NEQ2ASC	Convert binary NEQs from ADDNEQ2 into ASCII and vice versa "Menu>Conversion>Normal equations (binary/ASCII)"
<i>continued on next page</i>	

<i>continued from previous page</i>	
Name	Purpose Location in menu system
Programs which are not directly accessible through the menu system:	
AMBCHK	Check resolved ambiguities from different resolution strategies
ERPEST	Estimate amplitudes of specific frequencies from ERP results
POLINT	Concatenate pole information
SUBDIF	Compare different sub-daily ERP models
Miscellaneous programs:	
MENUAUX	Menu interface program
GETKEY	BPE utility
PUTKEYW	BPE utility
STA2ID	BPE utility

Chapter 15: “Clock Estimation” (page 353), Chapter 16: “Estimation of Satellite Orbits and Earth Orientation Parameters” (page 375), Chapter 17: “Orbit Determination for Low Earth Orbiters” (page 391), and Chapter 18: “Antenna Phase Center Offsets and Variations” (page 403). All of them start with a theoretical introduction to the topic and demonstrate the specific use of the software. Specific aspects of processing SLR measurements are discussed in Chapter 19: “Satellite Laser Ranging (SLR)” (page 423). The first part of this documentation finishes with the description of the simulation tool in Chapter 20: “Data Simulation Tool GPSSIM” (page 441).

The second part of the documentation is focusing on technical aspects. In Chapter 21: “The Menu System” (page 451) the features of the menu system and its efficient use are explained. Chapter 22: “Bernese Processing Engine (BPE)” (page 479) details the basic functions of the *Bernese Processing Engine* and shows how to adapt it to your own applications. It contains also a list of useful tools, programs and options for automated processing with the *Bernese GNSS Software* Version 5.2.

In Chapter 23: “Processing Examples” (page 531) the processing examples provided together with the software are described. Here you find a demonstration on how to process GNSS data for different applications with the *Bernese GNSS Software*. The chapter contains numerous references to the first part of the documentation and is a useful starting point to understand the processing steps and to develop your own processing schemes. The tutorial prepared for the participants of the *Bernese Introductory Course* may be downloaded at <http://www.bernese.unibe.ch> and it may act as a useful complement to this Chapter.

Chapter 24: “Data Structure” (page 679) gives examples and short descriptions for all file types available in the *Bernese GNSS Software*. The document terminates with Chapter 25: “Installation Guide” (page 775) (separately for Windows and UNIX platforms) and Chapter 26: “The Step from Version 5.0 to Version 5.2” (page 801).

Note that UNIX syntax for variables in paths to filenames is used consistently in this book (e.g., $\${X}/GEN/$). On Windows platforms you have to use the corresponding syntax (e.g., $\%X\%GEN$) for variables in path names outside the menu input fields.

1.5. Acknowledgments

The preparation of the new version of the *Bernese GNSS Software* would not have been possible without the support and help of a number of persons and institutions outside our institute. Many improvements were triggered by the daily processing at the CODE analysis center (AC), representing a high-end application of the software regarding accuracy, reliability and robustness. This activity allows us to thoroughly test the software every day. The contributions from the CODE partners, in particular from the Swiss Federal Office of Topography (swisstopo), Wabern, Switzerland, the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt a.M., Germany, and the Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG), Munich, Germany are gratefully acknowledged. In particular, the development of the SLR processing and the multi-GNSS (with focus on Galileo) capabilities were directly supported by BKG.

Important software developments were performed at the Technische Universität München (TUM), Germany, by Urs Hugentobler and his group. Peter Steigenberger¹ has carried out several reprocessing efforts in the frame of the CODE collaboration, leading to important software improvements. In the frame of other research projects the software could benefit from developments by Carlos Rodriguez-Solano². Mathias Fritsche³ from Institut für Planetare Geodäsie, Technische Universität Dresden (IPG), Germany also contributed significantly in the frame of a collaboration resulting from a research project.

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- *Carine Bruyninx and Veronique Dehant* from Royal Observatory of Belgium (ROB), Brussels, Belgium, for providing the routine `TIDE2000.f` computing tidal station displacements conforming to the latest IERS Conventions,
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- *Duncan Agnew*, University of California, San Diego, USA, for providing the routine `hardisp.f` that served as the basis for the routine `HARSUB.f` interpolating the ocean tidal loading deformations from 11 main to 342 constituents as a part of the latest IERS conventions,
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- *Tonie van Dam* from University of Luxembourg, Luxembourg, for providing a `grdintrp.f` routine that served as the basis for the `GRDS1S2.f` program,
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²Now at Trimble GmbH

³Now at Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ), Germany

- *Doug Hunt* from University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA for designing and developing the BPE client.

The intensive testing of the software at different stages of development has been performed by several institutions. In particular the detailed feedback from Swiss Federal Office of Topography (Elmar Brockmann), Technische Universität Dresden (Mathias Fritsche, Axel Rülke⁴), Technische Universität München (Urs Hugentobler and Peter Steigenberger), Swiss Federal Institute of Technology, Zurich (Michael Meindl and Markus Rothacher), and from several colleagues at Bundesamt für Kartographie und Geodäsie was very welcome and is acknowledged as well.

Finally, we thank all users of the *Bernese GNSS Software* for providing us feedback on the usage and problems of previous versions of the software, for reporting bugs, finding configurations for new compilers, and providing suggestions for improvements.

⁴Now at Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany

2. Fundamentals

This introductory chapter provides basic facts and fundamental knowledge on the GPS and GLONASS satellites, their equipment, orbits, and emitted signals. The first section focuses on the GPS and GLONASS satellite constellation, the signals and signal processing. The second section gives a short introduction to celestial mechanics applied to GNSS orbits, the effect of perturbing forces, orbit modeling, and numerical integration. The third section summarizes the GNSS observation equations and useful linear combinations of the observables. Additional information may be found in many textbooks on satellite navigation, e.g., in Hofmann-Wellenhof et al. (1992), in Leick (1995), or in Teunissen and Kleusberg (1998a).

2.1. Global Navigation Satellite Systems — A Short Review

In 1973 the U.S. Department of Defense decided to establish, develop, test, acquire, and deploy a spaceborne Global Positioning System (GPS). The result of this decision is the present NAVigation Satellite Timing And Ranging Global Positioning System (NAVSTAR GPS). According to Wooden (1985)

“The NAVSTAR Global Positioning System (GPS) is an all-weather, space-based navigation system under development by the U.S. Department of Defense to satisfy the requirements for the military forces to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis.”

From this definition it is clear that the primary goals for developing the GPS were of a military nature. But the U.S. Congress has allowed civilians to use this system with some restrictions. The civilian use of the NAVSTAR GPS has developed enormously within the last two decades. With the elimination of Selective Availability (SA) on May 2, 2000, the usefulness of the system for civilian users was even more pronounced. One of the most important events for the high-accuracy civilian applications of GPS was the establishment of the International GNSS Service (IGS) in 1994 — Mueller and Beutler (1992); Beutler (1992); Beutler et al. (1999); Dow et al. (2009).

Apart from GPS, nowadays also the Russian counterpart is fully operational: Глобальная навигационная спутниковая система: Global Navigation Satellite System (GLONASS) is the Russian counterpart of the GPS system. Starting with Version 4.2 the *Bernese GNSS Software* is also capable of processing GLONASS data (Habrich 1999). In this section we give more information on both GNSS and compare them.

Other GNSS like Galileo (European GNSS) or BeiDou (Chinese GNSS) are currently under development. The established systems are under dedicated modernization programs at the same time, providing new frequencies and signals to the users. The optimal usage of these new capabilities is one important field of research at the Astronomical Institute of the

University of Bern (AIUB). You may expect an operational usage of these new systems and signals for the future. With the current version Version 5.2 of the *Bernese GNSS Software* it is possible to process also European GNSS (Galileo) data, but (compared to the comfort for GPS and GLONASS data analysis) only on an experimental level. For that reason we have not yet included specific sections with a detailed description on this system into this chapter.

2.1.1. GPS System Description

2.1.1.1. GPS Satellites and Their Constellation

The GPS satellites are located in six orbital planes on almost circular orbits with an altitude of about 20 200 km above the surface of the Earth, inclined by 55° with respect to the equator (see Figure 2.1). The height of the satellites results in orbital periods of approximately 11 hours 58 minutes (half a sidereal day). Consequently, almost identical Earth–satellite configurations are repeated every sidereal day. For that reason the Figure 2.2 shows exactly one ground track line per GPS satellite — in total 32 different ground tracks. Due to this specific behaviour the GPS satellites do not need to be equally distributed within the orbital planes (see Figure 2.3) to ensure the global coverage needed for navigation purposes.

Two numbers are commonly used to label GPS satellites. The satellite vehicle number (SVN) is the serial number of the satellite. The pseudo-random noise (PRN) number is part of the pseudo-random noise code which is transmitted by each satellite to uniquely identify itself in the constellation (see below). While the SVN is attributed always to one and the same physical satellite, the PRN numbers may be permuted within the constellation.

The first GPS satellite, PRN 04, was launched on February 22, 1978. PRN 04 was the first in a series of 11 so-called Block I satellites. The Block I satellites had an inclination of about 63° with respect to the Earth's equator. The test configuration was optimized for

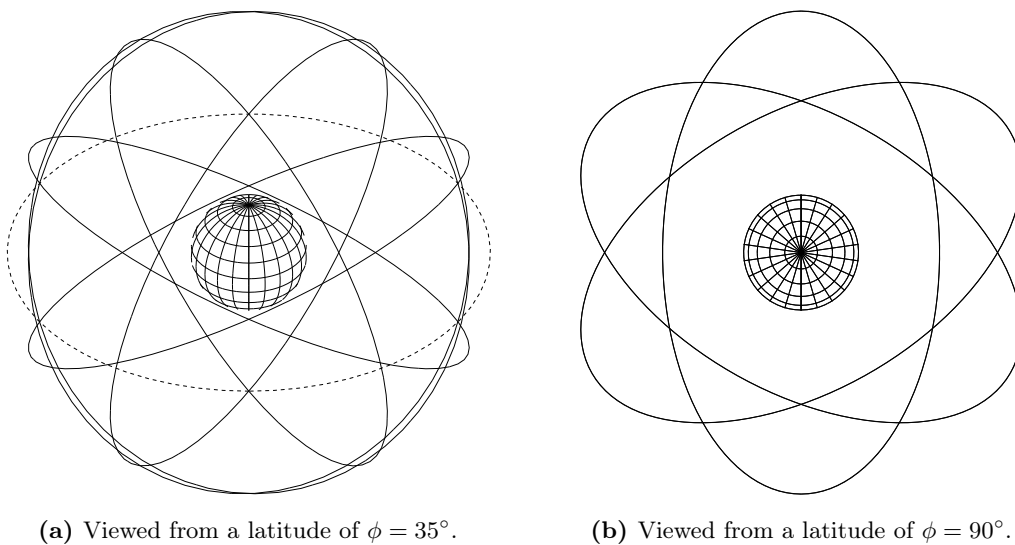


Figure 2.1.: GPS orbits (Earth and orbital planes in scale).

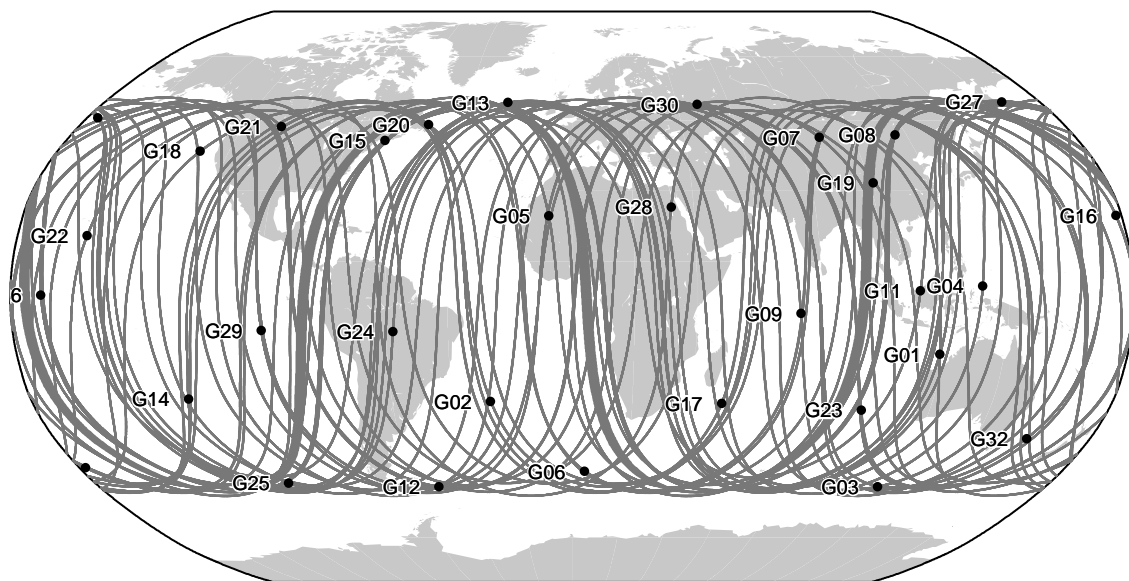


Figure 2.2.: Groundtrack of the GPS constellation during 10 days in September 2015.

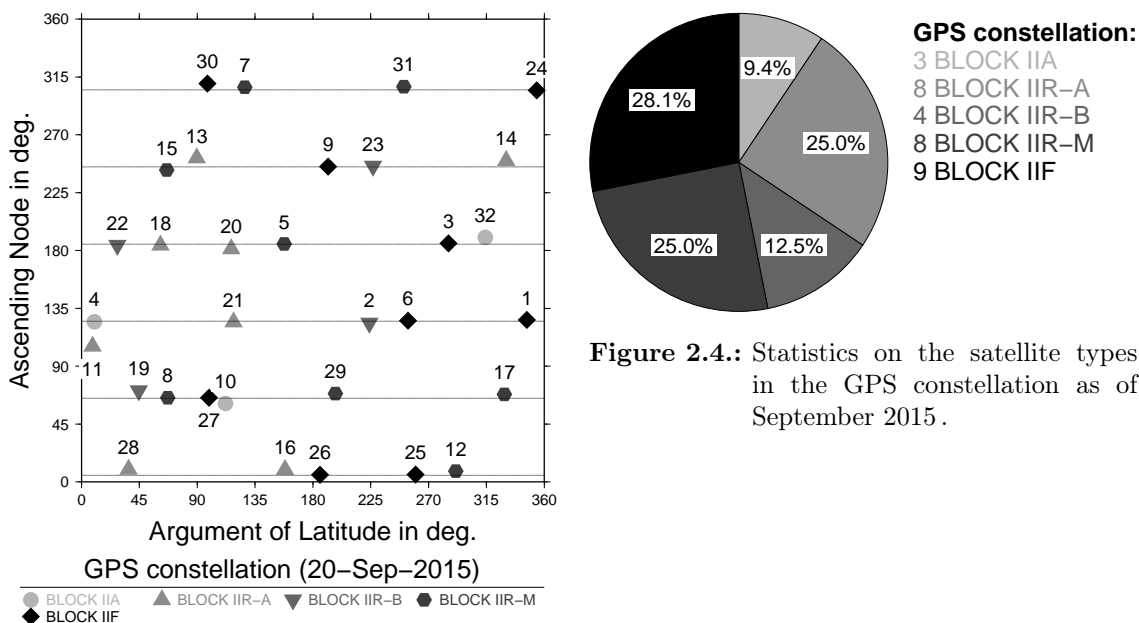


Figure 2.3.: GPS satellite types and their distribution in the constellation as of September 2015.

the North American region in the sense that four or more satellites could be observed there for a considerable fraction of the day. The test configuration was not optimal in other parts of the world. The last Block I satellite was deactivated end of March 1996. These satellite are only relevant in case of a reprocessing of old observations.

The second generation of GPS satellites (Block II) was introduced with the launch of SVN 14 (PRN 14) in February 14, 1989. The last Block II satellite was deactivated in March 2007. The current constellation (status September 2015) consists of Block IIA,

Block IIR–A, Block IIR–B, Block IIR–M, and Block IIF satellites (see Figures 2.3 and 2.4). The oldest still active satellites are more than 20 years old (in September 2015 the oldest one is SVN 23, launched in November 26, 1990). Between September 2005 and August 2009 eight Block IIR–M satellites and between May 2010 and September 2015 nine Block IIF satellites have been launched. These satellite types are providing additional signals. With 17 out of 32 active GPS satellites they constitute more than half of the entire constellation (see Figure 2.4). Two satellites, SVN 35 and SVN 36, launched in 1993 and 1994, are the only GPS satellites equipped with Satellite Laser Ranging (SLR) reflectors. Both are meanwhile decommissioned from the regular navigation service, only SVN 35 is reactivated from time to time using different unused PRN slots.

Even if since many years more than 30 GPS satellites are continuously active, the nominal constellation still consists of 24 satellites. This allows for a global coverage with at least four satellites above an elevation angle of 20 degrees.

The GPS satellites provide a platform for radio transmitter, atomic clocks, computers, and various equipment used for positioning and for a series of other military projects (e.g., atomic flash detection). The electronic equipment of the satellites allows the user to operate a receiver to measure quasi–simultaneously topocentric distances to more than three satellites. Each satellite broadcasts a message which allows the user to recognize the satellite and to determine its position in space for arbitrary time epochs. The satellites are equipped with solar panels for power supply, reaction wheels for attitude control, and a propulsion system for orbit adjustments.

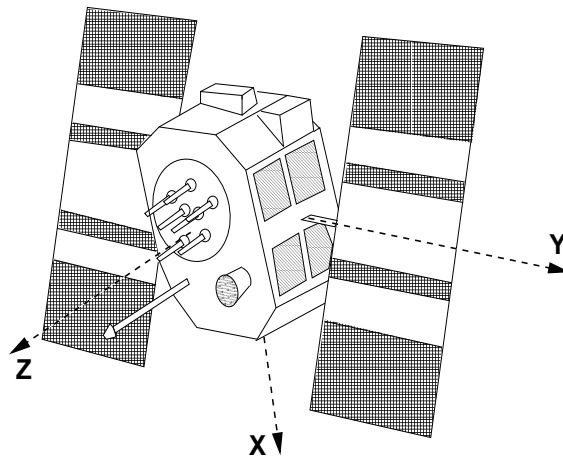


Figure 2.5.: GPS Block II satellite and satellite–fixed coordinate system.

2.1.1.2. The Satellite Signal

All signals transmitted by a GPS satellite are derived from the fundamental frequency f_0 of the satellite oscillator (see Table 2.1). The two sinusoidal carrier frequencies f_1 and f_2 (corresponding wavelengths $\lambda_1 \approx 19$ cm and $\lambda_2 \approx 24$ cm) are right–hand circular polarized and modulated with the codes and the navigation message to transmit information such as the readings of the satellite clocks, the orbital parameters, etc. The so–called biphasic modulation is used as shown in Figure 2.6.

All GPS satellites provide three code signals modulated onto two carrier frequencies: $P(t)$ is the precision code, $C(t)$ the coarse/acquisition (C/A) code and $D(t)$ the navigation

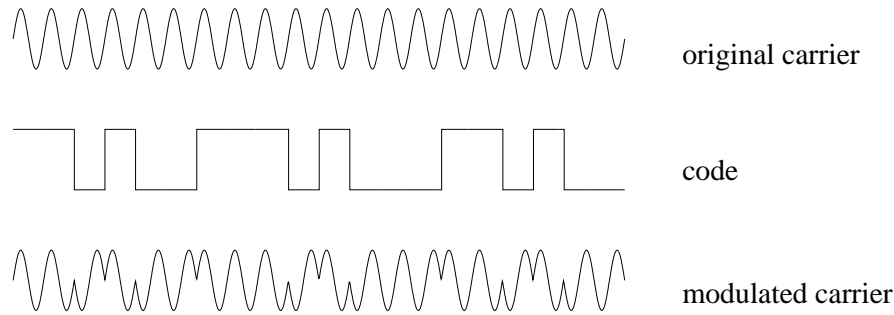


Figure 2.6.: Biphas modulation of the GPS signal.

message. They are sequences of +1 and −1 and, according to Baueršima (1982), modulate the signals as follows:

$$\begin{aligned} L_1(t) &= a_c C(t) D(t) \sin 2\pi(f_1 t) + a_p P(t) D(t) \cos 2\pi(f_1 t) \\ L_2(t) &= b_p P(t) \cos 2\pi(f_2 t), \end{aligned}$$

where a_p , a_c and b_p are the amplitudes of the signals which are not of interest in our context. Since the Block IIR–M generation also the second frequency provides a civil code (L2C-code) — different from the C/A-code signal. Furthermore, starting with the Block IIF GPS satellites, a navigation signal on a third carrier frequency (L_5) is emitted. Thus, for the latest generations of GPS satellites one has (GPS-IS 2013):

$$\begin{aligned} L_2(t) &= b_c C(t) D(t) \sin 2\pi(f_2 t) + b_p P(t) \cos 2\pi(f_2 t) \\ L_5(t) &= c_i I(t) D(t) \sin 2\pi(f_5 t) + c_q Q(t) \cos 2\pi(f_5 t). \end{aligned} \quad (2.1)$$

The new navigation signals on L_2 and L_5 are currently in a test phase (GPS-NAV 2013).

From the equations above it becomes clear that phase measurementw based on the P-code and from the C/A-code or L2C-code are equivalent but shifted by a quarter cycle. This is in particular important if the ambiguities shall be resolved and both types of phase observations are mixed between different satellites (according to the availability — about half of the GPS constellation is providing L2C-code, the other half does not, see Figure 2.4).

Table 2.1.: Components of the GPS satellite signal.

Component	Frequency [MHz]	
Fundamental frequency	f_0	= 10.23
Carrier L_1	$f_1 = 154 \times f_0$	= 1575.42 ($\lambda_1 \doteq 19.0$ cm)
Carrier L_2	$f_2 = 120 \times f_0$	= 1227.60 ($\lambda_2 \doteq 24.4$ cm)
Carrier L_5^a	$f_5 = 115 \times f_0$	= 1176.45 ($\lambda_5 \doteq 25.5$ cm)
P-code $P(t)$	f_0	= 10.23
C/A-code $C(t)$	$f_0/10$	= 1.023
L2C-code $C(t)^b$	$f_0/20$	= 0.5115
Navigation message $D(t)$	$f_0/204600$	= $50 \cdot 10^{-6}$

^aonly available for Block IIF satellites

^bonly available for Block IIR–M and Block IIF satellites

Pseudo–Random Codes

The two codes $P(t)$ and $C(t)$ consist of so-called PRN sequences. The generation of these sequences is based on hardware devices called tapped feedback shift registers. The Coarse-Acquisition or Clear-Access code (C/A-code) is generated by the combination of two 10-bit tapped feedback shift registers where the output of both registers are added again by binary operation to produce the code sequence. A unique code is assigned to each satellite, the sequence has a length of 1023 bits and because of the basic frequency of 1.023 MHz is repeated every millisecond. The time interval between two subsequent bits ($\approx 10^{-6}$ s) approximately corresponds to 300 meters.

The generation of the Precise or Precision code (P-code) is similar, but the length of the resulting sequence is approximately $2.3547 \cdot 10^{14}$ bits corresponding to a time span of about 266 days. The total code is partitioned into 37 one-week segments. One segment is assigned to each satellite and defines the PRN number of the satellite. The P-code repeats itself every week. The time interval between subsequent bits is 10 times smaller than in the case of the C/A-code. Therefore, the accuracy is approximately 10 times higher than for the C/A-code. The P-code may be encrypted. This procedure is called Anti-Spoofing (AS) and converts the P-code to the Y-code usable only if a secret conversion algorithm is accessible to the receiver which is not the case for civilian receivers. Since 1995 the encryption is activated for all satellites.

The Navigation Message

The navigation message is 1500 bits long and contains information concerning the satellite clock, the satellite orbit, the satellite health status, and various other data. The message is subdivided into five subframes. Each subframe contains 10 words. The first word is the so-called “telemetry word” containing a synchronization pattern and some diagnostic messages. The second word of each subframe is the “hand-over word”. This word contains, among others, the so-called Z-count which gives the number of 1.5 second intervals since the beginning of the current GPS week. This number and the P-code give the reading of the satellite clock at signal transmission time. The first subframe contains various flags and the polynomial coefficients which define the satellite clock correction (see Table 2.2).

The second and the third subframe contain the broadcast ephemerides of the satellite (see Table 2.3).

Table 2.2.: Broadcast clock parameters.

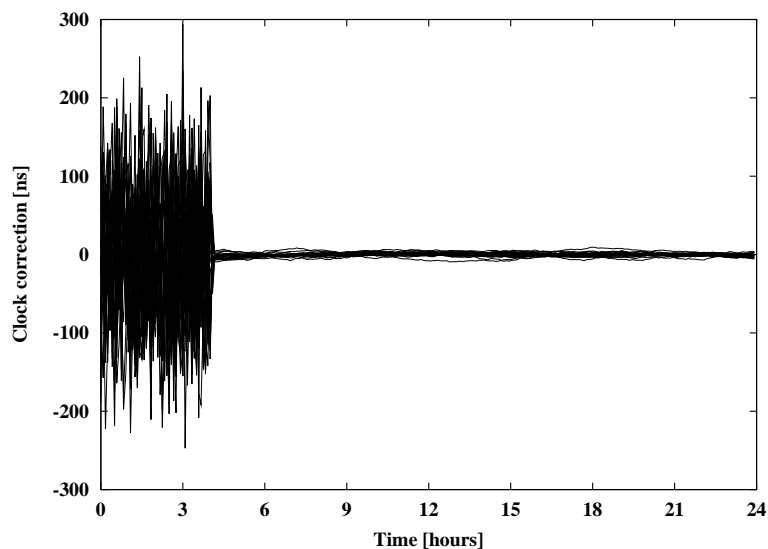
Parameter	Explanation
Code-Flag L_2	Indicator for C/A or P-code on L_2
Week No.	GPS week
L_2 -P-Data-Flag	Indicator for data on L_2 -P-code
SV-Accuracy (URA)	Measure for distance accuracy
SV-Health	Satellite health indicator
T_{GD}	Group delay difference L_1 - L_2 -P-Code
AODC	Age of clock data
t_{0c}	Reference epoch
a_0, a_1, a_2	Clock correction polynomial coefficients

Table 2.3.: Broadcast ephemerides.

Parameter	Explanation
AODE	Age of ephemerides data
t_e	Ephemerides reference epoch
\sqrt{a} , e , M_0 , ω_0 , i_0 , ℓ_0	Keplerian parameters at t_e
dn	Mean motion difference
di	Rate of inclination angle
$d\Omega$	Rate of node's right ascension
C_{uc} , C_{us}	Correction coeff. (argument of perigee)
C_{rc} , C_{rs}	Correction coeff. (geocentric distance)
C_{ic} , C_{is}	Correction coeff. (inclination)

Using the broadcast ephemerides, the Earth-fixed geocentric coordinates of the satellites may be computed according to the formulae given in van Dierendonck et al. (1978). The fourth and the fifth subframe contain data for military use, information on the ionosphere, and so-called almanac data (low-accuracy orbits of all GPS satellites).

The GPS user may decide whether to use the broadcast ephemerides or the precise ephemerides (produced by the IGS) for processing. The broadcast ephemerides are available in real-time, but they have an accuracy of “only” several meters. The precise ephemerides have an accuracy of few centimeters. They are available with a delay of about two weeks for final products, of below one day for so-called rapid products, and of three hours for so-called ultra-rapid products (see Section 2.2.1). The ultra-rapid products are predicted and may, therefore, be used for real-time or near real-time applications. With the start of the real-time service the IGS provides not only precise orbits but also the corresponding satellite clock corrections in real-time (Caissy et al. 2012). With an accuracy below one decimeter in the predicted part they are considerably better than broadcast orbits.

**Figure 2.7.:** SA switched off on May 2, 2000 — effect on GPS satellite clocks.

The satellite clock corrections are required for processing. The accuracy of this information in the broadcast message was artificially degraded (Selective Availability, SA) for non-privileged users until May 2, 2000, when the degradation was disabled by the U.S. Figure 2.7 illustrates the effect of disabling SA on the GPS satellite clocks. The effect of SA was fully eliminated in geodetic applications when only relative positions of receivers were estimated. The IGS precise orbits contain highly accurate satellite clock corrections, too.

2.1.1.3. Signal Processing

The receivers contain elements for signal reception and signal processing (antenna, pre-amplifier, radio frequency section, microprocessor, storage device, control device, and power supply). After signal input from the antenna, the signals are discriminated, i.e., separated into satellite-specific signals. Usually this is achieved through the C/A-codes which are unique for each satellite. The basic elements of the radio frequency section are oscillators to generate a reference frequency, filters to eliminate undesired frequencies, and mixers. The *pseudorange measurements* are achieved as follows: a reference carrier is generated in the receiver and then modulated with a copy of the known PRN code. This modulated reference signal is correlated with the received satellite signal. Assuming that the receiver and satellite clocks are perfectly synchronized (clock corrections are introduced later in Section 2.3) this correlation yields directly the travel time τ_k^i (or, multiplied by the velocity of light c , the so-called pseudorange $c \cdot \tau_k^i$) from satellite i to receiver k .

The *phase measurements* are based on processing the reconstructed signal carriers. This signal is usually obtained by the code demodulation technique using the correlation between the received signal and the signal copy generated by the receiver. Other techniques must be used for the L_2 phase in C/A-code receivers or for both phases in the case of the codeless receiver. One technique is the so-called squaring technique, where the received signal is multiplied with itself and hence all “ $\pm\pi$ modulations” are removed. The result is the unmodulated squared carrier with half the period. From this squared carrier a sine wave is derived with a wavelength of only half the wavelength of the original signal. Another possibility is the so-called cross-correlation technique. Today, also other ingenious tracking techniques are implemented in state-of-the-art geodetic receivers. The tracking technologies of the individual receivers are listed in the Bernese receiver information file.

The receiver records the signal at time t . This signal was transmitted by the satellite at time $t - \tau_k^i$ (see also Section 2.3). At time $t - \tau_k^i$ the phase of the satellite oscillator equals $\phi^i(t - \tau_k^i)$ and at time t the phase of the receiver oscillator equals $\phi_k(t)$. The receiver thus compares the following two signals:

$$y^i = a^i \cos 2\pi\phi^i(t - \tau_k^i) \quad \text{and} \quad y_k = a_k \cos 2\pi\phi_k(t),$$

where a^i and a_k are the amplitudes of the signals. Multiplying these two signals we obtain:

$$y_k^i = y^i y_k = \frac{a^i a_k}{2} \left\{ \cos 2\pi \left[\phi_k(t) - \phi^i(t - \tau_k^i) \right] + \cos 2\pi \left[\phi_k(t) + \phi^i(t - \tau_k^i) \right] \right\}.$$

After applying a low-pass filter, the high frequency part $\phi^i(t - \tau_k^i) + \phi_k(t)$ is eliminated and (compare Section 2.3)

$$\psi_k^i = \phi_k(t) - \phi^i(t - \tau_k^i) + n_k^i \tag{2.2}$$

may be measured. The accuracy of the phase measurements is about 1 – 3 mm, but the exact number n_k^i of integer wavelengths between the satellite and the receiver is not known at the time of the first measurement. The unknown integer number of cycles n_k^i to be added to the phase measurement to get a pseudorange is called the *initial phase ambiguity* (see also Section 2.3). This phase ambiguity has the same value as long as the receiver keeps lock on the phase transmitted by the satellite.

2.1.2. GLONASS System Description

2.1.2.1. GLONASS Satellites and Their Constellation

The GLONASS (GLObal NAVigation Satellite System or more precisely Глобальная навигационная спутниковая система — read as “GLObalnaya NAvigatsionnaya Sputnikovaya Sistema”) is like the GPS a satellite-based radio-navigation system which provides the user with positioning and timing information. It is operated by the Ministry of Defense of the Russian Federation. The nominal constellation of the GLONASS consists of 24 satellites, equally distributed in 3 orbital planes, which are separated by 120° in the equatorial plane (see Figure 2.8).

The GLONASS satellites are orbiting at an altitude of 19 130 km, i.e., about 1000 km below the GPS satellites (20 200 km). This results in an orbital period of $11^h15^m44^s$ corresponding to $8/17$ of a sidereal day. While the orbital periods of the GPS satellites are in deep 2:1 resonance with Earth rotation, the GLONASS satellites do not show such effects: the GLONASS satellites perform $2\frac{1}{8}$ revolutions per sidereal day, whereas the GPS satellites perform 2 revolutions per sidereal day. For illustration, the ground track of one GLONASS and one GPS satellite are compared in Figure 2.9. Figure 2.9 also shows that the higher inclination of the GLONASS orbital planes ($i = 64.8^\circ$) leads to an improved coverage of the high latitude regions compared to the GPS ($i = 55^\circ$).

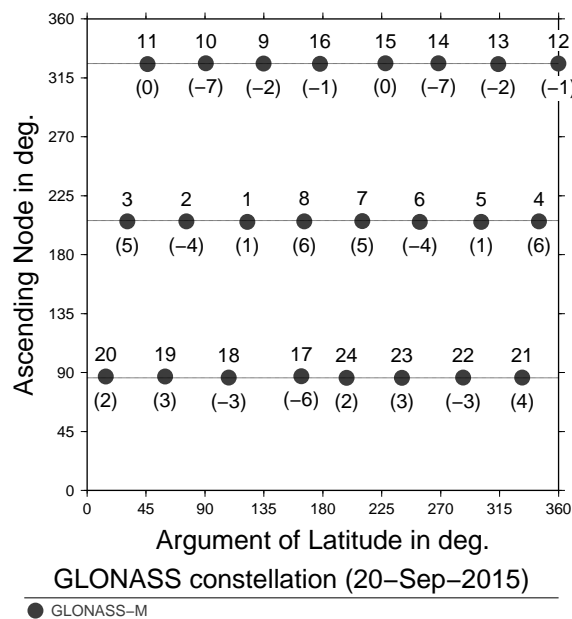


Figure 2.8.: GLONASS satellite types and their distribution in the constellation as of September 2015. The satellites are labeled with the slot number and the frequency number.

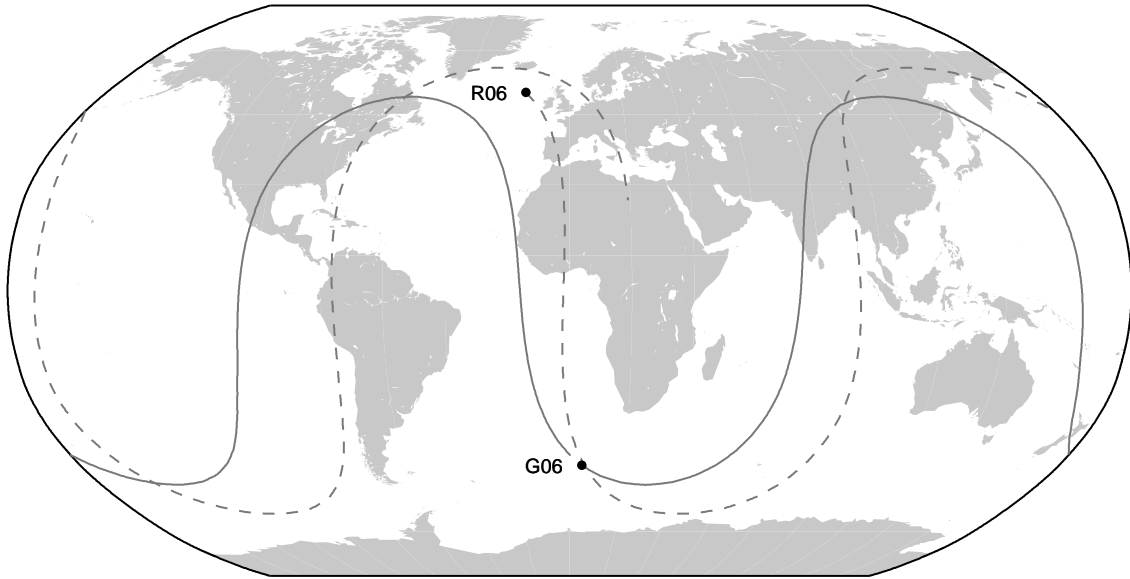


Figure 2.9.: Ground track of GLONASS satellite (R06) compared to the ground track of GPS satellite (G06) for the time interval of one sidereal day.

While the ground track of a GPS satellite repeats every sidereal day, the ground track of a GLONASS satellite repeats only after eight sidereal days. Because the full constellation consists of 8 satellites equally distributed in the orbital plane, the GLONASS geometry repeats itself every sidereal day with each individual satellite shifted by 45° within the orbital plane. After eight sidereal days, each GLONASS satellite has completed 17 orbital revolutions and appears at the same position with respect to an Earth-fixed system. For that reason, all GLONASS satellites follow the same ground track. Because the satellites between the planes are shifted by 15° (a third of the distance between two satellites in one plane) even the satellites of all three planes follow the same ground track — as illustrated in Figure 2.10.

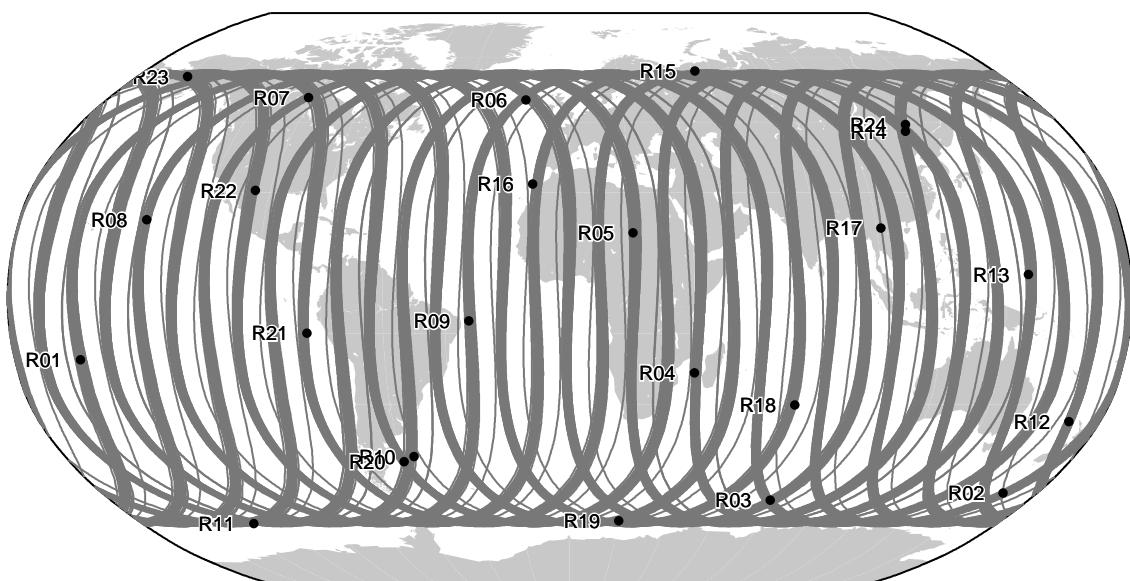


Figure 2.10.: Ground track of the GLONASS constellation during 10 days in September 2015.

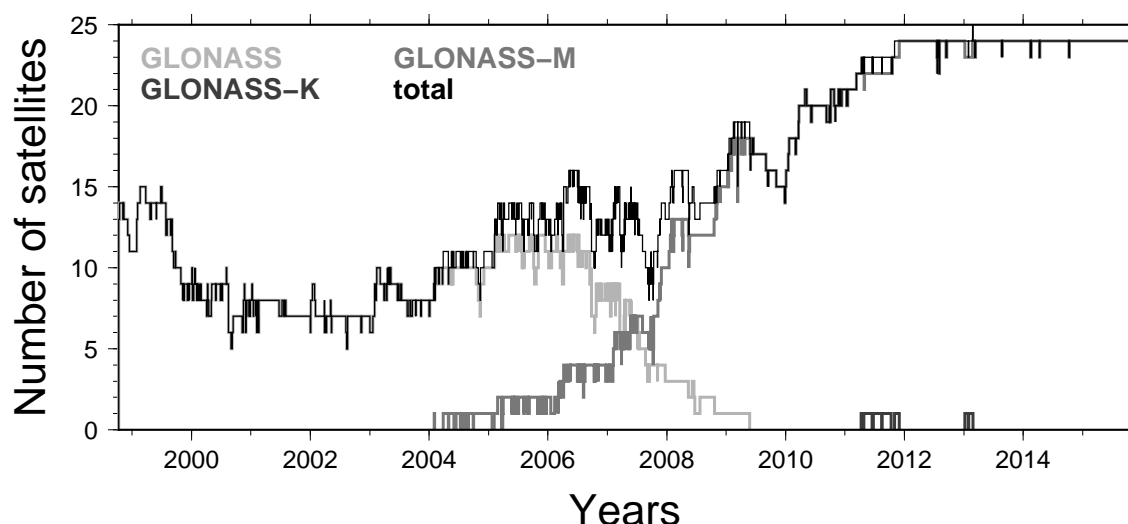


Figure 2.11.: Number of GLONASS satellites included in the IGEX/IGLOS solutions (until end of 2001) and the CODE solutions (since 2002).

After the full constellation of GLONASS with 24 active satellites was achieved in December 1995, the number of operational satellites was steadily decreasing. The launch of three new GLONASS satellites in December 1998 was the first launch after a lapse of 3 years. It then took two more years until the launch of three more GLONASS satellites in October 2000. After that, each year three new GLONASS satellites were launched (December 2001 until December 2006). This high replacement activity was necessary because the GLONASS satellites of the first generation had a very short lifetime of only one to two years for most of the space vehicles.

With the launch of the first type-M class satellite (also type GLONASS-M) in December 2003 (one out of the triple-launch of December 10), the second generation of GLONASS satellites have been put into orbit. These satellites have a much longer lifetime. The oldest of these satellites still active in September 2015 is SVN 716 (slot number R15, the equivalent of the PRN number for GPS) and was launched in December 2006. With the activation of the satellites launched on November 4, 2011, in December 2011 the full constellation (as shown in Figure 2.8) was established again and is maintained until now. The history of active GLONASS satellites as available in the CODE orbit products is shown in Figure 2.11. By February 26, 2011 the first test satellite of the third generation of GLONASS satellites (type GLONASS-K) was launched. It has an expected lifetime of 10 years and is not part of today's operational constellation.

Information on the latest status of the GLONASS may be found on the web page of the Information-Analytical Center:

<http://www.glonass-ianc.rsa.ru> (English version available).

Already in 1998, the IGS has considered the development of the GLONASS constellation as an alternative or complementary to GPS, when the International Glonass EXperiment (IGEX) was established (Slater et al. 1999; Willis et al. 2000), and later transferred into the International GLONASS Service Pilot Project (IGLOS-PP). In that environment, CODE started to contribute first with a separate GLONASS solution (Ineichen et al. 2000, 2001). Since GPS week 1222 (June 8, 2003) CODE takes part in the IGLOS-PP by delivering rapid and final GLONASS orbits (see IGS Mail 4474) to the IGS. GLONASS ultra-rapid orbits are delivered since July 30, 2003 (see IGS Mail 4530). Five years later

other ACs of the IGS started to contribute GLONASS products. Meanwhile, about half of the contributions are combined GPS/GLONASS products. Since GPS week 1603 (September 28, 2010) also the ultra-rapid orbits of the GLONASS satellites are combined (IGV product series).

2.1.2.2. The Signals of the GLONASS Satellites

The basic observations of the GLONASS are very similar to the observations of the GPS: C/A-code on L_1 , P-code on L_1 and L_2 , and carrier phase measurements on L_1 and L_2 . In addition, the next generation GLONASS satellites will transmit signals on a third carrier frequency L_3 (Povalyaev 2013). A big advantage of the GLONASS with respect to the GPS was the absence of Selective Availability (SA), the artificial degradation of the broadcast satellite clocks. This argument in favor of the GLONASS is no longer valid because SA was deactivated for the GPS on May 2, 2000.

The technology to attribute a signal to a satellite is different in the case of GPS and GLONASS: while GPS is based on Code Division Multiple Access (CDMA), GLONASS uses Frequency Division Multiple Access (FDMA). Therefore, all GLONASS satellites transmit the same C/A- and P-codes, but each satellite uses slightly different carrier frequencies.

The nominal carrier frequencies for the L_1 and L_2 signals may be written as follows:

$$\begin{aligned} f_1^n &= f_1^0 + n \cdot \Delta f_1 \\ f_2^n &= f_2^0 + n \cdot \Delta f_2 \end{aligned}$$

where

n	frequency channel number,
$f_1^0 = 1602 \text{ MHz}$	L_1 frequency for a GLONASS satellite with channel number 0,
$\Delta f_1 = 0.5625 \text{ MHz}$	frequency increment on L_1 for two subsequent channel numbers,
$f_2^0 = 1246 \text{ MHz}$	L_2 frequency for GLONASS satellite with channel number 0,
$\Delta f_2 = 0.4375 \text{ MHz}$	frequency increment on L_2 for two subsequent channel numbers.

The frequency ratio f_2^n/f_1^n is constant for all GLONASS satellites and amounts to 7/9. Because some of the GLONASS frequencies interfere with frequencies used for radio-astronomy, the following changes in the frequency plan have been implemented (GLONASS-ICD 2008):

- Before 1998: each GLONASS satellite had its own frequency number resulting in a range of $n = 1, \dots, 24$.
- 1998–2005: the GLONASS satellites only used frequency channel numbers $n = 0, \dots, 13$. The channel numbers 0 and 13 may be used for technical purposes. Antipodal satellites may use the same channel number.
- After 2005: the GLONASS satellites are using frequency channels $n = -7, \dots, +6$, where the channel numbers +5 and +6 are only used for technical purposes. Antipodal satellites may use the same channel number.

The frequency numbers of the current constellation (September 2015) are given in Figure 2.8. As in the case of GPS, all these signals are derived from one onboard satellite clock to guarantee coherence.

For the future, GLONASS announced to support a third FDMA-based frequency $f_3^n = f_3^0 + n \cdot \Delta f_3$ with $f_3^0 = 1201$ MHz and $\Delta f_3 = 0.4375$ MHz (Povalyaev 2013).

The GLONASS Navigation Message

The entire navigation message is contained in so-called superframes, which have a duration of 2.5 minutes. Each superframe consists of five frames with a duration of 30 seconds. Each of these frames contains the immediate data (data of the transmitting satellite) plus the non-immediate data (almanac information of 5 satellites in case of frames 1–4, almanac information of 4 satellites in case of frame 5). In this way the almanac information of the entire GLONASS system is broadcast within one superframe, whereas the immediate data is repeated 5 times within each superframe.

The immediate data comprise

- the time tag corresponding to the beginning of the frame,
- the time the broadcast ephemerides refer to,
- the health flag for the transmitting satellite,
- the difference between the satellite's clock reading and GLONASS system time,
- the (predicted) difference between the satellite's carrier frequency and its nominal value,
- the ephemerides of the satellite,
- the age of the ephemerides data.

In contrast to the GPS, where the broadcast ephemerides are defined by modified Keplerian elements, the broadcast ephemerides of GLONASS satellites are defined by positions and velocities referring to an Earth-centered and Earth-fixed system (PZ-90.11). In addition, the accelerations of the satellites caused by the Sun and the Moon are given in the same system. Usually, the broadcast ephemerides of the GLONASS satellites are updated every 30 minutes.

The non-immediate data comprise

- information on the health status of all GLONASS satellites,
- the orbital parameters of all GLONASS satellites within the space segment (almanac data),
- the frequency channel numbers of all GLONASS satellites,
- the correction of GLONASS system time with respect to UTC(SU).

For more details we refer to GLONASS-ICD (2008).

2.1.2.3. Comparison between GPS and GLONASS

The main differences between the GPS and the GLONASS are summarized in Table 2.4.

An important difference between the two systems is the effect of the orbit geometry and the constellation design. As a comparison of the two Figures 2.3 and 2.8 shows, the distribution of the GLONASS satellites is more regular than the distribution of the GPS

Table 2.4.: Comparison of the GPS and the GLONASS.

	GPS	GLONASS
Nominal number of satellites	24	24
Orbital planes	6 (separated by 60°)	3 (separated by 120°)
Satellites per orbital plane	4 (unequally spaced)	8 (equally spaced)
Orbital radius	26 560 km	25 510 km
Inclination of orbital planes	55°	64.8°
Revolution period	~ 11 ^h 58 ^{min}	~ 11 ^h 16 ^{min}
Nominal eccentricity	0	0
Ground track repeatability	after one sidereal day	after eight sidereal days
Constellation repeatability	~ 23 ^h 56 ^{min}	~ 23 ^h 56 ^{min}
SLR reflectors	two satellites (both are deactivated)	all satellites
Signal separation technique	CDMA	FDMA
Carrier L_1 (n=1...12)	1575.42 MHz	1602.5625 – 1608.75 MHz
Carrier L_2 (n=1...12)	1227.60 MHz	1246.4375 – 1251.25 MHz
C/A-code	1.023 MHz	0.511 MHz
P-code	10.23 MHz	5.110 MHz
Reference system	WGS-84	PZ-90
Time reference	UTC (USNO)	UTC (SU)

satellites. This has consequences on the number of satellites in view (i.e., the observation geometry) for different regions on the Earth, which is displayed in Figures 2.12 and 2.13.

In the plots for the GLONASS constellation only the three orbital planes are visible as a pattern moving around the Earth in the series of maps. It is noticeable that approximately the same pattern is already repeated after 8 hours (compare the columns of the plots) because of the three orbital planes occupied by the same configuration of satellites. In contrast to this behaviour, the maps for the GPS constellation show a dark area (above Kamchatka peninsula and the northern part of the Pacific Ocean at 01:00 on the upper left plot) — indicating a larger number of satellites. This pattern is moving around the Earth in the series of plots in Figure 2.12. Note that there are regions (e.g., Europe) that do not benefit from this higher number of satellites. Because the GPS satellites only follow one and the same ground track, this figure cannot change until the constellation of satellites is changed. Thus, for GLONASS the observation scenario depends on the geographical latitude only, but for GPS on both the latitude and the longitude.

Another aspect of the influence of the orbit geometry is related to the satellite repetition rate of 8 sidereal days for GLONASS and 1 sidereal day for GPS. Any satellite-specific error source (e.g., uncertainty in the satellite antenna calibration) propagates with this period into a solution. This may result in an eight day period in a solution using GLONASS observations. The corresponding period for GPS is one day, which cannot be detected as long as daily solutions are generated. In Dach et al. (2009) the related orbit geometry effects are discussed in more detail.

2.2. GNSS Satellite Orbits

Precise GNSS orbits are a prerequisite for all applications of the GNSS where high accuracy is required. Today, highest precision GPS and GLONASS orbits are available through the

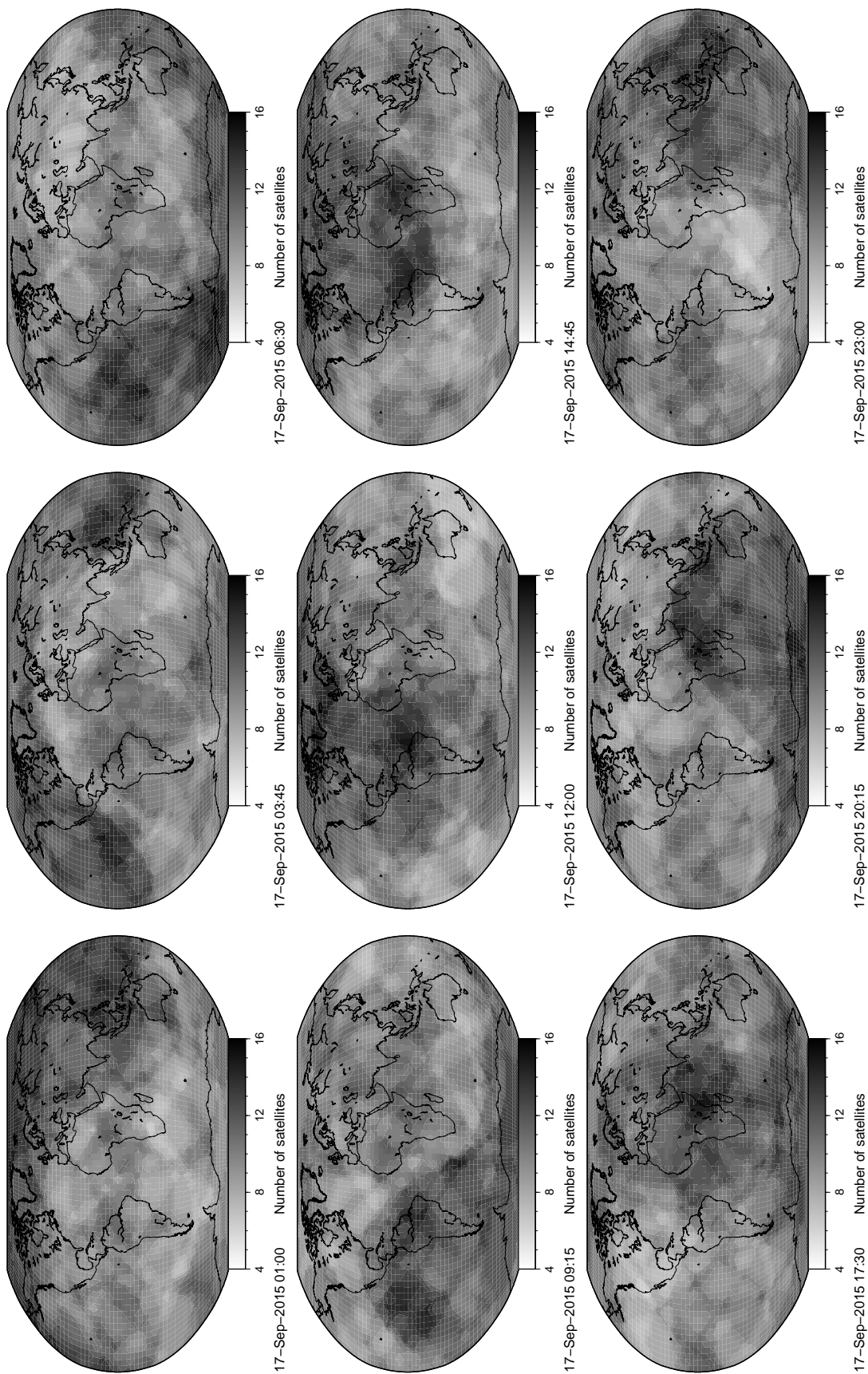


Figure 2.12.: Number of GPS satellites observable during one day.

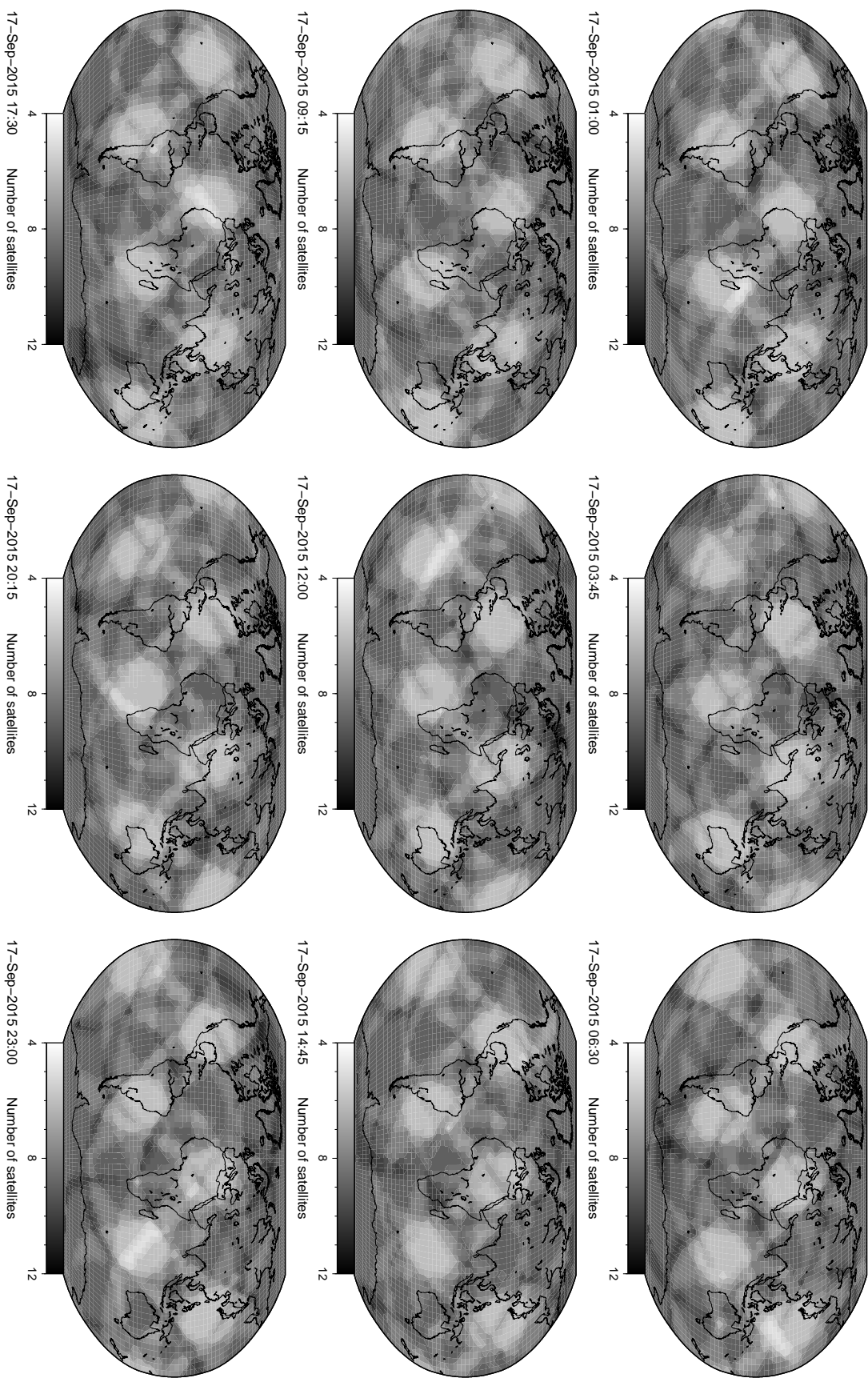


Figure 2.13.: Number of GLONASS satellites observable during one day.

IGS and its ACs (e.g., CODE). In the first section (motivation) we study the impact of orbit errors on the estimated station coordinates. We also include indications of precision for the currently available orbit products (broadcast orbits, CODE orbits, IGS orbits). In the following Sections 2.2.2 and 2.2.3 we present some of the basic concepts of celestial mechanics and orbit modeling relevant for the orbit part of the *Bernese GNSS Software* Version 5.2 .

The steps needed to make precise orbit information, e.g., obtained from the CODE, available for GNSS data processing with the *Bernese GNSS Software* and to introduce broadcast information are presented in Chapter 5. In Chapter 16 details concerning the estimation of orbit parameters are given.

2.2.1. Motivation

Prior to 1992, the orbit quality was considered as one of the primary factors limiting accuracy in the applications of the GPS for geodesy and geodynamics. Since the IGS started its operations on June 21, 1992, this statement is no longer true. Orbits of an unprecedented accuracy are available today for all active GPS satellites with a delay of less than 12 days after the observations. Since January 1, 1996, so-called IGS preliminary orbits were made available only 36 hours after the observation; since June 30, 1996 (beginning of GPS week 860) this type of preliminary orbit is called *IGS Rapid Orbit* and is ready to be used only 17 hours after the observations. The *IGS Final Orbit* is made available 13 days after the observations. A near real-time IGS product, the *IGS Ultra Rapid Orbit*, is generated since March 2000. Since April 19, 2004, these near real-time orbits are delivered four times a day at 3 UT, 9 UT, 15 UT, and 21 UT with an average delay of only 6 hours. The first 24 hours in the files are based on the analysis of GNSS measurements from IGS stations delivering hourly data, the following 24 hours are extrapolated and may be used for real-time applications. From June 8, 2003 (GPS week 1222) onwards, all orbit products generated at the CODE AC for the IGS also contain precise GLONASS orbits obtained in a combined analysis. From the IGS combined GLONASS products are only available for the *Final* and *Ultra Rapid* series (since September 28, 2010 — as an experimental product because of the limited number of contributions). They are obtained in a combination procedure that is independent from the combination of the GPS orbits and are provided in separate precise orbit files.

What is the impact of this development? In order to answer this question we study the effect of unmodeled orbit errors on the estimated station coordinates. There is a crude, but handy *rule of thumb* which was derived by Baueršima (1983), giving the error Δx in a component of a baseline of length l as a function of an orbit error of size ΔX :

$$\Delta x(\text{m}) \approx \frac{l}{d} \cdot \Delta X(\text{m}) \approx \frac{l(\text{km})}{25'000(\text{km})} \cdot \Delta X(\text{m}), \quad (2.3)$$

where $d \approx 25'000$ km is the approximate distance between the satellite system and the survey area. For sessions of about 1–2 hours (and shorter) Eqn. (2.3) gives satisfactory results (Beutler 1992). For permanent site occupations, the formulae given by Zielinski (1988), which were derived using statistical methods and are more optimistic by a factor of 4–10, seem to be more appropriate.

Table 2.5 gives the actual baseline errors in meters and in parts per million (ppm) for different baseline lengths and different orbit qualities as they have to be expected based on Eqn. (2.3). What orbits are available today? Let us mention seven types of orbits,

Table 2.5.: Errors in baseline components due to orbit errors.

Orbit Error	Baseline Length	Baseline Error	Baseline Error
2.5 m	1 km	0.1 ppm	– mm
2.5 m	10 km	0.1 ppm	1 mm
2.5 m	100 km	0.1 ppm	10 mm
2.5 m	1000 km	0.1 ppm	100 mm
0.05 m	1 km	0.002 ppm	– mm
0.05 m	10 km	0.002 ppm	– mm
0.05 m	100 km	0.002 ppm	0.2 mm
0.05 m	1000 km	0.002 ppm	2 mm

namely Broadcast Orbits, CODE Ultra Rapid Orbits, CODE Rapid Orbits, CODE Final Orbits, IGS Ultra Rapid Orbits, IGS Rapid Orbits, and IGS Final Orbits. The estimated accuracies, based on analyses performed by the IGS analysis center coordinator (ACC), are given in Table 2.6. The numbers quoted in Table 2.6 are conservative numbers. The consistency between the contributions of the best IGS ACs, including CODE, is of the order of 1.0 – 1.5 cm for the IGS Final Orbits, 1.0 – 2.0 cm for the IGS Rapid Orbits, and below 5 cm for the GLONASS orbits. The comparison between the predicted first 12 hours of the IGS Ultra Rapid Orbits with the IGS Rapid Orbits is for most satellites regularly at the order of 5 cm (available for real-time and near real-time applications!).

Table 2.6.: Estimated quality of orbits in 2015 (see <http://www.igs.org/products>).

Orbit Type	Quality	Delay of Availability	Available at
Broadcast Orbits	~ 1 m	Real-time	Broadcast message
CODE Ultra Rapid Orbits	< 5 cm	Real-time	CODE through FTP
CODE Rapid Orbits	< 2.5 cm	After 12 hours	CODE through FTP
CODE Final Orbits	< 2.5 cm	After 5–11 days	CODE, IGS Data Centers
IGS Ultra Rapid Orbit (pred)	~ 5 cm	Real-time	IGS Data Centers
IGS Ultra Rapid Orbit (obs)	< 3 cm	After 3 hours	IGS Data Centers
IGS Rapid Orbit	< 2.5 cm	After 17 hours	IGS Data Centers
IGS Final Orbit	< 2.5 cm	After ~13 days	IGS Data Centers

2.2.2. Celestial Mechanics

This section provides a short introduction into celestial mechanics and GNSS orbit modeling used in the *Bernese GNSS Software*. An extended presentation of celestial mechanics, orbit modeling, and related topics may be found in Beutler (2005).

2.2.2.1. The Keplerian Orbit

The mathematical description of a satellite orbit would be very simple if the gravity field of the Earth were spherically symmetric, if the Earth were the only celestial body acting on the satellite, and if, moreover, non-gravitational forces like air-drag and radiation

pressure would not exist. Maybe life on Earth would be problematic in this case, however.

Under these circumstances the geocentric orbit $\mathbf{r}(t)$ of a satellite in inertial space is described by a simple differential equation system of second order in time, the so-called equations of motion for the case of the two-body problem (actually even a reduced version of the two-body problem because we will always be allowed to neglect the satellite's mass for the gravitational attractions):

$$\ddot{\mathbf{r}} = -GM \frac{\mathbf{r}}{r^3}, \quad (2.4)$$

where GM is the product of the constant of gravity and the mass of the Earth, r is the length of the geocentric radius vector \mathbf{r} of the satellite, and the dot denotes the time derivative.

It is well known that the solution of the equations of motion (2.4) is either an ellipse, a parabola, or a hyperbola. We are obviously only interested in the first type of solutions. In Figure 2.14 we see one possible set of six parameters describing the orbit. Exactly this set is used for orbit characterization in the *Bernese GNSS Software*. Let us make a few comments concerning these orbital elements:

- a is the semimajor axis of the orbit, defining the size of the orbit.
- e is the numerical eccentricity or simply eccentricity of the orbit, describing the shape of the orbit, i.e., the deviation from circularity.
- i is the inclination of the orbital plane with respect to the equatorial plane.
- Ω is the right ascension of the ascending node, i.e., the angle between the direction to the vernal equinox (X -direction in Figure 2.14) and the intersection line of the satellite's orbital plane with the equatorial plane (in the direction of the satellite crossing the equatorial plane from the southern to the northern hemisphere). i and Ω are the Eulerian angles defining the orientation of the orbital plane in the equatorial system.
- ω is called the argument of perigee, the angle (in the orbital plane) between the ascending node and the perigee (measured in the direction of the motion of the satellite).

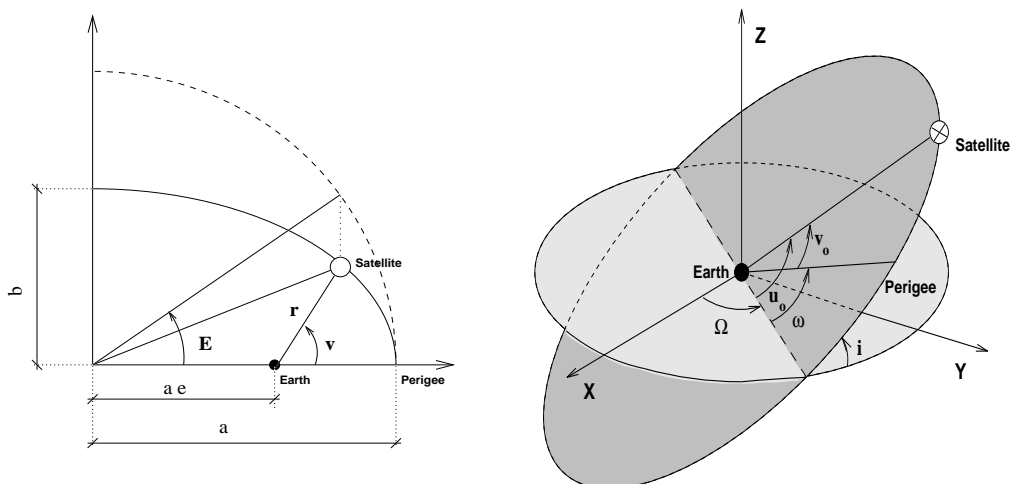


Figure 2.14.: The definition of orbital elements a , e , i , Ω , ω , and u_0 .

u_0 is called the argument of latitude, the angle between the ascending node and the position of the satellite at the (initial) time t_0 . We have $u_0 = \omega + \nu(t_0)$, i.e., the argument of latitude is equal to the sum of the argument of perigee and the true anomaly ν at time t_0 .

The reader familiar with basic astronomy knows that the vernal equinox, defined as the intersection line of the equatorial and the ecliptic planes, is not fixed in space due to precession and nutation. Therefore, we have to specify a reference epoch for equator and equinox to make the inertial frame unique. At the CODE AC we consequently use the system J2000.0. In the early days of the *Bernese GNSS Software* we used the system B1950.0, which is why both systems may still be selected, essentially to maintain compatibility with older results. For all new applications the system J2000.0 should be used. For a precise definition of reference systems we refer to Seidelmann (1992) and McCarthy and Petit (2004).

2.2.2.2. The Osculating Orbital Elements

The actual equations of motion are much more complicated than those of the two-body problem (see Eqn. (2.4)). For a real satellite we have to write:

$$\ddot{\mathbf{r}} = -GM \frac{\mathbf{r}}{r^3} + \mathbf{a}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \dots) = \mathbf{f}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \dots), \quad (2.5)$$

where we recognize the two-body term of the force field as the first term on the right hand side of Eqn. (2.5). As opposed to Eqn. (2.4), we have to take into account the perturbation term \mathbf{a} under real life conditions. The perturbing acceleration \mathbf{a} is characterized by many parameters p_0, p_1, p_2, \dots . Among them are, e.g., the coefficients of the Earth's gravity potential, but also parameters which are not known a priori and which have to be estimated in the orbit determination process. In the case of GNSS satellites the latter parameters are usually associated with solar radiation pressure (see Section 2.2.2.3).

The expression ‘‘perturbation’’ implies that the two-body term is dominant in the equations of motion (2.5). That this is actually true for our applications is illustrated by Table 2.7, where the most important acceleration terms acting on GNSS satellites are characterized.

The fact that the perturbing accelerations are small (in absolute value) compared to the main (two-body) term makes the concept of osculating orbital elements a reasonable

Table 2.7.: Perturbing accelerations acting on a GNSS satellite.

Perturbation	Acceleration m/s ²	Orbit Error after one Day (m)
Two-Body Term of Earth's Gravity Field	0.59	∞
Oblateness of the Earth	$5 \cdot 10^{-5}$	10'000
Lunar Gravitational Attraction	$5 \cdot 10^{-6}$	3000
Solar Gravitational Attraction	$2 \cdot 10^{-6}$	800
Other Terms of Earth's Gravity Field	$3 \cdot 10^{-7}$	200
Radiation Pressure (direct)	$9 \cdot 10^{-8}$	200
Y-Bias	$5 \cdot 10^{-10}$	2
Solid Earth Tides	$1 \cdot 10^{-9}$	0.3

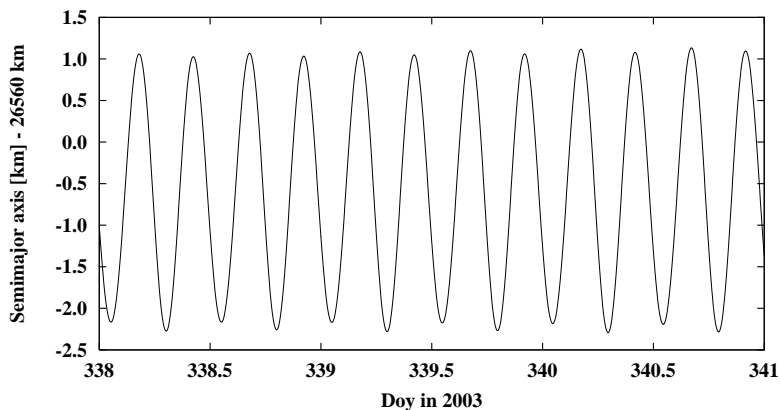


Figure 2.15.: Osculating semimajor axis of PRN 25 during three days of year 2003.

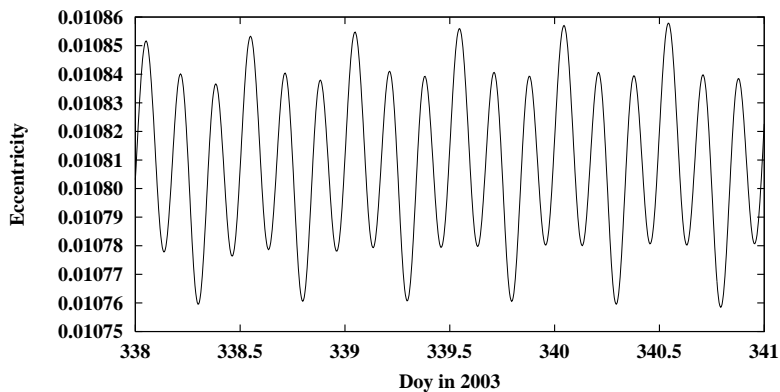


Figure 2.16.: Osculating eccentricity of PRN 25 during three days of year 2003.

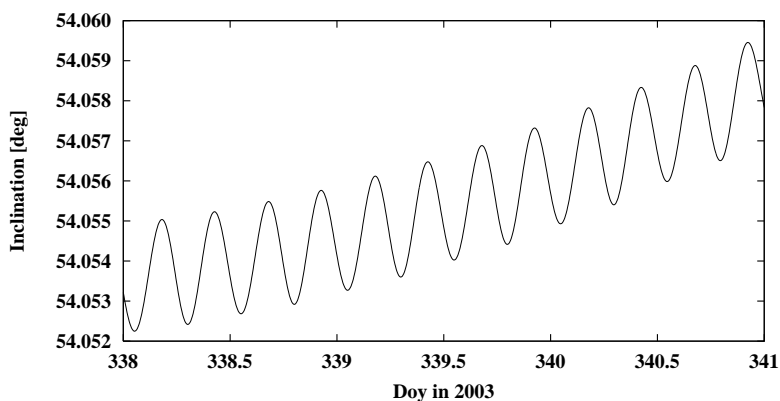


Figure 2.17.: Osculating inclination of PRN 25 during three days of year 2003.

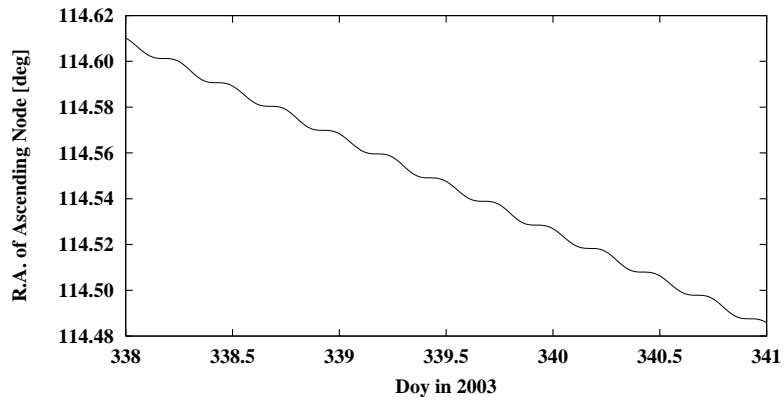


Figure 2.18.: Osculating right ascension of ascending node of PRN 25 during three days of year 2003.

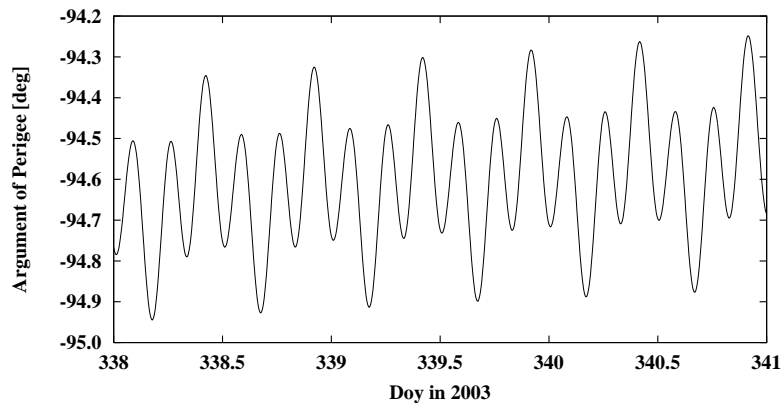


Figure 2.19.: Osculating argument of perigee of PRN 25 during three days of year 2003.

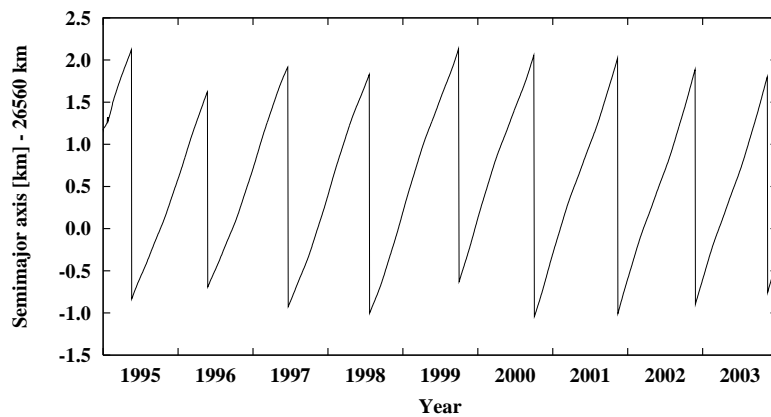


Figure 2.20.: Mean semimajor axis of PRN 25 over nine years.

one. Osculating elements may be defined in the following way: let us assume that we solve Eqn. (2.5) using numerical integration (see Section 2.2.3). As a result we have the satellite's geocentric position and velocity $\mathbf{r}(t)$, $\mathbf{v}(t)$ readily available for each time argument t within the time interval over which the integration was performed. Now, we may formally assign one set of orbital elements $a(t)$, $e(t)$, $i(t)$, $\Omega(t)$, $\omega(t)$, and $u_0(t)$ to each epoch t by computing the Keplerian elements from the position and velocity vectors $\mathbf{r}(t)$, $\mathbf{v}(t)$ using the formulae of the two-body problem. The resulting element set is called the set of osculating elements at time t . This may be done because there is a one-to-one correspondence between the position and velocity vectors and the Keplerian elements. In the *Bernese GNSS Software* the subroutine `{LG}/XYZELE.f` is used to compute elements from one set of position and velocity vectors, `{LG}/EPHEM.f` is used for computing these vectors from the elements. The osculating orbit (defined by the osculating elements) at time t is tangential to the actual orbit at time t . The actual orbit in a time interval $[t_1, t_2]$ is the envelope of all the osculating orbits in this interval.

Figures 2.15 to 2.19 show the osculating elements (except u_0) for GPS satellite PRN 25 over a time interval of three days in the year 2003. We see very pronounced short-period perturbations (one to four times per satellite revolution), most of them caused by the Earth's oblateness. Moreover, we see secular perturbations in the right ascension of the ascending node Ω of about -15° per year and long-period perturbations with periods of half a month for the inclination i (in addition to the short-period perturbations). From these perturbations in the elements we conclude that it is very convenient to think of the actual orbit as a time-series of osculating elements. We may, e.g., follow very nicely the precession of the orbital plane and we have the impression that there are only short-period perturbations in the semimajor axis a .

That there are more complex perturbations involved becomes obvious if we study the mean elements (mean values of the elements over one nodal revolution of the satellite) over longer time intervals. Figure 2.20 shows the development of the mean semimajor axis for PRN 25 over nine years (1995 to 2003).

Figure 2.20 illustrates an essential characteristic of the GPS: there are very pronounced very long-periodic perturbations of the semimajor axes a of the satellites which are actually due to the resonance terms of the Earth's gravity field (Ineichen et al. 2003). These resonance perturbations require relatively frequent station keeping maneuvers for the GPS satellites (about once per year). We see nine such events in Figure 2.20. Without maneuvers (along-track thruster pulses resulting in velocity changes) the distribution of the satellites within the orbital plane could not be maintained in their constellation for a long period of time. It is worth mentioning that GLONASS satellites do not show a similar resonance behavior due to their different orbital period. Station keeping maneuvers of GLONASS satellites are, therefore, not necessary.

At the CODE AC, maneuvers of GPS satellites are detected automatically and epoch and velocity changes of the events are estimated since November 2003. As Figure 2.21 shows, most of the events have a magnitude of a few hundreds of millimeters per second. They are mainly related to the constellation keeping maneuvers. There are also a number of big repositioning events of up to 5000 mm/s magnitude, which take place after a satellite launch or when the satellites are relocated within the constellation.

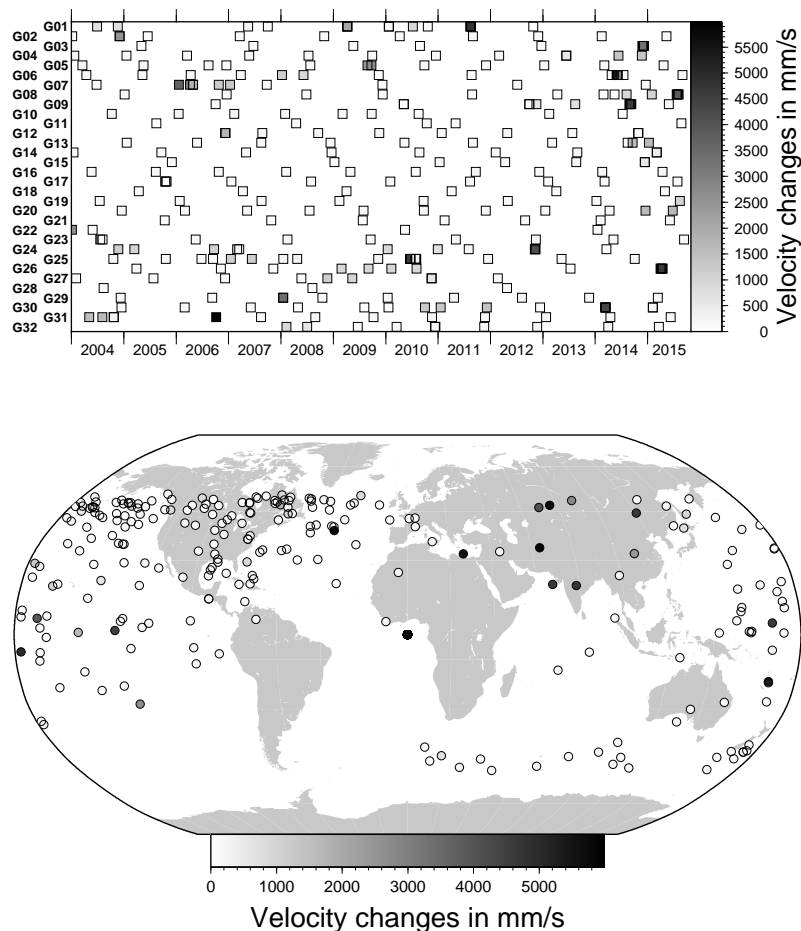


Figure 2.21.: Repositioning events as detected by the CODE AC (top: events per satellite and epoch; bottom: geographical distribution).

2.2.2.3. Deterministic Orbit Parameterization

The force model used within the *Bernese GNSS Software* Version 5.2 includes the Earth's potential up to a selectable degree and order, the gravitational attractions of Sun and Moon as well as of the planets Jupiter, Venus, and Mars, the changes in the gravitational potential due to the solid Earth and ocean tides as well as the related pole tides according to IERS 2010 conventions (Petit and Luzum 2010), and relevant general relativistic corrections (see Section 5.4). Solar radiation pressure is applied according to the model described in this section, including satellite-specific empirical force terms.

When determining or characterizing the orbit of a satellite, we first have to specify six parameters defining the position and the velocity vectors at the initial epoch t_0 of the arc. One might use the Cartesian components of the vectors $\mathbf{r}_0 = \mathbf{r}(t_0)$ and $\mathbf{v}_0 = \mathbf{v}(t_0)$ for that purpose. In the *Bernese GNSS Software*, we use the osculating elements of the initial epoch t_0 to define the initial conditions: $a_0 = a(t_0)$, $e_0 = e(t_0)$, $i_0 = i(t_0)$, $\Omega_0 = \Omega(t_0)$, $\omega_0 = \omega(t_0)$, and $u_{00} = u_0(t_0)$.

Each orbit (or, to be even more precise, each arc) is a solution of the equations of motion (2.5). Numerous parameters have to be known to solve these equations of motion: most of the force field constituents of Table 2.7 are characterized by many parameters (think of the parameters necessary for the Earth's gravity potential). So, in principle, each orbit is characterized by six osculating elements and by the set of all

model parameters. Most of these dynamical parameters are known with sufficient accuracy from other analyses and it is neither necessary nor possible (in most cases) to improve or solve for these parameters in GNSS analyses. Of course, each orbit determination center has to tell what orbit models it actually uses and what numerical values are adopted for the parameters. Within the IGS this is done through so-called Analysis Center Questionnaires. The questionnaire for the CODE AC is accessible at <http://www.aiub.unibe.ch/download/CODE/CODE.ACN> or alternatively at <ftp://ftp.igs.org/pub/center/analysis/code.acn>.

As mentioned previously, among the parameters p_0, p_1, \dots in Eqn. (2.5) are dynamical parameters which have to be estimated for each arc and each satellite individually in order to obtain a reliable orbital fit. If we assume that there are n_p such dynamical parameters, we may state that the orbit or arc is parameterized by $n = 6 + n_p$ parameters. If these parameters are known and if one and the same model is used for the known part of the force field, everybody should be able to reconstruct one and the same trajectory $\mathbf{r}(t)$ of the satellite using numerical integration starting from time t_0 (see Section 2.2.3). In this sense our $n = 6 + n_p$ orbit parameters uniquely specify a satellite orbit.

The dynamical parameters to be used in the *Bernese GNSS Software* shall primarily absorb solar radiation pressure (but other effects may be absorbed by them, as well). According to Beutler et al. (1994) solar radiation pressure-induced accelerations are decomposed into the three orthogonal directions \mathbf{e}_D (unit vector in direction satellite-to-Sun), \mathbf{e}_Y (unit vector along the satellite's solar panel axis, assuming nominal, yaw-steering satellite attitude, see Figure 2.5) and \mathbf{e}_X (completing the right-handed system). The acceleration is then written as

$$\mathbf{a}_{rpr} = \mathbf{a}_0 + D(u)\mathbf{e}_D + Y(u)\mathbf{e}_Y + X(u)\mathbf{e}_X ,$$

where \mathbf{a}_0 is the acceleration due to some a priori model and u is the satellite's argument of latitude. In the original formulation of the so-called Empirical CODE Orbit Model, ECOM, the functions $D(u)$, $Y(u)$ and $X(u)$ are represented as Fourier series truncated after the once-per-revolution terms:

$$\begin{aligned} D(u) &= D_0 + D_{1,C} \cdot \cos u + D_{1,S} \cdot \sin u \\ Y(u) &= Y_0 + Y_{1,C} \cdot \cos u + Y_{1,S} \cdot \sin u \\ X(u) &= X_0 + X_{1,C} \cdot \cos u + X_{1,S} \cdot \sin u . \end{aligned} \tag{2.6}$$

The coefficients D_0 , $D_{1,C}$, $D_{1,S}$, Y_0 , $Y_{1,C}$, $Y_{1,S}$, X_0 , $X_{1,C}$, and $X_{1,S}$ are the nine parameters of the original ECOM implemented in the *Bernese GNSS Software*. Arnold et al. (2015b) have extended the ECOM to better take into account the varyingly illuminated cross section of an elongated satellite body:

$$\begin{aligned} D(u) &= D_0 + \sum_{i=1}^{n_D} (D_{2i,C} \cdot \cos 2i\Delta u + D_{2i,S} \cdot \sin 2i\Delta u) \\ Y(u) &= Y_0 \\ X(u) &= X_0 + \sum_{i=1}^{n_X} (X_{2i-1,C} \cdot \cos(2i-1)\Delta u + X_{2i-1,S} \cdot \sin(2i-1)\Delta u) . \end{aligned} \tag{2.7}$$

This model (used at the CODE AC since January 4, 2015) contains only those components that are needed if the satellite is perfectly flying in a nominal, yaw-steering attitude mode: the D -component only needs even-order periodic terms whereas the X -component only requires odd-order periodic terms. Furthermore, the angular argument for the periodic

functions have been exchanged to $\Delta u = u - u_{\text{Sun}}$ with u_{Sun} being the argument of latitude for the Sun. In the *Bernese GNSS Software* Version 5.2 this extended version of the model — limited to $n_D \leq 2$ and $n_X \leq 1$ — is only available to represent given orbits but not for orbit estimation purposes (see Chapter 5).

Version 5.2 of the *Bernese GNSS Software* is using an updated version of the radiation pressure model developed by Springer et al. (1999) (see Dach et al. 2009) as a priori radiation pressure model \mathbf{a}_0 . The corresponding coefficients are contained in the satellite information file (e.g., `{X}/GEN/SATELLIT.I08`, see Section 24.3.4). Alternatively, you may also use the series of ROCK models or no a priori radiation pressure model — as it is done for new GPS and all GLONASS satellites because of a lack of reliable coefficients.

The acceleration due to the solar radiation pressure is switched off when the satellite is in the Earth's shadow and scaled according to the fraction of the solar disk covered by the Moon during partial lunar eclipses that regularly occur during New Moon.

In summary, in Version 5.2 of the *Bernese GNSS Software* each satellite arc is characterized by six osculating elements and by up to nine dynamical parameters as defined above. The parameterization of the a priori orbits is defined in program ORBGEN (see Section 5.4.3).

2.2.2.4. Pseudo–Stochastic Orbit Parameterization

In addition to the dynamical orbit parameters discussed in the previous section, the *Bernese GNSS Software* Version 5.2 allows to set up so-called pseudo-stochastic orbit parameters, characterizing instantaneous velocity changes at user-determined epochs in user-determined directions. The attribute stochastic is justified because usually a priori weights (i.e., variances) are associated with these parameters. In this sense the procedure is comparable to the “stochastic” orbit modeling used by other groups (Zumberge et al. 1994). The attribute “pseudo” is used because we are not allowing the orbits to adjust themselves continuously at every measurement epoch (as it is the case if Kalman filtering was used).

The use of pseudo-stochastic parameters proved to be a very powerful tool to improve the quality of estimated GNSS satellite orbits. Until about mid 1995 pseudo-stochastic parameters were set up at CODE only for eclipsing satellites and for problem satellites, afterwards pseudo-stochastic pulses in radial and in along-track directions were set up for every satellite twice per day (at midnight and at noon UT). This clearly improved the CODE orbits. For more information we refer to Beutler et al. (1994).

For the orbit determination of LEOs, pseudo-stochastic pulses can be seen as a means to generate contiguous “short-arc solutions” (the generation of usual, non-contiguous short-arcs would require the estimation of additional position offsets at user-defined times). See Chapter 17 for more details on LEO orbit determination.

Another application of the pseudo-stochastic pulses can be found in the program ORBGEN to compensate for differences in the orbit models between an external precise orbit file and the *Bernese GNSS Software*. This is in particular important when you are going to process your data in a Precise Point Positioning (PPP) mode. Please read the Sections 5.4.3 and 10.6 for more details.

2.2.2.5. Variational Equations

If the orbits of the GNSS satellites or LEOs are estimated using the *Bernese GNSS Software*, the partial derivatives of the position and velocity vectors with respect to all orbit parameters have to be computed by the program ORBGEN. Let us consider only the deterministic model parameters at present:

$$p \in \{a, e, i, \Omega, \omega, u_0, p_0, p_1, \dots\} .$$

We have to compute the partials

$$\mathbf{r}_p(t) = \frac{\partial \mathbf{r}(t)}{\partial p} \quad (2.8)$$

$$\mathbf{v}_p(t) = \frac{\partial \mathbf{v}(t)}{\partial p} . \quad (2.9)$$

If the orbit were given by the Eqn. (2.4), it would be rather simple to compute the above partials (at least for the osculating elements): we know the position and velocity vectors as functions of the osculating elements and, therefore, may simply take the partial derivatives of these known functions with respect to the orbit parameters. Since for longer arcs the analytical approximation is not sufficient in all cases, all partials (2.8) and (2.9) are computed in Version 5.2 using numerical integration. The procedure is very simple in principle. We derive one set of differential equations, called variational equations, and one set of initial conditions, for each orbit parameter p . Then we solve the resulting initial value problem by numerical integration (see Section 2.2.3).

Although the procedure to derive variational equations is standard and may be found in many textbooks, we include these variational equations for the sake of completeness. Let us start from the original initial value problem (2.5) and the associated initial conditions:

$$\ddot{\mathbf{r}} = -GM \frac{\mathbf{r}}{r^3} + \mathbf{a}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, p_2, \dots) = \mathbf{f}(t, \mathbf{r}, \dot{\mathbf{r}}, p_0, p_1, \dots) \quad (2.10)$$

$$\mathbf{r}_0 = \mathbf{r}(t_0; a, e, i, \Omega, \omega, u_0) \quad (2.11)$$

$$\mathbf{v}_0 = \mathbf{v}(t_0; a, e, i, \Omega, \omega, u_0) . \quad (2.12)$$

By taking the derivative of the above equations with respect to parameter p we obtain the following initial value problem (variational equation and associated initial conditions):

$$\ddot{\mathbf{r}}_p = \mathbf{A} \cdot \mathbf{r}_p + \mathbf{f}_p \quad (2.13)$$

$$\mathbf{r}_{0,p} = \mathbf{r}_p(t_0; a, e, i, \Omega, \omega, u_0) \quad (2.14)$$

$$\mathbf{v}_{0,p} = \mathbf{v}_p(t_0; a, e, i, \Omega, \omega, u_0) , \quad (2.15)$$

where we assume that for satellites there are no velocity-dependent forces. \mathbf{A} is a 3×3 matrix with $A_{ik} = \partial f_i / \partial r_k$, \mathbf{f}_p is the explicit derivative of \mathbf{f} with respect to the parameter p (equal to zero for osculating elements). The initial conditions are zero for the dynamical parameters.

We thus have to solve one linear initial value problem for each unknown parameter p . This means that, in general, we have to deal with 16 initial value problems in the orbit

generation step (one for the primary equations (2.5), 6 for the osculating elements, and 9 for all dynamical parameters).

The partials with respect to pseudo-stochastic parameters may, as a matter of fact, be computed rigorously as linear combinations of the partials with respect to the osculating elements. This fact is a consequence of some properties of linear differential equation systems. It is thus not necessary to store additional information for the pseudo-stochastic parameters.

2.2.3. Numerical Integration

The initial value problem (2.10), (2.11), (2.12) (initial value problem associated with the primary equations) and the 15 linear initial value problems associated with the variational equations of type (2.13), (2.14), (2.15) are all solved using the technique of numerical integration in the *Bernese GNSS Software* Version 5.2. The only program performing numerical integration is `ORBGEN` (see Section 5.4.3). It may be used to generate an orbit by fitting a set of tabular satellite positions (in the least squares sense) in an orbit determination process; it may also be used to update an orbit using the orbit parameters previously established by the programs `GPSEST` or `ADDNEQ2` and written into a orbital element file (see Chapter 16). In addition, it may be used as an orbit predictor — just by extending the right boundary of the integration interval.

The integration method used in program `ORBGEN` is a so-called collocation method. Let us briefly discuss the principles of such methods: The entire integration interval is divided into subintervals of a user-specified length. To give an example: a one-day interval is, e.g., divided into 24 one-hour subintervals. Within each subinterval (and for each of the 16 differential equation systems to be solved) an initial value problem is set up and solved, or, more precisely numerically approximated. In the first subinterval the initial value problems are precisely those defined in the previous section. In one of the subsequent intervals the initial values at the left subinterval boundary are computed by using the approximated solution of the previous subinterval. This subdivision of the integration interval was (probably) first proposed by Leonhard Euler (1707–1783).

How do we approximate the solution? Euler, in his simple algorithm, approximated each component of the solution vector by a polynomial of degree $q = 2$ by asking the approximating solution to have the same initial values as the true solution and by enforcing the approximating solution to satisfy the differential equation system at the left boundary epoch t_0 . Let us illustrate Euler's principle using the original initial value problem (2.10), (2.11), (2.12):

$$\mathbf{r}(t) = \mathbf{r}_0 + (t - t_0) \cdot \mathbf{v}_0 + \frac{1}{2} \cdot (t - t_0)^2 \cdot \mathbf{f}(t_0, \mathbf{r}_0, \mathbf{v}_0, \dots).$$

The above solution vector may of course be used to compute the velocity vector, too, just by taking the time derivative of the formula for $\mathbf{r}(t)$:

$$\mathbf{v}(t) = \mathbf{v}_0 + (t - t_0) \cdot \mathbf{f}(t_0, \mathbf{r}_0, \mathbf{v}_0, \dots).$$

Let us point out that the Eulerian formulae may be used to compute position and velocity at any point in the vicinity of the initial epoch t_0 . A collocation method has exactly the same property. The only difference lies in the fact that instead of using polynomials

of degree 2, we use higher-degree polynomials in the case of general collocation methods:

$$\mathbf{r}(t) = \sum_{i=0}^q (t - t_0)^i \cdot \mathbf{r}_{0i},$$

where q is the degree of the polynomials, \mathbf{r}_{0i} are the coefficients.

The determination of the coefficients \mathbf{r}_{0i} is the core of the of numerical integration using collocation methods. The principle is very simple to understand and very closely related to Euler's method: the coefficients are determined by asking that the above approximation passes through the same initial values as the true solution, and that the differential equation system is satisfied by the approximating function at exactly $q - 1$ different time epochs within the subinterval considered. The resulting condition equations are non-linear and in general have to be solved iteratively. Needless to say that the integration algorithm was programmed with efficiency in mind.

2.3. Observation Equations

The basic GNSS observation equations are discussed in this section, focusing on the most important aspects only. The implications of satellite-specific GLONASS frequencies are addressed in section 2.3.7.

The following notation is used throughout this section:

t	signal reception time (GPS system time),
τ_k^i	signal traveling time (from satellite to receiver),
t_k	reading of receiver clock at signal reception,
δ_k	correction of receiver clock at time t with respect to GPS time.

The signal reception time may be written as

$$t = t_k - \delta_k . \quad (2.16)$$

Let us further introduce

δ^i	correction of satellite clock at signal emission time $t - \tau_k^i$
$\mathbf{r}_k(t)$	position of receiver k at signal reception time t ,
$\mathbf{r}^i(t - \tau_k^i)$	position of satellite i at signal emission time $t - \tau_k^i$,
$\dot{\mathbf{r}}^i(t)$	velocity of satellite at signal reception time,
ϱ_k^i	geometric distance between satellite i (at signal emission time $t - \tau_k^i$) and receiver k (at signal reception time t).

The geometric distance ϱ_k^i may be written as

$$\varrho_k^i = |\mathbf{r}_k(t) - \mathbf{r}^i(t - \tau_k^i)| = c \tau_k^i - \Delta\varrho_k^i, \quad (2.17)$$

where c is the velocity of light in vacuum and where $\Delta\varrho_k^i$ shall contain all necessary delays due to propagation effects (see Section 2.3.3).

2.3.1. Code Pseudoranges

Using the known codes modulated onto the GNSS carriers, receivers are able to measure the quantity

$$P_k^i = c \left((t + \delta_k) - (t - \tau_k^i + \delta^i) \right) ,$$

which is called pseudorange (because it is biased by satellite and receiver clock deviations from a common time scale). Introducing the geometric distance ϱ_k^i , the code pseudorange for frequency F may also be written as

$$P_{Fk}^i = \varrho_k^i + \Delta\varrho_k^i + c \delta_k - c \delta^i . \quad (2.18)$$

2.3.2. Phase Pseudoranges

Geodetic GNSS receivers measure the difference between two carrier phases. The basic form of the observation equation is (see Eqn. (2.2))

$$\psi_{Fk}^i(t) = \phi_{Fk}(t) - \phi_F^i(t - \tau_k^i) + n_{Fk}^i ,$$

where

- $\psi_{Fk}^i(t)$ is the phase measurement (in cycles) at epoch t and frequency F ,
- $\phi_{Fk}(t)$ is the phase generated by the receiver oscillator at signal reception time t ,
- $\phi_F^i(t - \tau_k^i)$ is the phase of the carrier at emission time $t - \tau_k^i$, and
- n_{Fk}^i is an unknown integer number of cycles (the so-called initial phase ambiguity).

Using a Taylor series expansion we may rewrite the last equation as

$$\psi_{Fk}^i(t) = \phi_{Fk}(t) - \phi_F^i(t) + \tau_k^i f_F + n_{Fk}^i ,$$

where f_F is the frequency of the carrier. The difference

$$\phi_{Fk}(t) - \phi_F^i(t)$$

is zero in the case of ideal oscillators and equal to

$$(\delta_k - \delta^i) f_F$$

if the receiver clock correction δ_k and the satellite clock correction δ^i are taken into account. The observation equation is then given by

$$\psi_{Fk}^i(t) = (\delta_k - \delta^i) f_F + \tau_k^i f_F + n_{Fk}^i .$$

Multiplying this equation by the wavelength λ_F we obtain the phase observation L_{Fk}^i (in meters)

$$L_{Fk}^i = c \tau_k^i + c \delta_k - c \delta^i + \lambda_F n_{Fk}^i .$$

where $c \tau_k^i$ can again be replaced by the geometry term between the satellite and the receiver:

$$L_{Fk}^i = \varrho_k^i + \Delta\varrho_k^i + c \delta_k - c \delta^i + \lambda_F n_{Fk}^i . \quad (2.19)$$

2.3.3. Measurement Biases

The phase measurements and the code pseudoranges are affected by both, systematic and random errors (currently expressed in the term $\Delta\varrho_k^i$). There are many sources of systematic errors: satellite orbits, satellite and receiver clocks, propagation medium, relativistic effects, and antenna phase center variations to name only a few. In the *Bernese GNSS Software* all relevant systematic errors are carefully modeled. Here we discuss only two kinds of systematic errors, namely tropospheric and ionospheric refraction:

T_k^i is the tropospheric refraction (detailed discussion in Chapter 12: “Troposphere Modeling and Estimation”). It is the effect of the neutral (i.e. the non-ionized) part of the Earth’s atmosphere on signal propagation. Note that tropospheric refraction does not depend on the frequency and that the effect is the same for phase and code measurements.

I_k^i is the ionospheric refraction (where more insight is provided in Chapter 13: “Ionosphere Modeling and Estimation”). The ionosphere is a dispersive medium for microwave signals, which means that the refractive index for GPS signals is frequency-dependent.

In a first approximation ionospheric refraction is proportional to

$$\frac{1}{f^2} ,$$

where f is the carrier frequency. If the term I_k^i denotes the effect of the ionosphere on the first carrier L_1 , the ionospheric refraction on the second carrier L_2 may be written as

$$\frac{f_1^2}{f_2^2} I_k^i .$$

Ionospheric refraction delays the GNSS code measurements and advances the carrier phases. The effect has the same absolute value for code and phase measurements, but with opposite signs.

Taking into account these systematic errors, we may refine the observation equations (2.18) and (2.19) for both frequencies, yielding:

$$P_{1k}^i = \varrho_k^i + I_k^i + T_k^i + c \delta_k - c \delta^i \quad (2.20a)$$

$$P_{2k}^i = \varrho_k^i + \frac{f_1^2}{f_2^2} I_k^i + T_k^i + c \delta_k - c \delta^i \quad (2.20b)$$

$$L_{1k}^i = \varrho_k^i - I_k^i + T_k^i + c \delta_k - c \delta^i + \lambda_1 n_{1k}^i \quad (2.20c)$$

$$L_{2k}^i = \varrho_k^i - \frac{f_1^2}{f_2^2} I_k^i + T_k^i + c \delta_k - c \delta^i + \lambda_2 n_{2k}^i . \quad (2.20d)$$

The reader has to be aware of the fact that the consideration of further bias terms in Eqns. (2.20) is required in some cases. For example, the receiver and satellite clock corrections represent not only the instantaneous reading of the receiver or satellite clock but also the related hardware delays. The latter one depend on the frequency and the signal on the satellite side and the frequency, the signal, the tracking technology, and the GNSS for the receivers. The different hardware delay effects are resulting in so-called inter-frequency bias (IFB), inter-system bias (ISB), and Differential Code Bias (DCB) that become relevant when estimating clocks (see Chapter 15: “Clock Estimation”) or ionosphere maps

(see Chapter 13). The Chapter 14: “GNSS Related Biases” is dedicated to this topic.

Another aspect of biases is implicitly included in the geometry term ϱ_k^i as it has been defined in Eqn. (2.17): the position of the receiver and satellite is referencing to the points in the antennas where the signal is emitted and received. To relate these locations to the antenna referene points the so-called antenna phase center corrections need to be considered. These are discussed in a dedicated chapter (Chapter 18: “Antenna Phase Center Offsets and Variations”).

2.3.4. Forming Differences

Let us define the single-difference (between a pair of receivers k and ℓ) by

$$L_{Fk\ell}^i = L_{Fk}^i - L_{F\ell}^i,$$

and the double-difference (between a pair of receivers $k\ell$ and between a pair of satellites ij) by

$$L_{Fk\ell}^{ij} = L_{Fk\ell}^i - L_{Fk\ell}^j.$$

Double-differences are the basic observables in the *Bernese GNSS Software* for many purposes. The corresponding observation equations are

$$P_{1k\ell}^{ij} = \varrho_{k\ell}^{ij} + I_{k\ell}^{ij} + T_{k\ell}^{ij} \quad (2.21a)$$

$$P_{2k\ell}^{ij} = \varrho_{k\ell}^{ij} + \frac{f_1^2}{f_2^2} I_{k\ell}^{ij} + T_{k\ell}^{ij} \quad (2.21b)$$

$$L_{1k\ell}^{ij} = \varrho_{k\ell}^{ij} - I_{k\ell}^{ij} + T_{k\ell}^{ij} + \lambda_1 n_{1k\ell}^{ij} \quad (2.21c)$$

$$L_{2k\ell}^{ij} = \varrho_{k\ell}^{ij} - \frac{f_1^2}{f_2^2} I_{k\ell}^{ij} + T_{k\ell}^{ij} + \lambda_2 n_{2k\ell}^{ij}, \quad (2.21d)$$

where, e.g., $\varrho_{k\ell}^{ij} \equiv \varrho_k^i - \varrho_\ell^i - \varrho_k^j + \varrho_\ell^j$. By forming the double-difference observations, receiver and satellite clock corrections are eliminated (assuming that the receiver clock corrections are known accurately enough to compute the distances ϱ correctly — see Section 2.3.5). If in particular all correlations resulting from the double-differencing are correctly considered, the solution is fully equivalent to a zero-difference solution using the same observations. All effects that are common to all ground stations and that may therefore cancel out in a double-difference solution are absorbed by the satellite clock parameters in the corresponding zero-difference solution.

Using double-difference observations of two different epochs t_1 and t_2 , the triple-difference may be formed. In the *Bernese GNSS Software*, the triple-differences of the phase measurements are used in the data pre-processing (see Section 6.5):

$$\begin{aligned} L_{1k\ell}^{ij}(t_2) - L_{1k\ell}^{ij}(t_1) &= \varrho_{k\ell}^{ij}(t_2) - \varrho_{k\ell}^{ij}(t_1) - \left(I_{k\ell}^{ij}(t_2) - I_{k\ell}^{ij}(t_1) \right) \\ L_{2k\ell}^{ij}(t_2) - L_{2k\ell}^{ij}(t_1) &= \varrho_{k\ell}^{ij}(t_2) - \varrho_{k\ell}^{ij}(t_1) - \frac{f_1^2}{f_2^2} \left(I_{k\ell}^{ij}(t_2) - I_{k\ell}^{ij}(t_1) \right). \end{aligned}$$

In the above equations, we assumed that the unknown ambiguity parameters $n_{1k\ell}^{ij}, n_{2k\ell}^{ij}$ remained the same within the time interval $[t_1, t_2]$ and that, therefore, the phase ambiguities are eliminated (the main advantage of the triple-differences). This is indeed true

if the receivers did not loose lock within this time interval and if no cycle slip occurred. Otherwise an offset for one or two epoch–difference observations result — the remaining ones are not affected. This behaviour is different to the zero– to double–difference case where a cycle slip results in an constant offset in the phase measurements until the end of the satellite path.

Tropospheric refraction usually does not change rapidly with time and is thus considerably reduced on the triple–difference level. This is not true, however, for the ionospheric refraction, which may show very rapid variations in time, particularly in high northern and southern latitudes and near the magnetic equator.

2.3.5. Receiver Clocks

In Section 2.3.4 it became clear that the term $c \delta_k$ in Eqns. (2.18) and (2.19) may be eliminated by forming the differences of the measurements to two satellites (the term $c \delta^i$ may be eliminated using the differences between two receivers). This does not mean, however, that the receiver clock correction δ_k is completely eliminated in the differences. From Eqns. (2.16) and (2.17) it becomes clear, that in order to compute the geometric distance between satellite and receiver at time t (in GPS time scale) the receiver clock correction δ_k has to be known to correct the reading of the receiver clock t_k

$$\varrho_k^i(t) = \varrho_k^i(t_k - \delta_k) .$$

An error $d\delta_k$ in the receiver clock synchronization with GPS time therefore induces the error

$$d\varrho_k^i = -\dot{\varrho}_k^i d\delta_k ,$$

in the distance ϱ_k^i , where $\dot{\varrho}_k^i$ is the radial velocity of the satellite with respect to the receiver. This velocity is zero if the satellite is at the point of closest approach and may reach values up to 900 m/s for zenith distances $z \approx 80^\circ$. We conclude that the error $|d\varrho_k^i|$ in the geometric distance ϱ_k^i induced by a receiver clock correction $|d\delta_k|$ will be smaller than 1 mm if the receiver clock correction $|d\delta_k|$ is smaller than 1 μ s.

2.3.6. Linear Combinations of Observations

It is often useful to form particular linear combinations of the basic carrier phase and/or code measurements. The linear combinations used in the *Bernese GNSS Software* are discussed in this section. We form the linear combinations using either zero– or double–difference measurements. L_1, L_2 represent the phase observables on both frequencies (zero– or double–differences), P_1, P_2 represent the code observables, all in units of meters.

2.3.6.1. Ionosphere–Free Linear Combination L_3

The linear combination

$$L_3 = \frac{1}{f_1^2 - f_2^2} (f_1^2 L_1 - f_2^2 L_2) \quad (2.22)$$

is often called “ionosphere–free” because the first order ionospheric path delay is eliminated. The same is true for the corresponding combination of code measurements

$$P_3 = \frac{1}{f_1^2 - f_2^2} (f_1^2 P_1 - f_2^2 P_2) . \quad (2.23)$$

Taking into account the double-difference phase measurements and neglecting tropospheric refraction T_{kl}^{ij} in Eqns. (2.21c) and (2.21d), the ionosphere-free linear combination has the form

$$L_{3kl}^{ij} = \varrho_{kl}^{ij} + B_{3kl}^{ij}, \quad (2.24)$$

where the ionosphere-free bias B_{3kl}^{ij} may be written as

$$B_{3kl}^{ij} = \frac{1}{f_1^2 - f_2^2} \left(f_1^2 \lambda_1 n_{1kl}^{ij} - f_2^2 \lambda_2 n_{2kl}^{ij} \right). \quad (2.25)$$

This bias cannot be expressed in the form $\lambda_3 n_{3kl}^{ij}$, where n_{3kl}^{ij} is an integer ambiguity¹. If we know the difference $n_{5kl}^{ij} = n_{1kl}^{ij} - n_{2kl}^{ij}$ (the so-called wide-lane ambiguity — see below), however, the ionosphere-free bias B_{3kl}^{ij} may be written as

$$B_{3kl}^{ij} = c \frac{f_2}{f_1^2 - f_2^2} n_{5kl}^{ij} + \underbrace{\frac{c}{f_1 + f_2}}_{\lambda_3} n_{1kl}^{ij}, \quad (2.26)$$

where the first term on the right-hand side is known. The formal wavelength λ_3 is only approximately 11 cm. Therefore, the unknown ambiguity n_{1kl}^{ij} in Eqn. (2.26) is often called narrow-lane ambiguity.

2.3.6.2. Geometry-Free Linear Combination L_4

The linear combination

$$L_4 = L_1 - L_2 \quad (2.27)$$

is independent of receiver clocks, satellite clocks and geometry (orbits, station coordinates). It only contains the ionospheric delay and the initial phase ambiguities and may be used for the estimation of ionosphere models. The same linear combination may be formed using the code observations, too.

2.3.6.3. Wide-Lane Linear Combination L_5

The linear combination

$$L_5 = \frac{1}{f_1 - f_2} (f_1 L_1 - f_2 L_2)$$

is used in the *Bernese GNSS Software* on the double-difference level for phase observations to fix cycle slips and to resolve ambiguities to their integer values. Using Eqns. (2.21c) and (2.21d) and neglecting both, the ionospheric refraction I_{kl}^{ij} and the tropospheric refraction T_{kl}^{ij} , we obtain

$$L_{5kl}^{ij} = \varrho_{kl}^{ij} + \underbrace{\frac{c}{f_1 - f_2}}_{\lambda_5} \underbrace{(n_{1kl}^{ij} - n_{2kl}^{ij})}_{n_{5kl}^{ij}}.$$

The formal wavelength λ_5 is about 86 cm and is roughly four times larger than λ_1 or λ_2 . Therefore, this linear combination is called wide-lane combination and the corresponding ambiguity

$$n_{5kl}^{ij} = n_{1kl}^{ij} - n_{2kl}^{ij}$$

is called wide-lane ambiguity.

¹The ionosphere-free bias may be written as a multiple of a wavelength of 6 mm which has, in fact, no practical application.

Table 2.8.: linear combinations of the L_1 and L_2 observables used in the *Bernese GNSS Software* Version 5.2.

LC	Description	Wavelength in cm	Noise rel to L_1	Ionosphere rel to L_1
L_1	Basic carrier	19	1.0	1.0
L_2	Basic carrier	24	1.0	1.6
L_3	Ionosphere-free LC	0	3.0	0.0
L_4	Geometry-free LC	∞	1.4	0.6
L_5	Wide-lane LC	86	5.7	1.3
L_6	Melbourne-Wübbena LC	86	0.7	0.0

2.3.6.4. Melbourne–Wübbena Linear Combination L_6

The Melbourne–Wübbena combination is a linear combination of both, carrier phase (L_1 and L_2) and code (P_1 and P_2) observables as described by Wübbena (1985) and Melbourne (1985). This combination eliminates the effect of the ionosphere, the geometry, the clocks, and the troposphere. The combination is given by

$$L_6 = \frac{1}{f_1 - f_2} (f_1 L_1 - f_2 L_2) - \frac{1}{f_1 + f_2} (f_1 P_1 + f_2 P_2). \quad (2.28)$$

For double-difference observations, we obtain

$$L_{6kl}^{ij} = \lambda_5 n_{5kl}^{ij}.$$

With “good” P-code data (rms ≤ 1 m) this linear combination may be used for the resolution of the wide-lane ambiguities n_{5kl}^{ij} . On the zero-difference level, the same linear combination gives

$$L_{6k}^i = \lambda_5 n_{5k}^i$$

which means that this linear combination may be used to check zero-difference observations for cycle slips. However, only the difference $n_{1k}^i - n_{2k}^i$ can be checked in this way.

The most important linear combinations and their characteristics are summarized in Table 2.8. L_1 and L_2 (expressed in meters) are assumed to be equally accurate and uncorrelated. Note that the noise of “ L_6 ” is given relative to that of P_1 and P_2 , respectively, since this noise level is pre-determined exclusively by the quality of the P-code data considered (compare also Eqn. (2.28)).

2.3.7. GLONASS Single-Difference Bias Term

Let us shortly address one important issue when dealing with GLONASS observations. As pointed out in Section 2.1.2.2 the GLONASS system uses the FDMA technology for identifying individual satellites. The fact that GLONASS satellites transmit on slightly different frequencies leads to an additional term in the double-difference observation equations which reads (neglecting additional biases):

$$L_{kl}^{ij} = \varrho_{kl}^{ij} - I_{kl}^{ij} + T_{kl}^{ij} + n_{kl}^{ij} \lambda^i + \Delta \lambda^{ij} n_{kl}^j \quad (2.29)$$

where

- $n_{k\ell}^{ij}$ is the double-difference ambiguity with respect to receivers k, ℓ and satellites i, j ,
 $n_{k\ell}^j$ is the single-difference ambiguity with respect to receivers k, ℓ and satellite j ,
 λ^i is the carrier wavelength of satellite i , and
 $\Delta\lambda^{ij}$ is the carrier wavelength difference between satellites j and i , where $\lambda^i = \lambda^j + \Delta\lambda^{ij}$.

The quantity

$$b_{k\ell}^{ij} = \Delta\lambda^{ij} n_{k\ell}^j$$

is called single difference bias term. This term is the main problem in cycle slip detection and destroys the integer nature of double-difference ambiguities in Eqn. (2.29) compared to Eqn. (2.21). For an extensive discussion of GLONASS processing and GPS/GLONASS combination the reader is referred to Habrich (1999).

Part I.

Program Usage and Parameter Estimation

3. Directory Structure and Campaign Setup

3.1. Overview of the Directory Structure

Within the *Bernese GNSS Software* environment we distinguish between four major directory areas:

1. **Program area** containing the core of the program system, source code and executables, master options, BPE scripts, as well as general data files that provide basic information necessary for processing GNSS data. This area is independent from specific users and from any project.
2. **User area** containing user-specific configuration files including the BPE-related files (description in Chapter 22).
3. **Data area** which is divided into datapool, campaign, and savedisk areas (see below). All these areas are assumed to be user-independent.
4. **Temporary area** for temporary usage during a BPE run.

The directory trees for the first three areas are illustrated in Figure 3.1. The directory environment variables (defined during installation in the `LOADGPS.setvar` script for UNIX or in the registry for Windows) are given for UNIX systems (first entry) and Windows systems (second entry). In principle, these abbreviations are arbitrary. All “program area” subdirectories are shown in Figure 3.1.

3.1.1. Program Area

The location of the top directory `BERN52` of this area may be chosen by the user during the installation process. It is then addressed by the environment variable `#{C}` (UNIX) or `%C%` (Windows) — see Figure 3.1. Below, we give a short description of the contents of its subdirectories:

- PGM** The subdirectory `FOR` contains all Fortran source files of the programs and the subdirectory `EXE_#{F_VERS}/%F_VERS%` contains all corresponding executables compiled with the compiler specified with `#{F_VERS}/%F_VERS%`.
- LIB** The library directory contains the Fortran library `libBERN_#{F_VERS}.a/%F_VERS%.a` of the *Bernese GNSS Software*. The subdirectory `FOR` contains the Fortran source code files of the subroutines.
- INC** The include directory contains the Fortran source code files of the modules and the include file (e.g., `COMFREQ.inc`) in the subdirectory `FOR`. The module files are classified into five different types. Modules starting with `M_` contain general information, those starting with `D_` are data structure modules, those starting with `P_` are program-specific modules and those starting with `L_` contain general functions.

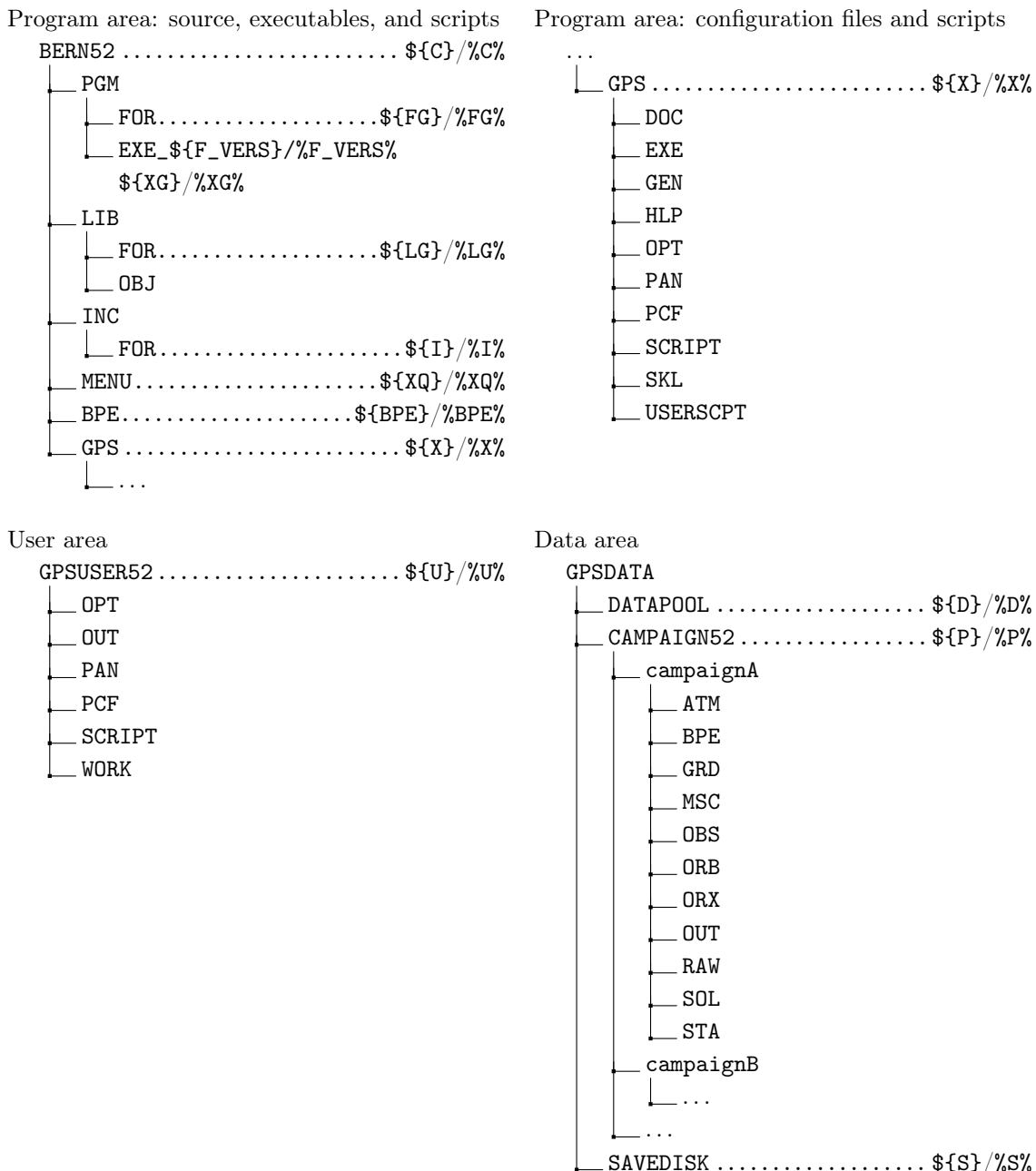


Figure 3.1.: Directory structure of the *Bernese GNSS Software* Version 5.2.

- MENU The menu directory contains the executable as well as the C++-source code for the graphical user interface.
- BPE The BPE directory contains scripts and utilities (Perl modules) that are used by the BPE or by BPE user scripts.
- GPS This directory contains software-related files of various kinds. Many of these files are described in Chapter 24.
- GEN contains important general files (e.g., satellite information files, geodetic datum definition files, the definition of the constants to be used by the Bernese programs, etc.).

EXE	contains a number of command files (scripts) to execute the menu or programs to compile and link particular routines or to recompile all modules of the software. The directory also contains the <code>configure.pm</code> module used to install the software or a new user environment. The content of the directory differs for UNIX and Windows.
PAN	contains the original program input panels (master copies). These panels are copied automatically to the corresponding user directories (<code>#{U}/PAN</code> or <code>%U%\PAN</code>) during the installation of the user environment.
HLP	contains the help panels. Help panels may be displayed on request as on-line help for each input panel of the menu system.
SKL	contains the default file for the session definition (<code>SESSIONS.SES</code>) which is automatically placed into the subdirectory <code>STA</code> when a new campaign is created using the menu.
DOC	contains examples for Bernese file types, readme files, and the entire software documentation.
SCRIPT	contains basic command files necessary for the automated processing using the BPE.
PCF	contains examples of process control files for the BPE (see Chapters 22 and 23).
OPT	contains directories with the panels for the example PCFs in the directory <code>PCF</code> . These panels are copied automatically to the corresponding user directories (<code>#{U}/OPT</code> or <code>%U%\OPT</code>).
USERSCPT	contains the BPE user scripts of the example PCFs in the directory <code>PCF</code> . These scripts are copied automatically to the corresponding user directories (<code>#{U}/SCRIPT</code> or <code>%U%\SCRIPT</code>).

Usually, no changes are necessary in the program environment. Exceptions are files in `#{X}/GEN` that may be updated from <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>.

Whereas the directory `PAN` contains the master copy of the program input files, the directories `OPT`, `PCF`, and `USERSCPT` provide the master copies of the BPE processing examples. The content of these directories is copied to the user-specific directories `OPT`, `PAN`, `PCF`, and `SCRIPT` when creating the user area.

On UNIX systems the directories `#{XG}`, `#{XQ}`, and `#{X}/EXE` have to be included in the execution path.

3.1.2. User Area

User-specific data directories are used for the manual processing mode (`PAN`, `OUT`, `WORK`). They are campaign-independent. Most of the directories contain, as already mentioned above, copies from the master files of the program directories: the directories `OPT`, `PAN`, `PCF`, and `SCRIPT` stemming from the directories with the same names in the program area. The only exception are files in the user directory `SCRIPT` that stem from the master directory `USERSCPT` and not from the `SCRIPT` directory. The directory `WORK` is used in the manual processing mode for temporary copies of files or for scratch files. Its content may be deleted if no BPE is running. The directories `SCRIPT`, `OPT`, and `PCF` are only used for the BPE.

3.1.3. Temporary Area

In addition, *temporary files* are stored in a temporary area ($\${T}/\%T\%$). These files are important for processing data with the BPE (see Chapter 22). The files of this group are, in principle, nothing else than local copies for the automated processing with the BPE. The directories may also be removed if no BPE is running. The directory structure of the temporary area is explained in detail in Chapter 22.

3.1.4. Data Area

The data flow philosophy through the *Bernese GNSS Software* can be summarized as follows:



DATAPPOOL area ($\${D}$ for UNIX or $\%D\%$ for Windows systems)

The datapool area is a place for local copies of external files somewhere on your filesystem. This has several advantages compared to downloading the data each time when starting the processing:

1. The files are downloaded only once, even if they are used for several campaigns.
2. The data download can be organized with a set of scripts running independently from the *Bernese GNSS Software* environment, scheduled by the expected availability of the external files to download.
3. The processing itself becomes independent from the availability of external data sources.

The structure of the datapool area is not fixed and can be modified. The structure described in Section 3.2 may serve as an example.

CAMPAIGN area ($\${P}$ for UNIX or $\%P\%$ for Windows systems)

Within the *Bernese GNSS Software*, we use the term *campaign* for a set of data which should be processed together. An alternative term to “campaign” (also commonly used) might be “project”. Each campaign has its own directory containing a set of subdirectories where all the campaign-specific data are stored. While processing the campaign, the Bernese processing programs work with these files. All files that need to be accessed by a processing program of a specific run need to be located in one and the same campaign.

All campaign-specific files are stored in the campaign directories following the structure. A detailed overview of the content of important files in these subdirectories is given in the indicated sections:

ATM:	files related to atmosphere (troposphere and ionosphere)	Section 24.8
BPE:	BPE-related output files	Section 22.10
GRD:	grid files for various purposes	Section 24.9
OBS:	Bernese-formatted observation files	Section 24.5
ORB:	orbit- and ERP-related files	Section 24.6
ORX:	original RINEX files	Sections 24.4 and 4.2.5
OUT:	program output and numerous miscellaneous files	Section 24.11
RAW:	RINEX files to be imported for processing	Section 24.4
SOL:	solution-related files (NEQ and SINEX)	Chapter 9
STA:	station-related files	Section 24.7

The names of the subdirectories and the distribution of the files within this structure may be configured using the menu system ("Menu>Configure>Paths and extensions"). This is not recommended, however. More information can be found in the Section 21.4.2.

How to create a campaign and how to prepare it for processing is discussed in the second part of this chapter, in particular in Sections 3.3 to 3.6.

Savedisk area ($\${S}$ for UNIX or $\%S\%$ for Windows systems)

When processing GNSS data, a lot of files from various processing steps will populate your campaign directories. The main result files from the data analysis are collected and copied over into the savedisk area. This area is intended as *long-term archive* for your result files. If the long-term archive area is separated and if it only consists of the result files from the processing they can be better protected (e.g., for a backup).

Because the result files are also stored in the savedisk area, you can easily clean up your campaign area without losing important files. Please keep in mind that the computing performance decreases if you have several thousands of files in a directory.

The structure of this area can be freely organized according to the user's needs. We propose to build subdirectories in the savedisk area for each of your projects. If these projects collect data over several years yearly subdirectories are recommended. It is also practical to use further subdirectories like ATM, ORB, OUT, SOL, STA to distribute the files and to get shorter listings when you are looking for a file.

3.2. Populating the Datapool Area

The structure for the datapool area can be freely organized. We recommend to use subdirectories according to different potential sources of the files and their formats. An example of such a structure is used to distribute the input files for the example BPEs with the *Bernese GNSS Software*. The corresponding description is available in $\${D}/\text{README_DATAPOOL.TXT}$.

RINEX files

RINEX observation files — and if available — navigation files from your own measurements may be completed by a set of reference stations for the datum definition. They are,

for instance, available from one of the data centers of the IGS (see <http://www.igs.org/about/data-centers>).

In the datapool area these files may be Hatanaka compressed. These RINEX files are assumed to be “original” files that are not changed during the processing. If you mix the station lists from different projects into one directory of your datapool area, take great care of the uniqueness of the four-character IDs of all stations in the RINEX file names!

GNSS orbit product files

Orbits, EOPs, and satellite clock corrections are the basic external information for a GNSS analysis. You may download them, for instance, from the CODE AC of the IGS (yearly subdirectories at <http://www.aiub.unibe.ch/download/CODE/>). Please visit Section 4.13.1 for further details.

Alternatively, you may also use a consistent set of products from any other AC of the IGS from the Crustal Dynamics Data Information System (CDDIS) FTP server. Be aware that the IGS provides GPS and GLONASS orbits in separate files (the IGS, respectively IGL series from the final product line) resulting from independent combination procedures among different contributing ACs.

Bernese-formatted product files

Various files in the format of the current version of the *Bernese GNSS Software* are available at <ftp://ftp.unibe.ch/aiub/> or <ftp://ftp.unibe.ch/aiub/BSWUSER52>. For processing your own GNSS data you typically need ionosphere maps to support the ambiguity resolution (see Chapter 8) and to compute the higher order ionosphere (HOI) corrections (see Section 13.6). As soon as you are going to use code measurements you will also need Differential Code Bias (DCB) information (see Chapter 14).

To support the reference frame realization, the <ftp://ftp.unibe.ch/aiub/BSWUSER52/STA> directory contains also Bernese-formatted coordinate and velocity files for the most recent IGS and International Terrestrial Reference Frame (ITRF) realization (e.g., IGB08_R.CRD, IGB08_R.VEL, and IGB08.FIX).

Other product files

If you plan to use specific models such as the Vienna Mapping Function (VMF1), you may need additional files to be provided to your processing scheme. For the most important ones README files are available in the `#{X}/DOC` directory with instructions how they have to be generated.

3.3. Create a New Campaign

First, the name of the new campaign (including the path to the campaign directories) has to be specified in "Menu>Campaign>Edit list of campaigns". Add the name of your new campaign (e.g., `#{P}/MYCAMP`) to the campaign list. This syntax (with curly brackets) has

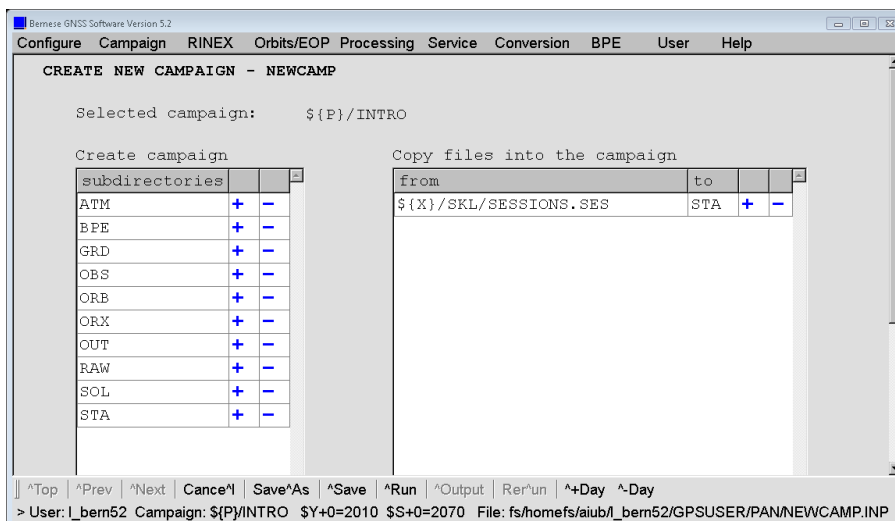


Figure 3.2.: Panel to create a new campaign structure.

to be used on both UNIX and Windows platforms because $\${P}$ is an environment variable internally handled by the *Bernese GNSS Software* (see Section 21.6 for more details).

It is important to note that the campaign list is a general file accessed by all users working with the same installation of the software. All available campaigns are visible to all users. The file $\${X}/PAN/MENU_CMP.INP$ contains the list of campaigns. If one user is editing the list using the menu, the file is locked for all other users (indicated by the existence of the file $\${X}/PAN/MENU_CMP.INP_1k$). On multi-user systems, all users must have *read AND write* privileges for $\${X}/PAN/MENU_CMP.INP$ ¹ and all users must have the permission to create and to remove a file in the $\${X}/PAN$ -directory such as the file $\${X}/PAN/MENU_CMP.INP_1k$.

If the campaign is located on a disk referred to by another environment variable than already defined (e.g., $\${Q}$), UNIX users have to add the definition of the environment variable to the file $\${X}/EXE/LOADGPS.setvar$ (and reload this file)². Windows users must define the corresponding environment variable in their user-environment. To run a BPE they also have to add the new variable to the existing `BERNESE_VARIABLES` environment variable (see Section 22.3.3). Finally, Windows users also have to add this new environment variable to the list in the $\${U}/PAN/MENU_VAR.INP$ file (use "Menu>Configure >Menu variables"). The new environment variable must also be provided to each BPE option directory ($\${U}/OPT/*/MENU_VAR.INP$).

Once the new campaign $\${P}/MYCAMP$ has been added to the list, it must be selected as the active campaign using the "Menu>Campaign>Select active campaign" sequence. You may get a message that no session table is available in your actual campaign. Do not worry about this at that stage: the session table will be provided later. The active campaign is now displayed in the status line of the menu.

¹ $\${X}/PAN/MENU_CMP.INP$ is the only file in the $\${X}/PAN$ -directory where all users need write privileges because all other input files are located in user-specific directories, located by default in $\${U}/PAN$.

²In any case, if you need to modify this file manually, take care to keep its syntax correct because the BPE reads this file to install the *Bernese GNSS Software* environment on a remote host (see Section 22.3.3).

ID	START EPOCH			END EPOCH													
	yyyy	mm	dd	hh	mm	ss			yyyy	mm	dd	hh	mm	ss			
???				00	00	00							23	59	59	+	-

ID	START EPOCH			END EPOCH													
	yyyy	mm	dd	hh	mm	ss			yyyy	mm	dd	hh	mm	ss			
???				00	00	00							00	59	59	+	-
???				01	00	00							01	59	59	+	-
???				02	00	00							02	59	59	+	-
???				03	00	00							03	59	59	+	-
???				04	00	00							04	59	59	+	-
???				05	00	00							05	59	59	+	-
???				06	00	00							06	59	59	+	-
???				07	00	00							07	59	59	+	-
???				08	00	00							08	59	59	+	-
???				09	00	00							09	59	59	+	-
???				10	00	00							10	59	59	+	-
???				11	00	00							11	59	59	+	-
???				12	00	00							12	59	59	+	-

Figure 3.3.: Examples of session tables: for a 24-hour processing scheme (top), and for a hourly processing scheme (bottom).

Now the campaign-specific directories for the active campaign have to be created. This is done via "Menu>Campaign>Create new campaign". Users on multi-user systems have to take care of the write protections, especially in the top-level directory where the campaign directory will be created. By default, the directories displayed in Figure 3.2 are created.

The right hand side of the panel displayed in Figure 3.2 offers the option "Copy files into the campaign". A list of files to be copied from any location on your system into the newly created campaign subdirectory structure can be specified by the user.

At least the default session table will be copied from $\${X}/SKL/SESSIONS.SES$ into the campaign ($\${P}/MYCAMP/STA/SESSIONS.SES$). Check the entry for the option "Session Table" in the dialogue "Menu>Configure>Set session/compute date". We refer to the subsequent Section 3.4 for more details on the setup of the session table.

3.4. Session Definition

A session is a time interval covering all observations that should be processed together. A campaign consists of one or more sessions that together cover the total observation interval. The session definition is independent for each campaign. Since the *Bernese*

GNSS Software uses a session-wise processing strategy, you *must* have a session table in each campaign defining at least one session.

The session identifier is a four-character string composed as `dddf`, where `ddd` represents the day of year (DoY) at the beginning of the time interval and `f` is an alphanumeric character identifying the session within the day. For daily sessions this session character usually is the zero character 0, for hourly sessions the characters A through X are used, and for hours the characters 00 to 23 are used. Only sessions defined in the session table can be used. Each session is assigned to an individual time window in the session table, and each observation processed in the *Bernese GNSS Software* must be associated to exactly one session.

The session identifier is stored in the observation header file. It is important to know that

- the program `SNGDIF` forms baselines only from zero-difference observation files belonging to the same session, and
- the program `GPSEST` considers correlations solely between observations of the same session.

The session identifier in the observation header file is defined when importing the data from the observation RINEX files with the program `RXOBV3` (see Section 4.2.3). It may be changed using the program `CHGHED` ("Menu>Service>Bernese observation files>Change header").

A default session table is copied into the new campaign when the campaign tree is created (see Section 3.3). Depending on the selection in "Copy files into the campaign" (in panel displayed in Figure 3.2) either

- `#{X}/SKL/SESSIONS.SES` or
- `#{X}/SKL/HOURLY.SES`

is used for a daily or for an hourly session definition scheme, respectively. If needed, the name of the session table can be adjusted in the dialog "Menu>Configure>Set session/compute date". With "Menu>Campaign>Edit session table" the content may be checked and adapted.

Two types of session tables exist:

- the *fixed session table* that explicitly defines each session to be processed by a separate entry, and
- the *open session table* that uses three question marks as wildcards (???) which are automatically replaced by the day of year according to the current session.

The session table contains a single line that covers any daily session. A mixture between the two types of session tables is not permitted. In Figure 3.3 two examples of open session tables referring to a daily session and to hourly sessions are shown. We recommend to use the open session definition. More information about the session definition strategy may be found in the corresponding online help.

Use "Menu>Configure>Set session/compute date" to select one of your sessions as the current session to be processed. This is mandatory for Version 5.2 of *Bernese GNSS Software* in order to use the menu variables (see Section 21.6). The current session is displayed in the status line of the menu. The session selection dialogue box may also be used to convert dates (button `Compute`). The current session is set using the buttons `Set` (dialogue box remains open) or `OK` (dialogue box is closed). Using the buttons `+1` and `-1` you may increment or decrement

the current day by one. The session character may be specified in the field "Session Char", and the name of a session table in the field "Session Table".

3.5. File Naming Convention

The user is responsible for the naming of the output and result files in the campaign directory. We recommend to use the default subdirectories and extensions for all file types. The filenames may be specified by the user in the program input panels. Filenames (as well as the path) must not contain blanks or any other special characters (dots, slashes, etc.). The complete string of the filename (starting from the campaign path to the extension, as, e.g., `#{P}/MYCAMP/DIR/FILENAME.EXT`) is limited to 32 characters in the *Bernese GNSS Software* Version 5.2. The menu displays a warning message if a filename is too long. The user can refer to Section 21.3.4 for more information about checks and warnings in the menu system.

Like earlier versions of the *Bernese GNSS Software*, Version 5.2 does *not* issue a warning message before overwriting files. It is the responsibility of the user to take care of the file naming within the campaign.

Since Version 5.0 the user can specify the filename of the program output for all programs (see Section 21.7 for a detailed description). We recommend to name all important program output and result files in a similar way, with a filename containing the session they refer to. E.g., the program output file of a GPSEST run generating a normal equation file `FIN$YSS+0.NQO` may get the name `FIN$YSS+0.OUT`. The session is indicated in this example by the menu variable `$YSS+0` (translated by the menu to `yysssss`, where `yy` is the two-digit year and `sssss` is the identifier of the current session). The use of these menu variables for the file naming is very comfortable, see Section 21.6 for a detailed description. As soon as you run the BPE in the multi-session mode (see Section 22.9), it is vital to label each file with the current session.

There are two exceptions to this basic convention. All session-independent files (e.g., the session table `SESSIONS.SES`) have names without the session identification. In addition, the names of the observation files are generated automatically. Zero-difference observation files are written by the programs `RXOBV3` (creates observation files from RINEX, "Menu >RINEX>Import RINEX to Bernese format>Observation files") and `GPSSIM` (creates observation files containing simulated data, "Menu>Service>Generate simulated observation data"). The name of these files consists of a four-character station name abbreviation and the session of the data without the year; the observation file `ZIMM2070`, for instance, contains data from the station Zimmerwald for session 2070. The program `SNGDIF` creates single-difference files from two zero-difference files. The name of the single-difference observation file is composed of the two-character abbreviations of the two baseline stations and the session of the data without the year. `BRZI2070`, for example, names data files for the baseline from Brussels to Zimmerwald for session 2070. The station name abbreviations are taken from a table specified in a program panel input field (e.g., `#{P}/MYCAMP/STA/EXAMPLE.ABB`). The automatic generation of the observation filenames requires that all abbreviations are *unique* for all stations.

3.6. Create Station Files

For a number of station files, the menu of the *Bernese GNSS Software* Version 5.2 provides input masks for creation and editing ("Menu>Campaign>Edit station files"). This is a convenient way for most applications. Since all station files are ASCII files, you can of course also use your favorite text editor for browsing and editing the files. Take care of the file format in this case.

When creating a new station file, a dialogue "Select Skeleton Coordinate File" appears for most file types. Cancel the dialogue box to get a plain input mask for the new station file. If you select a coordinate file, all station names contained in it are inserted into the input mask by default in the station name columns for the new file to be created. For some file types an additional input mask appears for creating a new file.

In this section we give an overview of some important station files that are necessary for processing your campaign. Some of them are needed to run a PPP similar to the example described in Section 23.4.1 to complete a list of a priori coordinates and velocities.

3.6.1. Create Reference Coordinate/Velocity Files

If you are about to process your regional/local campaign and you do not have accurate (decimeter-level) coordinates for any of your stations in the ITRF, we recommend to include at least one IGS site (near to the area of your campaign) into the processing. For more details on the realization of the geodetic datum we refer to Chapter 10.

At this point you have to create a coordinate and a velocity file (see Sections 24.7.1 and 24.7.3 for a description) for the reference sites of your network. For ITRF (currently ITRF 2008) or preferably IGS (currently IGB08) reference frames, you can start with the corresponding SINEX file. The program `SNX2NQ0` ("Menu>Conversion>SINEX to normal equations", see Section 4.5.2) extracts the information from SINEX files into *Bernese GNSS Software* coordinate and velocity files (along with writing a normal equation file). The input SINEX file has to be copied into the `SOL`-directory of the campaign.

The coordinate and velocity files for the reference sites of the IGB08 realization with the filenames `IGB08_R.CRD` and `IGB08_R.VEL` may be copied from the datapool area into the `STA`-directory of the campaign (the original source is <http://www.aiub.unibe.ch/download/BSWUSER52/STA>).

The Bernese coordinate and velocity files can be edited via an input mask using "Menu>Campaign>Edit station files>Station coordinates" and "Menu>Campaign>Edit station files>Station velocities", respectively. Use this menu item to check and adapt the downloaded files or to create the files manually. It is recommended that these files only contain the reference sites or stations with very accurate (one centimeter level) a priori coordinates and velocities. The remaining stations will be added by a PPP procedure described in Section 3.8.

The eccentricity files providing local tie information for the processing are still available in Version 5.2 of the *Bernese GNSS Software*. Use these files with care and only when it is indispensable.

3.6.2. Create Station Information File

Two sections of the station information file (see description in Section 24.7) are important at this stage:

TYPE 001: RENAMING OF STATIONS to get the correct station names for the processing and
TYPE 002: STATION INFORMATION to make sure that the correct receiver types, antenna types, and antenna heights are used in the processing.

The files IGS.STA and EUREF.STA, which are available at <http://www.aiub.unibe.ch/download/BSWUSER52/STA>, are regularly updated from the files `igs.snx` and `euref.snx`³. A skeleton of the station information file may also be extracted from a SINEX file using the program SNX2STA ("Menu>Service>Station information files>Extract information from SINEX", program description in Section 4.5.2). For this purpose the SINEX file has to be copied into the campaign's SOL directory.

The program RNX2STA ("Menu>Service>Station information files>Extract information from RINEX", program description in Section 4.2.5) provides another possibility to get a skeleton for the station information file. The header information from a set of RINEX observation files in the campaign's RAW directory is extracted to a station information file. Verify the information using observation protocols or any other station setup description.

In any case, check and adapt the content of the station information file before using it in the processing ("Menu>Campaign>Edit station files>Station information file"). It is one of the most important files because its content defines the station naming (must be consistent in all station files), the equipment, and the antenna eccentricities (must be defined in the "Phase center eccentricity"-file) used in the *Bernese GNSS Software*. We refer to Section 4.2.3 for a detailed description of converting observation RINEX files to Bernese format.

For the processing, complete sets of antenna phase center corrections for all GNSS are required. Assigning the receiver types (with their capability to track GPS, GLONASS or other systems) to specific antenna types, the corresponding antenna phase center eccentricity file should be updated. A description how to do this is provided in Section 18.3.2. The BPE processing examples provide this feature with the BPE server variable `V_MYATX` as described in Chapter 23.

3.6.3. Other Station Files

A few more station files are necessary or might be useful for the data processing. Some of them can be introduced into the PPP procedure that completes the list of a priori coordinates/velocities.

- Create a FIX file (station selection for reference sites in the processing, see the file description in Section 24.7.12) using "Menu>Campaign>Edit station files>Station selection list". If you select, e.g., the coordinate file IGB08_R.CRD in the dialogue "Select Skeleton Coordinate File" the list will contain the reference sites of the IGS and needs no further manipulation.

³Files are maintained by the central bureaus (CBs) of IGS and EUREF Permanent Network (EPN), respectively.

- Create a PLD file (tectonic plate assignment for the NUVEL model, file description in Section 24.7.16) for all your sites. You can use "Menu>Campaign>Edit station files>Tectonic plate assignment" to do this.
- The station name abbreviation table is used to generate the names of the Bernese observation files (see Section 3.5). The abbreviation table may be created automatically in the PPP procedure. If you want to have user-defined values you may create the list manually using "Menu>Campaign>Edit station files>Abbreviation table".
- Use the web-service at <http://holt.oso.chalmers.se/loading/> to get a table of the ocean loading coefficients for your stations (default extension BLQ). See Section 24.7.9 and the related README_BLQ.TXT in the $\${X}$ /DOC directory for more details on how to create the file. Only approximate site coordinates are required.

If you do not have a priori values at this stage of analysis, it does not matter. The BLQ-file is not mandatory for a PPP analysis and you may use the resulting coordinates as input to create the ocean loading file.

The file used for the processing at CODE is available at <http://www.aiub.unibe.ch/download/BSWUSER52/STA/FES2004.BLQ>.

- Following the instructions in $\${X}$ /DOC/README_ATL.TXT you may create the analogue file for considering the atmosphere tidal loading corrections. They are in particular important if you plan to apply atmosphere non-tidal corrections (see Sections 10.1.4 and 10.1.5 for more details). To create the necessary correction table (default extension ATL in the STA directory) the program GRDS1S2 ("Menu>Service>Coordinate tools>Extract atmospheric tidal loading coefficients") is available.

3.7. Copying Data from the Datapool Area into the Campaign

Before you can start with the manual processing of the data, the following files have to be copied from the datapool area to the campaign:

- RINEX observation files
The observation files in RINEX format must be copied into the RAW (or ORX) directory of your campaign (see Section 4.2.5). It is important to note that the files are not accepted in the Hatanaka compression format. They must be available in the fully developed RINEX version 2 or 3 format.
- GNSS satellite orbit and clock products
GNSS orbit product files are expected in the precise orbit file format (see Section 4.3) and must be copied into the ORB directory of the campaign with the extension PRE — independent from the extension that they have in the international databases (e.g., EPH or SP3).

The clock files are expected to be in the clock RINEX format and have to be copied into the OUT directory with the extension CLK.

- Earth rotation parameters
The ERP information has to be consistent with the orbit and clock products and is expected either in the international format or in the Bernese internal format. Both file types have to be located in the ORB directory of the campaign but they must

have different extensions: IEP for the international format and ERP for the Bernese internal format. In the general case you will have the international format — even if they have the extension ERP in the external databases.

The only location where you will find Bernese formatted files (asking for the extension ERP in the ORB directory of the campaign) is at <http://www.aiub.unibe.ch/download/BSWUSER52/> (or at the corresponding locations from reprocessing efforts, e.g., http://www.aiub.unibe.ch/download/REPRO_yyyy/BSWUSER52). Even at <http://www.aiub.unibe.ch/download/CODE/> (or http://www.aiub.unibe.ch/download//REPRO_yyyy/CODE) the files have the international format.

- Ionosphere maps
Ionosphere files have to be copied into the ATM directory of the campaign (extension ION); no Ionosphere model EXchange format (IONEX) files (extension INX) are accepted.
- DCB information
The files with DCB corrections are expected in the ORB directory of the campaign.

Note that all files in the campaign have to be available in their native format without applying any compression tool such as UNIX compress or gzip.

When running the BPE processing examples, files are copied automatically from the datapool area to the campaign by two scripts in these BPEs. The first script copies the RINEX files for all selected stations of the session being processed into the campaign. The second script calls the BPE-utility `copyRef` (from module `$BPE/bpe_util.pm`) to copy all other necessary files from the DATAPPOOL area (`{D}`) into the campaign. All operations regarding decompression and renaming is done automatically in that case.

3.8. Processing Overview

A PPP procedure (example in Section 23.4.1) is recommended to generate accurate a priori coordinates. The necessary files (listed in Section 23.4.1.2) are expected in the datapool area. They have to be downloaded according to the sources given in Section 3.2. The automated PPP procedure, which is provided in `PPP_BAS.PCF`, executes the steps from Table 3.1. The project-specific files (a priori coordinates and velocities as well as the abbreviation table) may also be updated by this BPE. On request, the antenna phase center eccentricity file may be updated as well.

The further processing of your data follows the strategy demonstrated in the processing examples in Chapter 23. Tables 3.2 and 3.3 provide an overview of the main processing steps for a double- or a zero-difference analysis using Version 5.2 of the *Bernese GNSS Software* as they are realized in the processing example BPEs `RNX2SNX.PCF` (description in Section 23.4.2) and `CLKDET.PCF` (description in Section 23.4.4), respectively.

Table 3.1.: Processing steps for a PPP zero-difference solution.

Processing step	Involved programs	Reference
1 Data transfer, copy data into the campaign	ftp	Chapter 4
2 Data preprocessing 1	RNXSMT	Chapter 6
3 Import data into the Bernese format	RXOBV3	Chapter 4
4 Prepare orbit and Earth orientation information	POLUPD, PRETAB, ORBGEN	Chapter 5
5 Data preprocessing 2	CODSPP, GPSEST, RESRMS, SATMRK	Chapter 6
6 Solution for epoch parameters and/or create normal equations	GPSEST	Chapter 7
7 NEQ-based final session solution	ADDNEQ2	Chapter 9

Table 3.2.: Processing steps for a double-difference solution.

Processing step	Involved programs	Reference
1 Data transfer, copy data into the campaign	ftp	Chapter 4
2 PPP procedure to complete the list of a priori coordinates/velocities (if necessary)	BPE examples PPP_BAS.PCF	Sec. 23.4.1
3 Import data into the Bernese format	RXOBV3	Chapter 4
4 Prepare Earth orientation and orbit information	POLUPD, PRETAB, ORBGEN	Chapter 5
5 Data preprocessing	CODSPP, SNGDIF, MAUPRP, GPSEST, RESRMS, SATMRK	Chapter 6
6 Make a first solution	GPSEST	Chapter 7
7 Resolve ambiguities	GPSEST	Chapter 8
8 Create normal equations	GPSEST	
9 NEQ-based final session solution	ADDNEQ2	Chapter 9

Table 3.3.: Processing steps for a zero-difference multi-GNSS solution.

Processing step	Involved programs	Reference
1 Data transfer, copy data into the campaign	ftp	Chapter 4
2 PPP procedure to complete the list of a priori coordinates/velocities (if necessary)	BPE example PPP_BAS.PCF	Sec. 23.4.1
3 Prepare orbit and Earth orientation information	POLUPD, PRETAB, ORBGEN	Chapter 5
4 Data preprocessing 1	RNXSMT	Chapter 6
5 Import data into the Bernese format	RXOBV3	Chapter 4
6 Data preprocessing 2	CODSPP, MAUPRP	Chapter 6
7 Compute the station-specific weight of the code measurements	GPSEST, RESRMS	Chapter 6
8 Compute the inter-frequency bias and inter-system bias	GPSEST, ADDNEQ2	Chapter 15
9 Residual screening	GPSEST, RESRMS, SATMRK	Chapter 6
10 Solution for epoch parameters and/or create normal equations	GPSEST	Chapter 7
11 NEQ-based final session solution	ADDNEQ2	Chapter 9

4. Import and Export of External File Formats

4.1. Overview

A number of formats are currently used within the international community for the exchange of data, products, and solutions. The most important and widely accepted format is certainly the RINEX format used for the exchange of GNSS observations, broadcast information, and meteorological measurements. The *Bernese GNSS Software* Version 5.2 supports all important formats and provides interfaces for importing and exporting data in these formats. The formats include

- RINEX (Receiver INdependent EXchange format) for the exchange of GNSS observation data, broadcast information, and meteorological data,
- SP3c for the exchange of precise orbit and satellite clock information,
- IERS and IGS format for the exchange of Earth orientation parameters,
- SINEX (Solution INdependent EXchange format) for the exchange of solutions (including the full normal equation or variance–covariance information) and of meta-information,
- Troposphere SINEX for the troposphere information,
- ANTEX (ANTenna EXchange format) for the receiver and satellite antenna information,
- IONEX (Ionosphere model EXchange format) for the ionosphere maps, and
- Clock RINEX for the exchange of satellite and receiver clock information.

Table 4.1 lists the programs which read, write, or manipulate the files in external formats together with their location in the menu system. The following sections describe these formats, provide information on the availability of corresponding data, as well as on the usage of the accessing programs and interfaces of the *Bernese GNSS Software*. For additional information you may consult the online help panels of the corresponding programs. The final section describes the data available at CODE’s anonymous ftp server in external and internal Bernese format and provides the access points to the IGS.

Table 4.1.: Programs of the *Bernese GNSS Software* accessing or writing external formats.

(1)	Observations:		
–	GNSS RINEX observation files:		
	Import:	RNXSMT	"Menu>RINEX>RINEX utilities>Clean/smooth observation files"
		RXOBV3	"Menu>RINEX>Import RINEX to Bernese format>Observation files"
	Export:	BV3RXO	"Menu>RINEX>Export RINEX from Bernese format>Observation files"
	Utilities:	CCRINEXO	"Menu>RINEX>Cut/concatenate RINEX files>Observation files"
		RNXGRA	"Menu>RINEX>RINEX utilities>Create observation statistics"

continued on next page

<i>continued from previous page</i>		
–	SLR Normal Point observation files:	
Import:	QLRINEXO	"Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX"
	CRD2RN XO	"Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX"
(2)	GNSS orbits and Earth rotation parameters:	
–	RINEX navigation files:	
Import:	RXNBV3	"Menu>RINEX>Import RINEX to Bernese format>Navigation files"
	RXNPRE	"Menu>RINEX>Import RINEX to Bernese format>Navigation files to SP3"
Export:	BV3RXN	"Menu>RINEX>Export RINEX from Bernese format>Navigation files"
Utilities:	CCRINEXN	"Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GPS)"
	CCRINEXG	"Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GLONASS)"
–	Precise orbit files (SP3c):	
Import:	PRETAB	"Menu>Orbits/EOP>Create tabular orbits"
	ORBGEN	"Menu>Orbits/EOP>Create/update standard orbits"
Export:	STDPRE	"Menu>Orbits/EOP>Convert standard to precise orbits"
	KINPRE	"Menu>Service>LEO utilities>Convert kinematic pos. to precise orbits"
Utilities:	CCPREORB	"Menu>Orbits/EOP>Concatenate/merge precise orbit files"
–	IERS pole files:	
Import:	POLUPD	"Menu>Orbits/EOP>Handle EOP files>Convert IERS to Bernese Format"
Export:	GPSEST	"Menu>Processing>Parameter estimation"
	ADDNEQ2	"Menu>Processing>Combine normal equation systems"
Utilities:	POLXTR	"Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files"
(3)	Solutions:	
–	SINEX:	
Import:	SNX2NQ0	"Menu>Conversion>SINEX to normal equations"
Export:	ADDNEQ2	"Menu>Processing>Combine normal equation systems"
–	Troposphere SINEX:	
Export:	GPSEST	"Menu>Processing>Parameter estimation"
	ADDNEQ2	"Menu>Processing>Combine normal equation systems"
Utilities:	TROTRO	"Menu>Conversion>Manipulate troposphere SINEX files"
–	IONEX:	
Export:	GPSEST	"Menu>Processing>Parameter estimation"
	ADDNEQ2	"Menu>Processing>Combine normal equation systems"
–	Clock RINEX:	
Import:	RNXCLK	"Menu>RINEX>RINEX utilities>Extract satellite clock"
Export:	GPSEST	"Menu>Processing>Parameter estimation"
	CLKEST	"Menu>Service>Clock tools>Epoch-wise clock interpolation"
Utilities:	CCRNXC	"Menu>Service>Clock tools>Combine/manipulate clock RINEX files"
(4)	Miscellaneous data:	
–	Meta data from RINEX:	
Import:	RNX2STA	"Menu>Service>Station information files>Extract information from RINEX"
–	Meta data from SINEX:	
Import:	SNX2STA	"Menu>Service>Station information files>Extract information from SINEX"
	SNX2SLR	"Menu>Service>SLR utilities>Prepare SLR data handling file"
Utilities:	STAMERGE	"Menu>Service>Station information files>Merge station information files"
	STA2STA	"Menu>Service>Station information files>Convert station information files"
–	Antenna phase center corrections:	
Import:	ATX2PCV	"Menu>Conversion>ANTEX to Bernese format"
–	RINEX meteorological files:	
Import:	RXMBV3	"Menu>RINEX>Import RINEX to Bernese format>Meteo files"

4.2. RINEX Observation Files

4.2.1. History of RINEX and Format Definitions

Each GNSS processing software requires the GNSS input data to be available in a certain format definition. On the other side the receiver manufacturers provide the GNSS observation data in their proprietary data formats. In order to mediate between data providers and data users an exchange format is needed as a common interface.

The AIUB developed a first version of such a format to be used for the data exchange and processing of the EUREF-89 GPS campaign, a campaign observed in 1989 involving four different receiver types and nearly one hundred stations in most countries of Western Europe. This format was based on a format developed and used by the US National Geodetic Survey for the exchange of GPS data collected in the Cooperative International GPS Network (CIGNET), the first global network of permanent GPS receivers used for civil geodetic purposes. The new format, named RINEX (Receiver INdependent EXchange format), was presented to the geodetic community at the Fifth International Geodetic Symposium on Satellite Positioning in Las Cruces, New Mexico in 1989, where it was accepted as the format to be recommended for geodetic GPS raw data exchange. The format description was published in the *CSTG GPS Bulletin May/June 1989*.

A second generation (RINEX Version 2) was discussed and accepted at the Second International Symposium on Precise Positioning with the Global Positioning System in Ottawa, Canada in 1990 and published in the *CSTG GPS Bulletin September/October 1990*. RINEX Version 2 developed to the standard observation data format of the IGS after its foundation in 1994. An important update was the introduction of RINEX Version 2.1 in 1997, allowing the handling of GLONASS and mixed GPS/GLONASS data. The currently most commonly used RINEX Version 2.11 was introduced in 2007. It supports Galileo and new observation types (e.g., L2C) for GPS. The format description can be found on various web and ftp servers, e.g., at

<ftp://ftp.igs.org/pub/data/format/rinex211.txt>

or at

<http://www.aiub.unibe.ch/download/rinex/rinex211.txt>.

RINEX Version 2.12, which was proposed in 2009 as a RINEX2-based multi-GNSS data format, has never been accepted as a standard. Figure 4.1 shows an excerpt of a RINEX2 observation file containing GPS and GLONASS observations.

The third generation of RINEX (Version 3) was developed starting in 2007 in order to support the extensions needed due to the modernization programs of the established GNSS as well as the full range of frequencies, signal types, and tracking modes from the new systems under development. The development is in the responsibility of the *IGS RINEX Working Group* in cooperation with the Radio Technical Commission for Maritime Services (RTCM). The first widely used version for multi-GNSS purposes is 3.02, published in 2013 (version 3.03 is already under final discussion). At the IGS Workshop 2014 this format was recommended as the new future IGS standard format (to be established after a transition phase). The format description is available at

<ftp://ftp.igs.org/pub/data/format/rinex302.pdf>.

Figure 4.2 shows an excerpt of a RINEX3 observation file containing observations of several GNSS.

4. Import and Export of External File Formats

2.11	OBSERVATION DATA								M (MIXED)	RINEX VERSION / TYPE
JPS2RIN v.2.0.99	JAVAD GNSS								20150823 020104 UTC	PGM / RUN BY / DATE
AIUB	AIUB									OBSERVER / AGENCY
ZIMJ										MARKER NAME
14001M006										MARKER NUMBER
00634	JAVAD TRE_G3TH DELTA3.4.9								Apr, 18, 2013	REC # / TYPE / VERS
4331290.7193	567541.4271	4633135.5216								APPROX POSITION XYZ
00427	JAVRINGANT_DM NONE									ANT # / TYPE
0.0770	0.0000								0.0000	ANTENNA: DELTA H/E/N
1	1								WAVELENGTH FACT L1/2	
8	C1	P1	L1	S1	C2	P2	L2	S2	# / TYPES OF OBSERV	
30.000										INTERVAL
2015	8	22	0	0	0.0000000	GPS			TIME OF FIRST OBS	
2015	8	22	23	59	30.0000000	GPS			TIME OF LAST OBS	
17										LEAP SECONDS
55										# OF SATELLITES
END OF HEADER										
15	8	22	0	0	0.0000000	0	19R04G02R20R02G06G05G09G13R19R13G30G23			
R14R11G07R03R12G28G16										
22974737.146	22974737.246	123028705.178	7	43.250	22974740.716					
22974741.206	95688999.573	6	38.500							
22478344.414	22478343.534	118124534.126	5	34.250						
22478340.494	92045100.401	5	34.250							
23888209.055	23888212.965	127740992.926	6	36.750	23888220.495					
23888218.615	99354112.538	6	40.000							
20318059.054	20318059.244	108421113.527	8	53.500	20318062.574					
20318063.494	84327549.142	7	46.750							
24136132.701	24136135.111	126836265.259	4	24.500	24136136.761					
24136139.041	98833459.617	4	24.500							
21340435.652	21340435.272	112144777.740	7	43.000	21340433.202					
21340432.742	87385550.304	7	43.000							
22302805.087	22302804.637	117202106.230	6	37.500	22302804.417					
22302804.007	91326336.381	6	37.500							
23645905.611	23645904.221	124260093.185	4	25.500						
23645902.181	96826050.924	4	25.500							
23326417.269	23326417.319	124780615.017	7	43.000	23326423.409					
23326421.499	97051593.125	6	39.250							
19926774.224	19926774.334	106407885.414	7	44.750	19926779.984					
19926779.854	82761685.843	8	48.000							
20509341.118	20509340.428	107777344.480	7	46.000	20509341.638					
20509341.078	83982353.706	7	46.000							
25525860.959										
23668929.119	23668932.349	126168691.625	6	36.000	23668935.959					
23668938.879	98131229.135	5	31.750							
24298495.410	24298496.220	129843865.052	5	34.500	24298502.120					
24298501.190	100989617.867	4	24.750							
20561101.494	20561101.614	108049350.930	7	45.000	20561099.254					
20561099.094	84194308.404	7	45.000							
19489544.203	19489543.753	104329108.305	8	51.500	19489548.473					
19489548.203	81144875.328	8	50.000							
20053385.874	20053384.974	107121619.247	8	49.000	20053390.714					
20053391.704	83316821.968	8	48.250							
24521139.156	24521136.166	128859439.812	2	14.500						
24521132.406	100409951.511	2	14.500							
25278952.989	25278948.679	132841806.496	2	12.750						
25278948.959	103513099.804	2	12.750							
15	8	22	0	0	30.0000000	0	18R04G02R20R02G06G05G09G13R19R13G30R14			
R11G07R03R12G28G16										
22936843.077	22936843.087	122825783.113	7	43.750	22936847.847					
22936848.617	95531171.336	6	40.250							
22473258.256	22473258.076	118097805.703	5	34.000						
22473253.556	92024273.049	5	34.000							
23864004.390	23864003.860	127611551.839	5	35.500	23864012.530					
23864010.890	99253436.129	6	38.500							
20313957.707	20313957.807	108399228.292	8	53.250	20313961.917					
20313962.377	84310527.277	7	46.250							
24139490.690	24139493.050	126853900.663	3	23.500	24139493.780					
24139491.360	98847201.445	3	23.500							
21312443.414	21312443.094	111997679.493	7	43.000	21312441.664					
21312441.074	87270928.301	7	43.000							
22300480.603	22300480.353	117189894.125	6	36.750	22300480.123					
22300480.333	91316820.447	6	36.750							
23611903.088	23611904.318	124081412.331	4	25.750						
23611903.588	96686819.124	4	25.750							
23319880.621	23319881.951	124745654.655	7	42.750	23319887.571					
23319886.641	97024401.690	6	39.250							
19896674.183	19896673.623	106247148.634	7	44.500	19896678.303					
19896679.163	82636668.365	8	48.250							
.										
.										
.										

Figure 4.1.: RINEX2 observation file (GPS and GLONASS).

3.02		OBSERVATION DATA		M		RINEX VERSION / TYPE	
JPS2RIN v.2.0.99	JAVAD GNSS	20150823	020111	UTC		PGM / RUN BY / DATE	
AIUB	AIUB					OBSERVER / AGENCY	
ZIMJ						MARKER NAME	
14001M006						MARKER NUMBER	
00634	JAVAD TRE_G3TH DELTA3.4.9	Apr, 18, 2013				REC # / TYPE / VERS	
4331290.7193	567541.4271	4633135.5216				APPROX POSITION XYZ	
00427	JAVRINGANT_DM	NONE				ANT # / TYPE	
0.0770	0.0000	0.0000				ANTENNA: DELTA H/E/N	
G 15	C1C L1C S1C	C1W L1W S1W	C2X L2X S2X	C2W L2W S2W	C5X	SYS / # / OBS TYPES	
	L5X S5X					SYS / # / OBS TYPES	
R 12	C1C L1C S1C	C1P L1P S1P	C2C L2C S2C	C2P L2P S2P		SYS / # / OBS TYPES	
E 6	C1X L1X S1X	C5X L5X S5X				SYS / # / OBS TYPES	
S 6	C1C L1C S1C	C5I L5I S5I				SYS / # / OBS TYPES	
30.000						INTERVAL	
2015	8	22	0	0	0.00000000	GPS	TIME OF FIRST OBS
2015	8	22	23	59	30.00000000	GPS	TIME OF LAST OBS
17							LEAP SECONDS
G L1W	-0.25000	31	G01 G02 G03 G04 G05 G06 G07 G08 G09 G11			SYS / PHASE SHIFT	
			G12 G13 G14 G15 G16 G17 G18 G19 G20 G21			SYS / PHASE SHIFT	
			G22 G23 G24 G25 G26 G27 G28 G29 G30 G31			SYS / PHASE SHIFT	
			G32			SYS / PHASE SHIFT	
G L2X	0.25000	17	G01 G03 G05 G06 G07 G08 G09 G12 G15 G17			SYS / PHASE SHIFT	
			G24 G25 G26 G27 G29 G30 G31			SYS / PHASE SHIFT	
R L1P	-0.25000	24	R01 R02 R03 R04 R05 R06 R07 R08 R09 R10			SYS / PHASE SHIFT	
			R11 R12 R13 R14 R15 R16 R17 R18 R19 R20			SYS / PHASE SHIFT	
			R21 R22 R23 R24			SYS / PHASE SHIFT	
R L2C	0.25000	24	R01 R02 R03 R04 R05 R06 R07 R08 R09 R10			SYS / PHASE SHIFT	
			R11 R12 R13 R14 R15 R16 R17 R18 R19 R20			SYS / PHASE SHIFT	
			R21 R22 R23 R24			SYS / PHASE SHIFT	
64						# OF SATELLITES	
						END OF HEADER	
> 2015 08 22 00 00	0.0000000	0 23					
R04	22974737.146		123028686.917 7	44.000	22974737.246	123028704.928 7	...
G02	22478344.414		118124534.885 7	46.250	22478343.534	118124533.876 5	...
R20	23888209.055		127741028.661 6	37.500	23888212.965	127740992.676 6	...
R02	20318059.054		108421116.270 9	54.250	20318059.244	108421113.277 8	...
G06	24136132.701		126836262.001 6	40.500	24136135.111	126836265.009 4	...
G05	21340435.652		112144785.476 8	51.750	21340435.272	112144777.490 7	...
G09	22302805.087		117202111.970 8	49.750	22302804.637	117202105.980 6	...
G13	23645905.611		124260097.925 6	41.500	23645904.221	124260092.935 4	...
S26	38315809.005		201351931.595 6	41.750			...
R19	23326417.269		124780602.768 7	44.250	23326417.319	124780614.767 7	...
R13	19926774.224		106407880.163 7	45.250	19926774.334	106407885.164 7	...
G30	20509341.118		107777348.221 9	55.750	20509340.428	107777344.230 7	...
G23	25525860.959		134139349.148 3	22.250			...
R14	23668929.119		126168733.370 6	37.000	23668932.349	126168691.375 6	...
R11	24298495.410		129843739.774 5	35.500	24298496.220	129843864.802 5	...
G07	20561101.494		108049355.672 8	52.750	20561101.614	108049350.680 7	...
R03	19489544.203		104329109.052 8	52.750	19489543.753	104329108.055 8	...
R12	20053385.874		107121625.992 8	49.750	20053384.974	107121618.997 8	...
G28	24521139.156		128859433.514 5	35.250	24521136.166	128859439.562 2	...
G16	25278952.989		132841800.227 5	31.250	25278948.679	132841806.246 2	...
S36	38057490.463		199993684.534 7	44.000	38057479.473	149345722.958 7	...
S20	38545811.058		202559533.331 6	40.750			...
S27	39603129.285		208115900.638 5	34.500	39603142.165	155411242.079 7	...
> 2015 08 22 00 00	30.0000000	0 22					
R04	22936843.077		122825764.851 7	45.000	22936843.087	122825782.863 7	...
G02	22473258.256		118097806.453 7	45.750	22473258.076	118097805.453 5	...
R20	23864004.390		127611587.562 6	36.250	23864003.860	127611551.589 5	...
R02	20313957.707		108399231.035 9	54.000	20313957.807	108399228.042 8	...
G06	24139490.690		126853897.391 6	40.250	24139493.050	126853900.413 3	...
G05	21312443.414		111997687.237 8	51.500	21312443.094	111997679.243 7	...
G09	22300480.603		117189899.868 8	49.000	22300480.353	117189893.875 6	...
G13	23611903.088		124081417.065 7	42.000	23611904.318	124081412.081 4	...
S26	38298526.257		201261105.799 7	42.000			...
R19	23319880.621		124745642.399 7	43.250	23319881.951	124745654.405 7	...
R13	19896674.183		106247143.380 7	45.500	19896673.623	106247148.384 7	...
G30	20485058.352		107649741.711 9	55.500	20485057.952	107649737.721 7	...
R14	23626739.185		125943815.693 6	36.000	23626736.995	125943773.710 5	...
R11	24306308.556		129885478.868 6	38.750	24306307.286	129885603.879 6	...
G07	20549542.642		107988612.671 8	52.750	20549542.232	107988607.679 7	...
R03	19464636.685		104195780.193 8	52.500	19464637.005	104195779.197 8	...
R12	20047880.553		107092217.610 8	49.750	20047879.673	107092210.617 8	...
G28	24485360.568		128671425.327 5	34.500	24485360.498	128671431.349 2	...
G16	25277775.538		132835611.858 5	35.250	25277774.398	132835617.831 2	...
S36	38040685.468		199905373.911 7	43.250	38040673.628	149279771.710 7	...
S20	38529181.464		202472151.607 6	41.000			...
S27	39586360.154		208027789.488 5	34.250	39586375.274	155345444.697 7	...

Figure 4.2.: RINEX3 observation file (multiple GNSS).

4.2.2. Content of RINEX Observation Files and Naming Convention

The basic observables to be used in the RINEX format are:

- The epochs of observations defined as the reception time of the signals expressed in the receiver time frame. The epochs are identical for all satellites (i.e., simultaneous observations with respect to receiver time).
- Carrier phase observations (integrated negative beat frequency between the received carrier of the satellite signal and the receiver-generated reference frequency). The sign is the same as for the pseudorange, i.e., decreasing phase if the satellite approaches the receiver.
- Pseudorange observations, i.e., the difference between the time of reception of a satellite code signal, expressed in receiver time, and the time of emission of the same signal, expressed in satellite time.

The three quantities are based on the same oscillator, such that any offsets and drifts of the oscillator show up directly in the basic observables. Other observables have been defined for the direct Doppler frequency observations.

Usually, a RINEX observation file contains data collected by a single receiver, one station and one session, only. It is, however, possible to store data collected by moving receivers (e.g., onboard a LEO) during kinematic or pseudokinematic surveys.

Each RINEX file consists of a header section, containing all auxiliary information on the station and receiver necessary for post-processing, and a data section containing the basic observables.

The recommended file naming convention is as follows:

`ccccdddf.yy0` ,

where `cccc` is a four-character station code, `ddd` and `yy` are the day of the year and the two-digit year of the first observation epoch in the file, `f` is a file sequence number (to separate files collected during the same day, e.g., `A-X` for hourly RINEX observation files), and the letter `0` is the label for observation files (e.g. `ZIM22340.150`, a one day RINEX observation file for receiver `ZIM2`). The *Bernese GNSS Software* expects the RINEX observation files stored in the `campaign` and `datapool` directories to follow this naming convention.

RINEX version 3.02 introduced a new file naming convention:

`cccc00CCC_R_yyyydddhhmm_111_sss_M0.rnx`

where

`cccc00CCC` : 9 characters defining the receiver (proposed usage: four-character site/station code, one-digit number to indicate the monument/receiver at the site, and ISO country code)

`R` : data source: one of the three items — `S` from streams, `R` directly from the receiver, `U` unknown

`yyydddhhmm` : start epoch (specified for the minute)

`111` : the intended (nominal) file period (e.g., `01D`, `01H`, `15M`, ...)

`sss` : the sampling rate of the observations (e.g., `30S`, `01S`, ...)

`M0` : data type (indicating the GNSS or `M` for multi-GNSS) and content (`0` for observation, `N` for navigation)

`rnx` : extension to be used for all RINEX files

The daily RINEX file displayed in the example of Figure 4.2 contains multi-GNSS observations obtained directly from the receiver ZIM2 (Zimmerwald, Switzerland) for one day with a sampling of 30 seconds. The corresponding filename according to the extended naming convention reads as

ZIM200CHE_R_20152340000_01D_30S_MO.rnx .

The transition to the new naming convention is a complex process and takes time. It has the advantage that the source of the RINEX records is indicated which is important because streamed data packages may not be as complete as those directly generated by the receiver. These extended filenames can be kept in the datapool area. They are renamed to the above mentioned short naming convention while they are copied to the campaign directory. The subroutine `crz2rnx` in the perl module `bpe_util.pm` located in the `$BPE` directory of the *Bernese GNSS Software* installation is adapted accordingly. In the BPE user script `RNX_COP` a priority list is implemented, in case RINEX3 files from different sources for the same site exist:

```

1 sub run{
2   my $bpe = shift;
3
4   # Priority list for RINEX3 handling:
5   # "R","r": long RINEX3 filename; generated by the receiver
6   # "S","s": long RINEX3 filename; generated from a stream
7   # "U","u": long RINEX3 filename; source unknown
8   # "short": short RINEX3 filename; source unknown
9   # "rx2" : RINEX2 (short filename)
10  # -----
11  # left to right: highest to lowest priority
12  my @rx3Typ = ("R","r","S","s","U","u","short","rx2");
13
14  ...

```

4.2.3. Import to Bernese

The *Bernese GNSS Software* Version 5.2 exclusively uses the RINEX format as interface for the observation data. If you would like to use data provided in a receiver- or manufacturer-specific format please convert it to RINEX using a dedicated format converter (provided by the receiver manufacturer or available as freeware on the internet).

RINEX observation files provided by data centers are usually compressed. Software for decompressing compressed and Hatanaka compressed files for different platforms may be found at <ftp://ftp.igs.org/pub/software>.

After Hatanaka decompression the RINEX observation files are imported into the *Bernese GNSS Software* using the program `RXOBV3` ("Menu>RINEX>Import RINEX to Bernese format >Observation files"). This program not only converts the RINEX observation files into Bernese format, but also performs numerous checks on the RINEX header information as well. This allows to draw the user's attention to RINEX problems and, e.g., to skip files with dubious header content in a robust automatic processing procedure.

Please read Section 4.2.3.7 when you have to import RINEX3 formatted observation files (independent of whether they are given in the extended long or traditional short filename).

4.2.3.1. Data Selection

In the first panel “RXOBV3 1: Filenames” you have to specify the filename(s) of the RINEX observation files to be converted to the Bernese binary format (see Section 24.5). These have to be either “Original RINEX observation files” or “Smoothed RINEX observation files”. The smoothed files are output of the preprocessing program RNXSMT (“Menu>RINEX>RINEX_utilities >Clean/smooth observation files”, Section 6.2) and are written in an internal RINEX2–style format.

Either GNSS code and/or phase observations or SLR ranges may be converted (option “Select measurement types to save (Code/Phase)” or “Select measurement types to save (Range)” in panel “RXOBV3 1: Filenames”).

A station coordinate file (see Section 24.7.1) may be updated or created based on the coordinates specified in the RINEX headers by specifying a filename in option “Station information file”. Coordinates of stations that are not included in this file are added with the coordinate flag “R”. They can be used as a starting point for a PPP analysis to obtain a priori coordinates for the high–precision data analysis.

Further options concerning the data selection are provided in panel “RXOBV3 2: Input Options 1” (Figure 4.3). The option “Satellite system to be considered” allows to reduce the data amount by selecting only those GNSS you are interested in. In addition, you may specify an observation window in panel “RXOBV3 3: Observation Window”.

The default sampling rate within the IGS is 30 seconds but there may be stations with a higher sampling rate (e.g., 10 seconds). You may define the sampling for the Bernese observation files in option “Sampling interval” in panel “RXOBV3 2: Input Options 1”. If the input field is left empty, or set to 0, all observations from the RINEX file are converted. The selected sampling rate is counted starting with an offset that might be specified in option “Sampling offset to full minute”. If you, e.g., sample 10 seconds data to 60 seconds and specify an offset of 10 seconds the observation epochs of the resulting Bernese observation file will be at 10, 70, 130 seconds, etc. Note that at least the current version of the *Bernese GNSS Software* does not process data with sampling higher than 1 Hz.

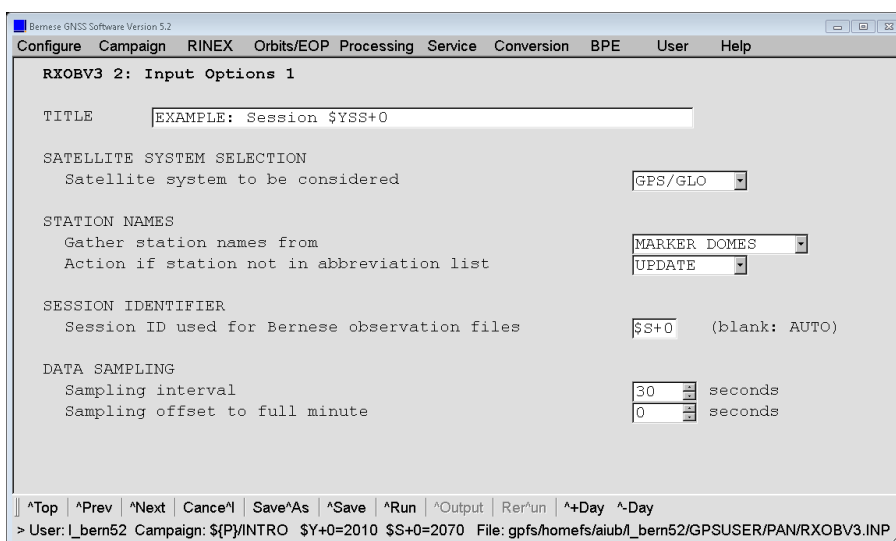


Figure 4.3.: Input options for RXOBV3 (1).

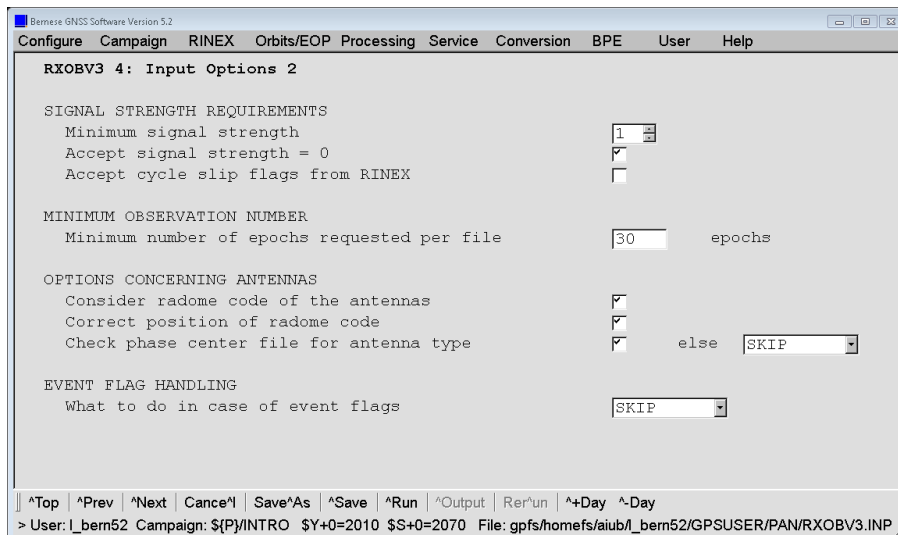


Figure 4.4.: Input options for RXOBV3 (2).

The panel “RXOBV3 4: Input Options 2” (Figure 4.4) addresses input options concerning signal strength requirements, observation number, and antennas. The option “Minimum signal strength” can be used to eliminate data with a low signal-to-noise ratio. According to the RINEX format definition the signal-to-noise ratio is mapped into values from 0 to 9. A value of 0 means either a bad observation (some RINEX converters use it like this) or an unknown signal-to-noise ratio. If you use original RINEX files it is recommended to use all available observations by accepting all available signal-to-noise ratios. Bad observations will be identified and excluded in the further processing.

You may, in addition to the above option, activate “Accept signal strength = 0” to keep data with a signal strength of 0. This is recommended and makes sense if you wish to exclude observations with low signal-to-noise ratio but want to process observations with unknown quality.

If you have preprocessed the RINEX files with program RNXSMT (see Section 6.2) you have to set the option “Minimum signal strength” to 2 in order to eliminate bad observations (marked by program RNXSMT with a signal strength of 1). You should also disable the option “Accept signal strength = 0” in this case.

Cycle slip flags from RINEX can be accepted by enabling the option “Accept cycle slip flags from RINEX”. This option might be interesting for processing zero difference phase observations. If the RINEX files are already cleaned, e.g., by the program RNXSMT, cycle slip flags can be accepted. Cycle slip flags from original RINEX files should, however, not be accepted due to their potentially large number and because they will be reliably identified in any case in the preprocessing procedures available in the *Bernese GNSS Software*.

The exclusion of stations providing a small number of epochs is possible by defining a “Minimum number of epochs requested per file”. Furthermore, observations of a certain station and interval may be excluded by adding a corresponding entry to the section TYPE 003: HANDLING OF STATION PROBLEMS of the station information file (see Section 24.7.6) — what may lead to a complete exclusion of a station from the processing. Observations of particular satellites may be excluded by adding a “bad data” entry in the satellite problem file (see Section 6.7.2).

4.2.3.2. Station Names

RXOBV3 stores the station name in the Bernese observation file header. It is important that this name is unique. In particular, it has to correspond to the station name used in the coordinate as well as all other station-related files. RXOBV3 allows to gather information on the station name from different sources in the RINEX file. Additionally, a station information file can be used to translate this name to a well-defined station (see below) and to report possible inconsistencies (see Section 4.2.3.4).

The header of a RINEX file contains two keywords which allow to identify the station, namely `MARKER NAME` and `MARKER NUMBER`. In addition, the first four characters of the filename may be used to identify the station. The user may select one of the following options (“Gather station names from” in panel “RXOBV3 2: Input Options 1”, Figure 4.3):

- `MARKER NAME`: The station name is taken from the characterization of the station in the keyword `MARKER NAME` of the RINEX header.
- `MARKER NUMBER`: The station name is taken from the characterization of the station in the keyword `MARKER NUMBER` of the RINEX header.
- `MARKER DOMES`: The station name is composed from the entries of the keywords `MARKER NAME` and `MARKER NUMBER` according to IGS conventions: the first four characters of the `MARKER NAME` (assuming the four-character station identifier) and the first nine characters of the `MARKER NUMBER` (assuming a `DOMES` code) are concatenated names of the form “ZIMM 14001M004”.
- `FILE NAME`: The first four characters of the RINEX observation filename are used as station name.

The first three modes use information from the RINEX file header whereas the fourth mode makes use of the RINEX filename. The best choice for you depends on the convention adopted for your campaign. If you have specified a “Station information file” we suggest to use `FILE NAME` for the transfer of RINEX observation files from IGS.

The station name obtained in the procedure described above is compared with the `OLD STATION NAME` in the section `TYPE 001` of the station information file specified in option “Station information file” (panel “RXOBV3 1: Filenames”). Wildcards are allowed. If the name is found for a time window covering the observations, the name is translated to the corresponding new `STATION NAME`. This new station name is used for all following checks and is stored in the Bernese formatted binary observation files to be used during the processing. If the station is not found or if no station information file is specified, the station name from RINEX is used as it is.

4.2.3.3. Antenna Names

GNSS antennas may have radomes that influence the phase center location of the antenna. According to IGS standards the radome type is coded in the RINEX observation files in characters 17 to 20 of the antenna name (`ANT # / TYPE`). If you disable the option “Consider radome code” in panel “RXOBV3 4: Input Options 2” (Figure 4.4, page 81) the characters 17–20 are set to blank before saving the antenna name to the Bernese observation header. If you enable this option you have to include the radome codes in the “Station information file” as well as in the file containing antenna phase offsets and patterns (option “Phase center eccentricities”, panel “RXOBV3 1.1: General Files”) in a consistent way. Note that the radomes have been ignored in the relative antenna phase center modeling used within

the IGS before GPS week 1400 (November 05, 2006, day 309 of year 2006) whereas they are considered after this date — we refer to Section 18.1 for more details on the antenna models used within the IGS. The option “Correct position of radome code” can be activated to correct antenna name strings containing shifted radome codes.

The option “Check phase center file for antenna type” in panel “RXOBV3 4: Input Options 2” offers the possibility to check whether the antenna phase center file specified in “Phase center eccentricities” contains the antenna type given by the RINEX file. You may enable this option in order to avoid that data tracked by an unknown antenna enters the processing which would stop the processing with an error. The possible actions to be taken if the antenna type is not found in the phase center file are:

- **WARNING:** The program issues a warning but the Bernese observation file will nevertheless be written.
- **SKIP:** The Bernese observation file is not written and program execution continues with the next RINEX file removing the corresponding file for the following processing steps. This selection is recommended for automatic processing.
- **ERROR:** The program issues an error message and stops execution.

If a station information file is specified in option “Station information file” the program checks whether the (new) station name is listed in section `TYPE 002: STATION INFORMATION`. If an entry with the correct time window is found, the antenna and receiver names specified in this section (with the exception of a string “*** UNDEFINED ***”) overwrite the names found in the RINEX file. This renaming takes place in any case, independent of any verification option (see next section).

4.2.3.4. Verification of RINEX Header Information

The specification of a “Station information file” (Section 24.7.6) in the panel “RXOBV3 1: Filenames” is optional, but strongly recommended. By using a station information file when importing RINEX files into Bernese format, you have control over receiver, antenna, and other equipment changes, which is particularly important for ensuring consistency in a permanent network data analysis.

The station information file is used to verify RINEX header information and to adapt the station information records to well defined names before writing the Bernese observation header file. If you have specified a “Station information file” the panel “RXOBV3 5.1: Check Content of RINEX Header 1” (Figure 4.5) will be accessible. The options in this panel define the actions to be taken if an inconsistency between RINEX header and station information file is found. These actions are: Do not perform any checks (`NO_CHECK`), issue a warning message but write the corresponding Bernese observation file (`WARNING`), issue a warning message and skip the conversion of the affected RINEX file (`SKIP`), or stop with an error message (`ERROR`).

The available verifications are:

- The “Station names” (see setting in option “Gather station names from” in panel “RXOBV3 2: Input Options 1” and Section 4.2.3.2) are compared with the `OLD STATION NAME` in the station information file (section `TYPE 001: RENAMING OF STATIONS`, wildcards allowed) and translated to the `NEW STATION NAME` even if the option is set to `NO_CHECK`. All following checks refer to the new name of the station. If the option “Try also RINEX filename for station name” is activated and the station name is not found in the station information file, the procedure is repeated using

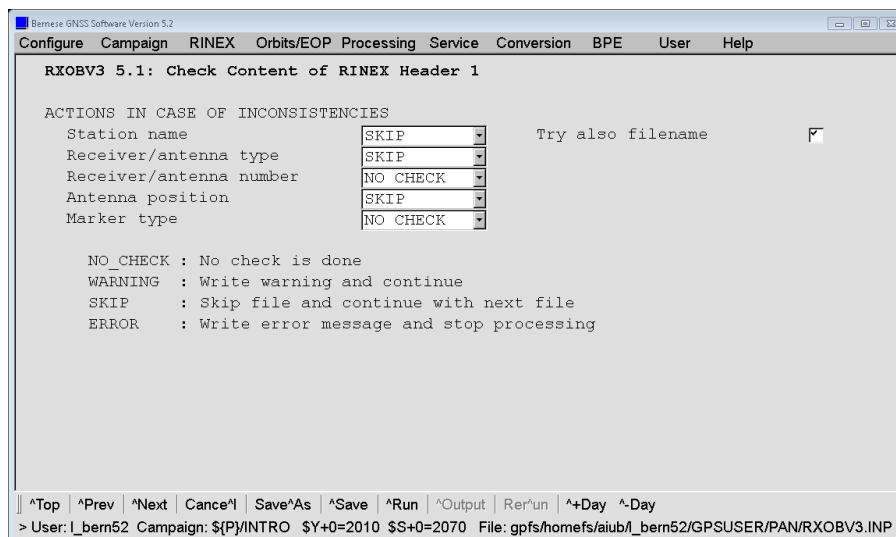


Figure 4.5.: Consistency check of RINEX header information using a station information file.

the four-character ID from the RINEX filename. This option is futile if the option “Gather station names from” is already set to FILE_NAME.

If the station name cannot be found in the station information file the station name is used as it is and the action specified for the inconsistency of the “Station names” is executed.

- “Receiver/Antenna type”: The entries for the REC TYPE and ANT TYPE in the RINEX observation file are compared with the RECEIVER TYPE and ANTENNA TYPE in the station information file (section TYPE 002: STATION INFORMATION). The string “*** UNDEFINED ***” in the station information file suppresses the test.
- “Receiver/Antenna number”: The entry for the REC # and ANT # in the RINEX observation file is compared with the entries for RECEIVER SERIAL NBR and ANTENNA SERIAL NBR in the section TYPE 002: STATION INFORMATION in the station information file. We recommend this test in particular if you are going to apply individual antenna phase center corrections.

Note that for the internal use within the processing in the *Bernese GNSS Software* the integer values from the REC # and ANT # are used.

- “Antenna position”: The entry for the ANTENNA: DELTA H/E/N in the RINEX observation file is compared with the values for NORTH, EAST and UP in the station information file (section TYPE 002: STATION INFORMATION).
- “Marker type”: The entry for the MARKER TYPE in the RINEX observation file is compared with the corresponding value in the station information file (section TYPE 005: HANDLING STATION TYPES). This option is, e.g., useful for verifying the RINEX headers from spaceborne receivers.

This record in the header entry is required except for “GEODETIC” (Earth-fixed, high-precision monument) for RINEX version 3.02 or later. In RINEX2 it is defined but not in use.

If no entry or a different one is found in the appropriate time window, the program takes the action specified by the user. The recommended selection is WARNING for manual processing and SKIP for a robust automated processing.

It is important to know that in case an inconsistency is encountered and the corresponding option is set to `NO_CHECK` or `WARNING`, the program uses the value found in the station information file, starting from the assumption that the entry in the RINEX header is erroneous. In any case, check the warnings issued by the program. The program output contains a compact summary of station naming and station information. Lines containing problems are labeled with a string `#Problem`, the other lines are labeled with `#OK`.

If, for a particular station, a certain inconsistency regularly appears (e.g., misspelled receiver name or wrong antenna height in the RINEX file) you may suppress the corresponding warning or error message by adding a line to a station problem file (see description in Section 24.7.7). If you specify the name of this file in the field “Accepted station information” in panel “RXOBV3 5.2: Check Content of RINEX Header 2”, the program compares RINEX entries not only with the content of the station information file but also with the entries in this file. In any case the values from the station information file will be used. See the online help for further information.

Note, if the option “Consider radome code” is enabled, a blank antenna radome code gets automatically replaced by `NONE` before the antenna type is compared with the entries in the station information file.

The options in the last panel “RXOBV3 5.2: Check Content of RINEX Header 2” may be used to perform additional verifications on station names in order to monitor the consistency of the information from the RINEX file headers. If a verification fails, the corresponding line in the information summary provided in the program output will contain a string `#Verify`. The failure of a verification step has no effect on the execution of the program.

- “Verify station name/number using”: Enable this option if you want to verify the (new) station name with respect to the station name given in the header of the RINEX observation file. The station name may be compared to the
 - `MARKER NAME`: The `MARKER NAME` entry of the RINEX observation file.
 - `MARKER NUMBER`: The `MARKER NUMBER` entry of the RINEX observation file.
 - `MARKER DOMES`: The `MARKER NAME` and the `MARKER NUMBER` entry of the RINEX observation file is combined to get a station name according to IGS conventions. The appropriate choice depends on the convention you adopted for your campaign. For the transfer of RINEX observation files from IGS, we propose to verify with respect to the `MARKER DOMES` entry.
- “Verify station name using RINEX filename”: Enable this option to verify the first four characters of the (new) station name with respect to the first four characters of the RINEX filename. This convention applies for RINEX observation files from the IGS. It may not be true for your own campaign.

4.2.3.5. Metadata Verification for SLR Processing

As described in Section 19.3, SLR Normal Points are introduced into the *Bernese GNSS Software* processing scheme via a RINEX-style observation file. The frequencies of the SLR measurements as reported in the Normal Point (NP) files have also been transferred into the RINEX files. They may now be compared with the expected frequency according to “Frequency information” file (given in panel “RXOBV3 1.1: General Files”). The option “Check frequency information file for frequency” in panel “RXOBV3 4: Input Options 2” defines how the program shall react based on a discrepancy.

4.2.3.6. Naming of Bernese Observation Files

Binary Bernese observation files created by RXOBV3 follow a file naming convention similar to RINEX: Filenames `ccccssss` are composed of a four-character station code `cccc` and the session identifier `ssss`.

The station code is generated using the “Abbreviation table” for station names specified in panel “RXOBV3 1.1: General Files”. This file contains the four-character and two-character station abbreviations for a list of station names. The file can be generated using “Menu > Campaign > Edit station files > Abbreviation table”.

The option “Action if station not in abbreviation list” (panel “RXOBV3 2: Input Options 1”, Figure 4.3 on page 80) defines the behavior of RXOBV3 if the four-character station abbreviation is not found in the abbreviation list:

- **ERROR:** The program stops with an error.
- **UPDATE:** Based on the station name the program automatically creates new and unique four-character and two-character abbreviations in capital letters.
- **UPDATE+:** Same as previous option but in addition lower case letters are used. This option should not be used on Windows platforms due to missing case sensitivity for filenames.

Do not enable UPDATE if RXOBV3 is running in parallel (e.g., in the BPE). Simultaneous modification of the abbreviation table may lead to unpredictable results.

In option “Session ID used for Bernese observation files” you may define the session identifier that should be used for the observation filenames. This session ID is also written to the Bernese observation header files and must be defined in the session table. The session will be determined automatically if this field is left empty, based on the start, end, middle, and median epochs: If at least three of these epochs fall into the same session or if the median epoch falls into the same session as the start or the end epoch, this session is used for naming the output file. Otherwise the program stops execution. It is recommended to specify the session explicitly in case of RINEX observation files covering more than one session (after being cut to the observation window specified in panel “RXOBV3 3: Observation Window”).

The session identifier in the observation files is needed to form baselines between stations within one and the same session (program SNGDIF, description in Section 6.4). Correlations are also only considered correctly between baselines with the same session identifier in program GPSEST (option “Correlation strategy”, description in Section 7.4.5).

4.2.3.7. Import of RINEX3 Observation Files

The *Bernese GNSS Software* Version 5.2 is designed to process up to two observation frequencies (i.e., four observations: two phase and two code observations) in parallel. Depending on the GNSS, RINEX3 files may contain observations of more than two frequencies and of different tracking modes. It is, thus, necessary to select the signals to be processed. This selection is performed by the program RNXSMT (“Menu > RINEX > RINEX utilities > Clean/smooth observation files”, description in Section 6.2). Therefore, it is mandatory to run RNXSMT prior to RXOBV3 if RINEX3 files shall be processed (for RINEX2 files also the direct import is possible).

If you would like to process RINEX3 files, please enter their file names in the field “Original RINEX observation files” in panel “RNXSMT 1: Filenames”. You also have to introduce an observation type selection file (see Section 24.3.7 for a description) in the field “Receiver-specific observation type priority” of panel “RNXSMT 1.1: General Files” defining a priority list for the observation type selection. The observation type selection file has to be defined by the user according to his requirements. Program RNXSMT expects the file to be located in the `GEN` directory of the software distribution.

The program RNXSMT checks the input RINEX files for available observation types, the number of observations per observation type per satellite and system. Based on the receiver type (no adaption with a station information file is possible), the satellite- or system-specific priority lists are compared with the lists of actually available observations. Considering data availability and priority, one observation type is assigned to each signal channel. A detailed summary of the observation type selection is written to the output file if the option “Print observation statistics” is activated.

The results of the observation type selection are stored satellite-wise in the headers of the smoothed output RINEX files. The corresponding lines are marked with the keywords `GEOS` at the beginning and `COMMENT` at the end of the line. Note that you can deactivate the smoothing and preprocessing functionality of RNXSMT and save the original observations in the smoothed output RINEX files by deactivating the checkboxes “Use smoothed code instead of raw code)” and “Preprocess phase observations” in panel “RNXSMT 4: Output Options”. The smoothed RINEX observation files are then imported by the program `RXOBV3` in the same way as described in Section 4.2.3.1. If observation type selection information is stored in the header of a smoothed RINEX file, `RXOBV3` writes this information automatically into the headers of the resulting Bernese observation files disregarding the information given for the keyword `# / TYPES OF OBSERV` in the RINEX header.

4.2.4. Export from Bernese

Program `BV3RXO` (“Menu>RINEX>Export RINEX from Bernese format>Observation files”) converts Bernese code and phase observation files to RINEX2 format. More than one file may be converted in one program run. A receiver information file (`{X}/GEN/RECEIVER.`) has to be selected in panel “BV3RXO 1.1: General Files” for this procedure (see Section 24.3.6) to define whether the code measurements shall be exported as P-code or as C/A-code into the output RINEX observation file.

4.2.5. Utilities

`CCRINEXO` (“Menu>RINEX>Cut/concatenate RINEX files>Observation files”), `RNXGRA` (“Menu>RINEX>RINEX utilities>Create observation statistics”), and `RNX2STA` (“Menu>Service>Station information files>Extract information from RINEX”) are utility programs based on RINEX observation files.

The program `CCRINEXO` cuts and concatenates RINEX observation files according to a given time window and/or a specified data sampling. In addition, GPS or GLONASS data may be filtered. Probably the most important application of `CCRINEXO` is the concatenation of hourly RINEX observation files to daily files. The program expects the RINEX observation files to be in the `ORX` subdirectory of the campaign. The resulting files are written to the `RAW` directory. The output filenames retain their first four characters

(station identifier). The following four characters contain the session, which is generated from the day specified in the input field "Reference epoch for output files" in panel "CCRINEXO 1: Filenames", and the session character. The session character can be changed using "Menu >Configure>Set session/compute date".

The program RNXGRA generates pseudo-graphics of RINEX observation files. A part of a RNXGRA output file is shown in Figure 4.7. An asterisk (*) indicates that in the corresponding 20 minute interval less epochs are missing than specified by the user in option "Epochs allowed per character". A dash (–) marks intervals with more missing epochs. Station names may be translated using a station information file (section TYPE 001: RENAMING OF STATIONS). Consult the online help for more information.

After activating the option "Get a list of RINEX files" in panel "RNXGRA 2: Options" the panel "RNXGRA 3: Options for RINEX File Selection" is displayed, shown in Figure 4.6. It allows to select or unselect RINEX observation files for the processing. In this way, files with a limited data coverage or files with obvious tracking problems of the receiver can be excluded from the processing. Assuming that the numbers in the input fields are referring to daily RINEX files, they may be rescaled for files covering a shorter period if the option "Normalize limits for non-daily session processing" is enabled. This is an interesting feature for an hourly processing scheme.

The program RNX2STA ("Menu>Service>Station information files>Extract information from RINEX") compiles a station information file (description see Section 24.7.6) from the header information of multiple RINEX observation files. It is obvious that this file is fully consistent with the RINEX headers. For that reason, this station information file cannot be used for verification purposes during the data import using the program RXOBV3. The file can be used as a skeleton to generate your own station information file.

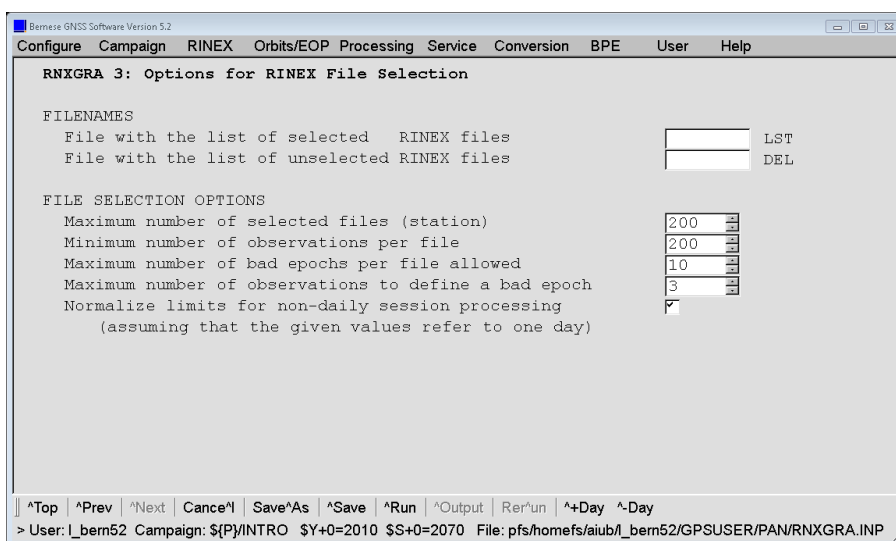


Figure 4.6.: RINEX file selection in program RNXGRA.


```

=====
Bernese GNSS Software, Version 5.2
-----
Program       : RNXGRA
Purpose       : Create observation statistics
-----
Campaign      : ${P}/INTRO
Default session: 2070 year 2010
Date         : 17-Apr-2015 18:35:41
User name    : l_bern52
=====

RNX2SNX_102070: Summary on RINEX file content
-----

File RINEX observation files
-----
1  ${P}/EX_GNUn/RAW/GANP2070.100
2  ${P}/EX_GNUn/RAW/HERT2070.100
...
-----

DATE : 2010  7  26  STATION : GANP 11515M001

TYPES OF OBSERVATIONS :  L1  L2  L5  C1  P1  C2  P2  C5  S1  S2
TYPES OF OBSERVATIONS :  S5
CHECKED OBSERVATIONS  :  L1  L2

 2 |          -*****-          -*****-
 3 | -          -****          -*****
 4 |          -*****-          -*****-
 5 |          -*****-          *****-
 6 |          **          -*****-
 7 |          -*****          -****-
 8 |          -*****-          -*
 9 |          -*****-          -*****-          -*
10 |          -*****-          *****-
11 | *****-          -**-          -*****
12 |          -*****-          -*****-
13 |          *****-
14 | *****-          -*****-          -*****
15 |          -*****-          -*****-          -*****-
16 |          -*****-          -*****-          -*****-
17 | *****-          -*****-          -
18 |          -*****-          -*****-          -
19 | ****-          -*****-          -*****
20 | *****-          -
21 |          -*****-          -**
22 | *-          -*****-          -*****
23 | -*****-
24 | **          -*****
26 |          -*****          -***-
27 |          -*****-
28 | *-          -*****-          -*****
29 |          -*****-
30 |          -*****-          -
31 | -*****-          -*****-
32 | *****-          -*****
101 |          -*****-          -*****-
102 |          -*****-          -*****-
103 |          -*****-          -*****-
104 |          -*****-          -*****-
105 | *****-          -*****-          -*****-
107 | *****          -***          -*****
108 | -*****-          -***-          -
110 |          -*****-          -*****
111 |          -*****-          -*****-
113 |          -*****-          -*****-          -****-
114 | ***-          -*****-          -*****-
115 | *****-          -*****-          **
...
-----+-----+-----+-----+-----+
      0                      12                      24
      .
      .
      .

```

Figure 4.7.: RNXGRA program output file.

4.3. Precise Orbit Files

4.3.1. Definition

The SP3 (Standard Product 3) orbit format is internationally used for the exchange of precise GNSS orbit information. It is the successor of the original National Geodetic Survey (NGS) Standard Product 1 format (Remondi 1985). It was proposed by Remondi (1989) and modified and adopted in Remondi (1991). In 1998, W. Gurtner and M. Rothacher defined an SP3b format to allow for the combination of GPS and GLONASS orbits and at the IGS Workshop 2002 in Ottawa, Canada, S. Hilla presented the extended SP3c orbit format (Hilla 2002) that is still in use today.

The precise orbit files contain satellite position (in kilometers) and clock information (in microseconds). The format supports in principle all kinds of satellites that are used in satellite geodesy nowadays (e.g., GNSS, LEO, SLR). The satellite positions are defined in an Earth-fixed system and are stored epoch-wise in a table. The file extension may be SP3, PRE, or EPH. Within the *Bernese GNSS Software* the default extension is PRE. The format description can be found at

<ftp://ftp.igs.org/pub/data/format/sp3c.txt> .

Figure 4.8 shows an example for a precise orbit file in SP3c-format. Consult Section 4.13 for information on downloading precise GNSS orbit files from CODE or other ACs of the IGS.

```
#cP2015 8 22 0 0 0.00000000 96 d IGb08 FIT AIUB
## 1858 518400.00000000 900.00000000 57256 0.00000000000000
+ 55 G01G02G03G04G05G06G07G08G09G11G12G13G14G15G16G17G18
+ G19G20G21G22G23G24G25G26G27G28G29G30G31G32R01R02R03
+ R04R05R06R07R08R09R10R11R12R13R14R15R16R17R18R19R20
+ R21R22R23R24 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
+ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 6 6 5 6 5 6 5 5 5 5 5 5 5 5 5 5 5 5
++ 5 5 6 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
++ 5 5 5 5 5 5 7 6 7 7 6 7 6 6 5 5 5 5
++ 5 5 5 6 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
%c M cc GPS ecc cccc cccc cccc cccc cccc cccc cccc cccc
%c cc cc ecc ccc cccc cccc cccc cccc cccc cccc cccc cccc
%f 1.2500000 1.025000000 0.00000000000 0.000000000000000
%f 0.00000000 0.000000000 0.00000000000 0.000000000000000
%i 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
%i 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
/* Center for Orbit Determination in Europe (CODE)
/* Rapid GNSS orbits and clocks for year-day 15234
/* Note: Middle day of a 3-day arc GPS/GLONASS solution
/* PCV: IGS08 OL/AL:FES2004 NONE YN ORB:CoN CLK:CoN
* 2015 8 22 0 0 0.00000000
PG01 -1418.397870 16344.405563 -20911.509638 -0.858191
PG02 20872.275324 -14845.862131 6464.378895 585.218836
PG03 8428.328408 19895.182022 -15415.329292 17.689058
PG04 -10785.811175 17967.318742 -16505.261567 -12.498290
....
PR20 -10190.596781 -3577.099327 23106.318377 -190.658961
PR21 -15108.598847 12731.034934 16146.508325 25.982254
PR22 -11623.803437 22625.398350 -150.349147 173.061297
PR23 -861.273359 18946.249501 -17071.847372 -24.667986
PR24 9514.138545 5007.582526 -23160.114442 -127.948984
* 2015 8 22 0 15 0.00000000
PG01 -3575.314776 17221.520839 -19905.568425 -0.857725
PG02 21510.765809 -14797.065495 3702.736382 585.220539
PG03 6796.087843 18956.742925 -17290.762664 17.691217
PG04 -12445.680065 18523.670910 -14542.900653 -12.502252
....
EOF
```

Figure 4.8.: Example of a SP3c file.

4.3.2. Import/Export

The precise orbit files may either be used directly in program ORBGEN to generate a Bernese standard orbit file (default extension `STD`, see Section 24.6.4) or to generate a so-called tabular file (default extension `TAB`, see Section 24.6.3) with program PRETAB. Section 5.4 provides a detailed description of the usage of these programs.

Program STDPRE ("Menu>Orbits/EOP>Convert standard to precise orbits", description in Section 16.2.3) transforms a Bernese standard orbit file into a precise orbit file. Kinematic orbits from LEOs that are available in an internal format (default extension `KIN`) may also be transferred into the precise orbit format by using the program KINPRE ("Menu>Service>LEO utilities>Convert kinematic pos. to precise orbits", description in Chapter 17).

4.3.3. Utilities

You may cut or concatenate precise orbit files using program CCPREORB ("Menu>Orbits/EOP>Concatenate/merge precise orbit files", description in Section 5.5.1). Typical applications are merging orbits (e.g., of GLONASS satellites) into an existing precise file (e.g., of GPS orbits) or merging orbits from different sources (e.g., broadcast orbits with own predicted orbits).

4.4. IGS and IERS Pole Files

4.4.1. Definition

The pole files contain time series of pole coordinates, length of day, etc., necessary to perform the transformation between the terrestrial and the celestial (inertial) reference frame. This information is exchanged using a large variety of file formats. Within the IGS, the IGS pole file format version 2 is used. The format description can be found at

`ftp://ftp.igs.org/pub/data/format/erp.txt`.

Figure 4.9 shows an example for an IGS formatted pole file generated at CODE.

Other EOP series may be obtained via anonymous ftp, too. These are in particular the IERS C04 EOP series and the IERS Bulletin A and B series. Data files concerning Earth rotation (C04 series, IERS Bulletin B) and celestial reference frame are stored at the IERS Central Bureau and may be downloaded from `http://hpiers.obspm.fr/eop-pc`. These EOP time series are the product of a combined analysis of different space-geodetic techniques (Very Long Baseline Interferometry (VLBI), GPS, SLR, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)). The IERS C04 time series provides slightly smoothed pole information at daily intervals twice per week. Quick-look EOP series (IERS Bulletin A, containing also predicted values) can be obtained from `ftp://maia.usno.navy.mil/ser7`.

Information concerning updates of internet addresses and server names is always provided by the most recent IERS Annual Report. IERS pole files already transformed into the

```

VERSION 2
CODE'S 3-DAY FINAL ERP RESULTS FOR WEEK 1858
-----
MUTATION MODEL : IAU2000R06
SUBDAILY POLE MODEL: IERS2010
27-AUG-15 02:27
-----
MJD      X-P      Y-P      UT1UTC      LOD      S-X      S-Y      S-UT      S-LD      NR      NF      NT      Y-RT      Y-RT      S-XR      S-YR      C-XY      C-YT      C-YT      DPSI      DEPS      S-DP      S-DE
      E-6"      E-6"      E-7S E-7S/D      E-6"      E-6"      E-6"      E-6"      E-7S E-7S/D      E-6"      E-6"      E-6"/D      E-6"/D      E-2      E-2      E-2      E-6"      E-6"      E-6"      E-6"
57250.50 218931 396190 2881961 8395 6 6 6 6 8 235 114 55 1032 -1357 8 8 4 4 4 0 0 0 0
57251.50 219735 394758 2873442 8411 6 6 6 6 8 241 111 55 551 -1439 8 8 3 3 3 0 0 0 0
57252.50 219685 393229 2865064 8012 6 6 6 6 8 242 114 55 -531 -1686 8 8 3 3 3 0 0 0 0
57253.50 219457 391434 2857256 8022 6 6 6 6 7 243 110 55 53 -1953 8 8 4 4 4 0 0 0 0
57254.50 219771 389541 2849028 8179 6 6 6 6 8 242 110 55 574 -1894 8 8 4 4 4 0 0 0 0
57255.50 220671 387505 2840330 8275 6 6 6 6 8 241 110 55 1198 -2138 8 8 4 4 4 0 0 0 0
57256.50 221803 385595 2832371 7625 6 6 6 6 8 238 108 55 1035 -1718 8 8 3 3 3 0 0 0 0
    
```

Figure 4.9.: Example of a pole file in IGS format version 2.

Bernese format may be downloaded via AIUB's anonymous ftp. They are located in the directory <http://www.aiub.unibe.ch/download/BSWUSER52/ORB/> (files C04_yyyy.ERP, BULLET_A.ERP).

4.4.2. Import/Export

The official files from the IGS have the extension ERP. Because the internal Bernese pole files have the same default extension but a different format, the IERS pole files have to be renamed using the default extension IEP before conversion to Bernese format (for a description see Section 24.6.8). The conversion is performed by the program POLUPD ("Menu>Orbits/EOP>Handle EOP files>Convert IERS to Bernese Format"), which supports not only the IGS version 2 format, the formats of the IERS C04, and of the IERS Bulletin A and B, but about 20 foreign formats. For details see Section 5.2.2.

Pole files in IGS format version 2 are written by programs GPSEST and ADDNEQ2 (in addition to pole files in Bernese format). Program POLXTR ("Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files") extracts pole information from a series of consecutive IERS pole files and writes a combined pole file in IGS format. Section 16.4 provides more details on the estimation of EOPs with the *Bernese GNSS Software*.

4.5. SINEX

4.5.1. Definition

At the 1994 IGS Workshop on the Densification of the IERS Terrestrial Reference Frame through Regional GPS Networks (JPL, Pasadena, December 1994, Blewitt et al. 1994), it was decided to start an IGS pilot project to prove the concept for a distributed processing of GPS data. For that purpose a data (resp. solution) exchange format, the Solution INdependent EXchange format, SINEX (Kouba et al. 1996) was defined. The format was supposed to contain all important information necessary to combine coordinates, velocities, and Earth orientation parameters (EOPs) in a statistically correct way. With the possible combination of solutions from different space-geodetic techniques in view, SINEX version 2 was developed and suggested for use in IGS Mail 3903. The latest format version is 2.02. The format is maintained by the "IERS Working Group on SINEX Format":

<http://www.iers.org/IERS/EN/Organization/WorkingGroups/SINEX/SINEX.html> .

The SINEX format descriptions are available at

<http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html> .

The latest SINEX version that can be written by the *Bernese GNSS Software* Version 5.2 is 2.01. Coordinate, velocity, and EOP parameters, as well as troposphere zenith path delays and gradients, geocenter coordinates, satellite antenna offsets, and SLR range biases can be stored. In Section 24.10.2 more information concerning the contents of SINEX files is given. The generation and use of SINEX files within the *Bernese GNSS Software* is discussed in Sections 9.4.9 and 24.11.11.

4.5.2. Import to Bernese

ADDNEQ2 requires normal equations in the Bernese normal equation format (default extension `NQ0`, see Section 24.10.1) as input. The program `SNX2NQ0` ("Menu>Conversion>SINEX to normal equations", description in Section 9.4.9.2) allows to convert SINEX files into Bernese normal equation files. In addition, `SNX2NQ0` is able to extract station coordinate and velocity information from SINEX files and to generate corresponding Bernese coordinate (default extension `CRD`) and velocity (default extension `VEL`) files. You may thus "import" and process results obtained from other ACs using different processing tools.

Program `SNX2STA` ("Menu>Service>Station information files>Extract information from SINEX", description in Section 9.4.9.2) allows to extract station information (station names, receiver and antenna type, antenna eccentricities) from SINEX files and to write a corresponding station information file.

It is worth mentioning that two station information files, `IGS.STA` and `EUREF.STA`, are regularly derived from the latest versions of the `igs.snx` and `euref.snx` templates (maintained by the IGS/EUREF CBs) and posted to the following AIUB/CODE ftp address: <http://www.aiub.unibe.ch/download/BSWUSER52/STA>. These station information files (created using the program `SNX2STA`) should contain the complete station information history and may be helpful for updating your station information file with the receiver antenna radome codes. For creation of the two mentioned station information files, receiver and antenna serial number information is masked out. In case you are interested in antenna serial numbers you may have a look at `IGS_FULL.STA` and `EUREF_FULL.STA`, respectively. Note that serial numbers with more than 5 digits are handled differently (in the SINEX templates) within IGS and IAG Reference Frame Sub-Commission for Europe (EUREF). For completeness, the station information used at CODE (`CODE.STA`) is also regularly uploaded to the above mentioned ftp address.

The International Laser Ranging Service (ILRS) also provides some information supporting the processing of SLR data in an SINEX-style format. This information can be extracted by the program `SNX2SLR` ("Menu>Service>SLR utilities>Prepare SLR data handling file", description in Section 19.1.1).

4.5.3. Writing SINEX Files

SINEX files contain a subset of the information available in the Bernese normal equation files (see Sections 24.10.1). The conversion of Bernese normal equations to SINEX is performed by the combination program `ADDNEQ2`, which allows to store normal equation files as well as SINEX files. For details see Section 9.4.9.1.

The SINEX files may contain additional information such as the three-character identification of the agency, the identification of the data source as well as information concerning the blocks `FILE/REFERENCE`, `FILE/COMMENT`, and `INPUT/ACKNOWLEDGMENTS`. A template file (`#{X}/GEN/SINEX.`), described in detail in Section 24.3.18, makes it possible to include this information into the SINEX file automatically. Make sure that you adapt this file to your agency/institution before writing SINEX files.

4.6. Troposphere SINEX

4.6.1. Definition

The Troposphere SINEX file format was developed in 1999 to be used for the submission of troposphere zenith delay solutions by the IGS ACs for the combination and distribution of the combined IGS product. The file contains information on tropospheric zenith path delays and troposphere gradients of terrestrial stations. The format version is 0.01. The format description may be found at

ftp://ftp.igs.org/pub/data/format/sinex_tropo.txt.

```

%=TRO 0.01 COD 14:205:05414 IGS 14:200:00000 14:201:00000 P MIX
*-----
+FILE/REFERENCE
*INFO_TYPE----- INFO-----
DESCRIPTION      CODE, Astronomical Institute, University of Bern
OUTPUT           CODE IGS 3-day solution
CONTACT          code@aiub.unibe.ch
SOFTWARE         Bernese GNSS Software Version 5.2
HARDWARE         UBELIX: Linux, x86_64
INPUT            CODE IGS 1-day solutions
-FILE/REFERENCE
*-----
+TROP/DESCRIPTION
*-----KEYWORD----- _VALUE(S)-----
ELEVATION CUTOFF ANGLE                3
SAMPLING INTERVAL                     180
SAMPLING TROP                          7200
TROP MAPPING FUNCTION                 WET VMF
SOLUTION_FIELDS_1                     TROTOT STDDEV TGNTOT STDDEV TGETOT STDDEV
-TROP/DESCRIPTION
*-----
+TROP/STA_COORDINATES
*SITE PT SOLN T  __STA_X__  __STA_Y__  __STA_Z__  SYSTEM REMRK
ABMF A 1 P 2919785.749 -5383745.000 1774604.777 Igb08 COD
ABPO A 1 P 4097216.594 4429119.108 -2065771.264 Igb08 COD
.
.
ZIMM A 1 P 4331296.934 567556.052 4633134.045 Igb08 COD
ZWE2 A 1 P 2886335.649 2155987.690 5245818.874 Igb08 COD
-TROP/STA_COORDINATES
*-----
+TROP/SOLUTION
*SITE __EPOCH__ TROTOT STDDEV TGNTOT STDDEV TGETOT STDDEV
ABMF 14:200:03600 2590.0 0.5 0.736 0.049 -0.953 0.052
ABMF 14:200:10800 2595.4 0.4 0.725 0.045 -0.892 0.047
ABMF 14:200:18000 2599.7 0.5 0.714 0.041 -0.832 0.043
ABMF 14:200:25200 2611.5 0.5 0.702 0.037 -0.771 0.040
ABMF 14:200:32400 2613.8 0.5 0.691 0.034 -0.710 0.037
ABMF 14:200:39600 2604.3 0.5 0.680 0.032 -0.650 0.036
ABMF 14:200:46800 2605.0 0.5 0.668 0.031 -0.589 0.036
ABMF 14:200:54000 2601.5 0.5 0.657 0.031 -0.528 0.037
ABMF 14:200:61200 2585.9 0.4 0.645 0.033 -0.468 0.039
ABMF 14:200:68400 2577.4 0.4 0.634 0.035 -0.407 0.043
ABMF 14:200:75600 2583.6 0.4 0.623 0.038 -0.346 0.046
ABMF 14:200:82800 2580.0 0.5 0.611 0.042 -0.286 0.051
ABPO 14:200:03600 2006.3 0.7 -0.197 0.064 -0.057 0.069
ABPO 14:200:10800 2002.8 0.6 -0.172 0.058 -0.010 0.063
.
.
ZWE2 14:201:46800 2361.4 0.6 -0.116 0.044 -0.251 0.037
ZWE2 14:201:54000 2367.0 0.6 -0.156 0.046 -0.318 0.038
ZWE2 14:201:61200 2368.6 0.6 -0.197 0.049 -0.385 0.041
ZWE2 14:201:68400 2367.9 0.5 -0.237 0.053 -0.453 0.044
ZWE2 14:200:75600 2365.2 0.5 0.067 0.056 0.042 0.047
ZWE2 14:200:82800 2367.6 0.5 0.065 0.062 0.080 0.052
-TROP/SOLUTION
%=ENDTRO

```

Figure 4.10.: Example of a Troposphere SINEX file.

Strictly speaking, the inclusion of gradients is not defined in the format description (and there has been no format update so far), but user demand has forced the IGS ACs to extend the format unofficially. Figure 4.10 shows an example for a Troposphere SINEX file.

4.6.2. Writing Troposphere SINEX Files

Troposphere SINEX files (default extension TR0) may be written by the parameter estimation program GPSEST and by the normal equation combination program ADDNEQ2. In addition, both programs write troposphere files in Bernese format (default extension TRP). No Bernese program reads Troposphere SINEX files.

The Troposphere SINEX files may contain additional information such as the three-character identification of the agency and information concerning the blocks FILE/REFERENCE. A template file (`/${X}/GEN/SINEX.`), described in detail in Section 24.3.18, makes it possible to include this information into the Troposphere SINEX file automatically. Make sure that you adapt this file to your agency/institution before writing Troposphere SINEX files.

4.6.3. Utility

The program TROTRO ("Menu>Conversion>Manipulate troposphere SINEX files") allows to remove problematic records from an existing Troposphere SINEX file, which are indicated in TYPE 003: HANDLING OF STATION PROBLEMS section of a station information file.

4.7. ANTEX Files

4.7.1. Definition

The ANTenna EXchange format (ANTEX) was proposed by M. Rothacher and R. Schmid at the 2002 IGS Workshop in Ottawa, Canada. It is designed to hold information for ground antennas as well as for GNSS satellite antennas concerning phase center offsets and phase patterns. After several updates the current version 1.4 (see example in Figure 4.11) was defined in 2010. Its format description may be found at

`ftp://ftp.igs.org/pub/station/general/antex14.txt.`

4.7.2. Import to Bernese

ANTEX is supported by the *Bernese GNSS Software*. Antenna information given in the ANTEX format can be converted to the Bernese antenna phase center format (see Section 24.3.3) with the program ATX2PCV ("Menu>Conversion>ANTEX to Bernese format", see Section 18.3 for a detailed program description). No Bernese program is writing antenna phase center information in ANTEX format.


```

1.4          M          ANTEX VERSION / SYST
A           PCV TYPE / REFANT
##### COMMENT
Compiled by Ralf Schmid (DGFI), e-mail: schmid@dgfi.badw.de COMMENT
##### COMMENT
.           END OF HEADER
.
.
BLOCK IIF          G01          G063          2011-036A          START OF ANTENNA
                                0          18-JUL-11          TYPE / SERIAL NO
                                METH / BY / # / DATE
0.0          DAZI
0.0 17.0 1.0          ZEN1 / ZEN2 / DZEN
2          # OF FREQUENCIES
2011 7 16 0 0 0.000000          VALID FROM
IGS08_1805          SINEX CODE
Z-OFFSET UPDATE IN GPS WEEK 1706: 1650.0 mm --> 1561.3 mm          COMMENT
G01          START OF FREQUENCY
394.00          0.00 1561.30          NORTH / EAST / UP
NOAZI 6.10 4.40 2.80 1.30 -0.20 -1.40 -2.80 -3.90 -4.40 ...
G01          END OF FREQUENCY
G02          START OF FREQUENCY
394.00          0.00 1561.30          NORTH / EAST / UP
NOAZI 6.10 4.40 2.80 1.30 -0.20 -1.40 -2.80 -3.90 -4.40 ...
G02          END OF FREQUENCY
.           END OF ANTENNA
.
.
AOAD/M_T          NONE          START OF ANTENNA
ROBOT          Geo++ GmbH          2          25-MAR-11          TYPE / SERIAL NO
                                METH / BY / # / DATE
5.0          DAZI
0.0 90.0 5.0          ZEN1 / ZEN2 / DZEN
2          # OF FREQUENCIES
IGS08_1805          SINEX CODE
Number of Calibrated Antennas GPS: 002          COMMENT
Number of Individual Calibrations GPS: 062          COMMENT
G01          START OF FREQUENCY
0.58 -0.37 91.85          NORTH / EAST / UP
NOAZI 0.00 -0.23 -0.90 -1.93 -3.22 -4.62 -5.96 -7.09 -7.87 ...
0.0 0.00 -0.27 -0.98 -2.07 -3.42 -4.87 -6.26 -7.43 -8.21 ...
5.0 0.00 -0.27 -0.98 -2.06 -3.41 -4.86 -6.25 -7.41 -8.20 ...
10.0 0.00 -0.26 -0.97 -2.05 -3.39 -4.84 -6.23 -7.40 -8.19 ...
15.0 0.00 -0.26 -0.97 -2.05 -3.38 -4.82 -6.21 -7.37 -8.17 ...
.
.
345.0 0.00 -0.13 -0.50 -1.04 -1.71 -2.46 -3.25 -4.05 -4.73 ...
350.0 0.00 -0.13 -0.49 -1.03 -1.70 -2.45 -3.25 -4.04 -4.73 ...
355.0 0.00 -0.13 -0.49 -1.03 -1.69 -2.44 -3.24 -4.04 -4.73 ...
360.0 0.00 -0.12 -0.48 -1.02 -1.69 -2.44 -3.24 -4.04 -4.72 ...
G02          END OF FREQUENCY
.           END OF ANTENNA
.
.
.

```

Figure 4.11.: Example of an ANTEX file.

4.8. IONEX

4.8.1. Definition

The Ionosphere model EXchange format (IONEX) format was developed for the exchange of ionosphere maps. A first version of the format was presented by Schaer et al. (1996). The currently used version 1 of the format was presented and approved at the 1998 IGS Workshop in Darmstadt (Schaer et al. 1998). The format supports the exchange of two- and three-dimensional Total Electron Content (TEC) maps given as a geographic grid. An example is shown in Figure 4.12. The format description may be found at

<ftp://ftp.igs.org/pub/data/format/ionex1.pdf> or
<ftp://ftp.igs.org/pub/data/format/ionex1.ps> .

```

1.0 IONOSPHERE MAPS GNSS IONEX VERSION / TYPE
ADDNEQ2 V5.2 AIUB 12-DEC-03 09:52 PGM / RUN BY / DATE
CODE'S RAPID IONOSPHERE MAPS FOR DAY 345, 2003 COMMENT
Global ionosphere maps (GIM) are generated on a daily basis DESCRIPTION
.
.
2003 12 11 0 0 0 EPOCH OF FIRST MAP
2003 12 12 0 0 0 EPOCH OF LAST MAP
7200 INTERVAL
13 # OF MAPS IN FILE
NONE MAPPING FUNCTION
10.0 ELEVATION CUTOFF
One-way carrier phase leveled to code OBSERVABLES USED
104 # OF STATIONS
36 # OF SATELLITES
6371.0 BASE RADIUS
2 MAP DIMENSION
450.0 450.0 0.0 HGT1 / HGT2 / DHGT
87.5 -87.5 -2.5 LAT1 / LAT2 / DLAT
-180.0 180.0 5.0 LON1 / LON2 / DLON
-1 EXPONENT
TEC/RMS values in 0.1 TECU; 9999, if no value available COMMENT
DIFFERENTIAL CODE BIASES START OF AUX DATA
G01 -1.805 0.013 PRN / BIAS / RMS
.
.
R24 -7.066 0.028 PRN / BIAS / RMS
G ALBH 40129M003 7.174 0.070 STATION / BIAS / RMS
.
.
G ZIMM 14001M004 17.218 0.136 STATION / BIAS / RMS
DCB values in ns; zero-mean condition wrt satellite values COMMENT
DIFFERENTIAL CODE BIASES END OF AUX DATA
.
.
1 START OF TEC MAP
2003 12 11 0 0 0 EPOCH OF CURRENT MAP
87.5-180.0 180.0 5.0 450.0 LAT/LON1/LON2/DLON/H
26 25 25 24 24 23 22 22 21 20 19 19 18 17 16 15
14 14 13 12 12 11 11 11 11 11 11 11 12 12 13 14
14 15 16 18 19 20 21 22 23 24 25 26 27 28 28 29
29 30 30 30 31 31 31 31 31 31 31 30 30 30 30 29
29 29 28 28 28 27 27 26 26 LAT/LON1/LON2/DLON/H
85.0-180.0 180.0 5.0 450.0
35 35 35 34 34 33 32 31 30 29 27 25 24 22 20 18
16 14 12 10 9 7 6 5 4 4 4 5 6 7 9 11
13 15 18 21 24 27 30 32 35 37 39 40 42 43 44 44
45 45 45 45 45 44 44 43 43 42 42 41 40 40 39 39
38 38 37 37 37 36 36 36 35
.
.
13 END OF RMS MAP
END OF FILE

```

Figure 4.12.: Example of an IONEX file.

4.8.2. Writing IONEX Files

IONEX files (default extension INX) are written by the parameter estimation program GPSEST and the normal equation combination program ADDNEQ2 in addition to ionosphere files in Bernese format (default extension ION). No Bernese program reads IONEX files.

The IONEX files contain meta data such as the identification of the agency, comment lines, or the definition of the data grid. A template file ($\${X}/GEN/IONEX.$), described in detail in Section 24.3.19, makes it possible to include this information into the IONEX file automatically. Make sure that you adapt this file to your agency/institution before writing IONEX files.

4.9. Clock RINEX File

4.9.1. Definition

The Clock RINEX format has been defined by J. Ray and W. Gurtner in 1998 for exchanging clock corrections to GPS system time not only for satellites but also for receivers and at a higher sampling than available in the IGS precise orbit files. The file format consists of a header and a data section. An updated version 2 (see an example in Figure 4.13) was introduced in 1999 in order to support GLONASS clocks, too. This is the latest version supported by *Bernese GNSS Software* Version 5.2. In 2010, a new version of the Clock RINEX format (format number 3.02) was defined in order to be compatible with the RINEX3.02 observation file format and to support new GNSS. The format description of this version may be found at

ftp://ftp.igs.org/pub/data/format/rinex_clock302.txt.

4.9.2. Import to Bernese

The *Bernese GNSS Software* uses an independent satellite clock format (see Section 24.6.10). The Bernese clock files (default extension CLK) reside in the campaign's default ORB subdirectory. Clock RINEX files have the same default extension but are located in the campaign's OUT directory.

```

2.00          CLOCK DATA          RINEX VERSION / TYPE
CCRNXC        AIUB                12-DEC-03 09:04    PGM / RUN BY / DATE
CODE PRECISE CLOCK INFORMATION      COMMENT
BASED ON CODE AND PHASE MEASUREMENTS COMMENT
  2   AR   AS                      # / TYPES OF DATA
COD Center for Orbit Determination in Europe ANALYSIS CENTER
  1                                     # OF CLK REF
NLIB 40465M001                      0.000000000000E+00 ANALYSIS CLK REF
 115   IGS00                          # OF SOLN STA / TRF
NLIB 40465M001                      -130934591 -4762291737 4226854648 SOLN STA NAME / NUM
ALBH 40129M003                      -2341332946 -3539049508 4745791310 SOLN STA NAME / NUM
ALGO 40104M002                      918129393 -4346071275 4561977849 SOLN STA NAME / NUM
.
.
YSSK 12329M003                      -3465320923 2638269370 4644085393 SOLN STA NAME / NUM
ZAMB 34601M001                      5415353043 2917209880 -1685888909 SOLN STA NAME / NUM
ZECK 12351M001B                      3451174733 3060335426 4391955630 SOLN STA NAME / NUM
 28                                     # OF SOLN SATS
G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G13 G14 G15 G16 PRN LIST
G17 G18 G20 G21 G23 G24 G25 G26 G27 G28 G29 G30 G31 PRN LIST
END OF HEADER
AR NLIB 2003 12 07 00 00 0.000000 2 -0.973573763043E-06 0.840715453012E-08
AR ALBH 2003 12 07 00 00 0.000000 2 0.270685608715E-08 0.837644005734E-08
AR ALGO 2003 12 07 00 00 0.000000 2 0.952996575283E-06 0.100049161811E-07
.
.
AR YELL 2003 12 07 00 00 0.000000 2 0.587719954270E-05 0.810391030829E-08
AR ZAMB 2003 12 07 00 00 0.000000 2 0.238403284208E-08 0.888057059285E-08
AR ZECK 2003 12 07 00 00 0.000000 2 -0.733499966014E-08 0.850077851865E-08
AS G01 2003 12 07 00 00 0.000000 2 0.318638198904E-03 0.404238883816E-08
AS G02 2003 12 07 00 00 0.000000 2 -0.234422320869E-03 0.502851071366E-08
AS G03 2003 12 07 00 00 0.000000 2 0.676875613732E-04 0.517712366686E-08
.
.
AS G29 2003 12 07 00 00 0.000000 2 0.182346083001E-03 0.760633184834E-08
AS G30 2003 12 07 00 00 0.000000 2 0.674860089771E-03 0.456847346247E-08
AS G31 2003 12 07 00 00 0.000000 2 0.434724448350E-03 0.703601363364E-08

```

Figure 4.13.: Example of a Clock RINEX file.

A clock RINEX file can be converted to the Bernese satellite clock format with the program `RNXCLK` ("Menu>RINEX>RINEX utilities>Extract satellite clock", description in Section 15.3.1). It is a one-by-one copy of the satellite clock values from the external to the internal format.

4.9.3. Writing Clock RINEX Files

Clock RINEX files may be written by the programs `CODSPP`, `GPSEST`, `ADDNEQ2`, and `CLKEST`. See Chapter 15 for details on clock estimation in the *Bernese GNSS Software*.

4.9.4. Utility

With the program `CCRNXC` ("Menu>Service> Clock tools>Combine/manipulate clock RINEX files") the *Bernese GNSS Software* Version 5.2 provides a powerful utility for various operations on clock RINEX files. A full description of this program is given in Section 15.3.

4.10. RINEX Navigation Files

The RINEX navigation message files contain broadcast messages for all satellites collected during the observation time. An example is shown in Figure 4.14. The document referenced in Section 4.2.1 includes a description of this file format. The Version 5.2 of the *Bernese GNSS Software* only supports RINEX2 formatted navigation files. The related recommended file naming convention is

```
ccccdddf.yyN
ccccdddf.yyG
```

where `N` and `G` designate GPS and GLONASS files, respectively. `cccc` is a station identifier and `dddf` a session string composed of day of year (`ddd`) and session character (`f`); `yy` is the two-digit year. GPS navigation messages contain orbital elements, whereas GLONASS messages give tabulated Cartesian positions in the PZ-90 Earth-fixed frame.

Usually, there is no need to exchange navigation messages collected by all the stations of a network in separate files. One comprehensive file containing non-redundantly all possible messages might be preferable. In this case, `cccc` could be a code for the agency producing this file.

4.10.1. Import to Bernese

`RXNBV3` ("Menu>RINEX>Import RINEX to Bernese format>Navigation files") converts the GPS RINEX navigation messages (but not GLONASS messages, see below) into Bernese broadcast files. Differential code biases may be extracted from the RINEX navigation message files and written to corresponding Bernese files.

`RXNPRE` ("Menu>RINEX>Import RINEX to Bernese format>Navigation files to SP3") converts GPS and GLONASS navigation messages directly to the SP3-/SP3c-format (see Sections 4.3 and

```

2.11      N: GPS NAV DATA      RINEX VERSION / TYPE
NetR9 5.03 Receiver Operator 22-AUG-15 00:00:00 PGM / RUN BY / DATE
      .9313D-08 .2235D-07 -.5960D-07 -.1192D-06 ION ALPHA
      .9216D+05 .1147D+06 -.1311D+06 -.5898D+06 ION BETA
      -.186264514923D-08 -.799360577730D-14 61440 1859 DELTA-UTC: A0,A1,T,W
17 LEAP SECONDS
      END OF HEADER
16 15 8 22 0 0 0.0 -.949008390307D-04 .409272615798D-11 .000000000000D+00
      .800000000000D+02 -.395937500000D+02 .367658171581D-08 .138204518245D+01
      -.194460153580D-05 .808877684176D-02 .741891562939D-05 .515360955620D+04
      .518400000000D+06 -.102445483208D-06 .815978780563D+00 .279396772385D-07
      .990592274350D+00 .254218750000D+03 .324706056511D+00 -.773746515362D-08
      -.163578242262D-09 .100000000000D+01 .185800000000D+04 .000000000000D+00
      .240000000000D+01 .000000000000D+00 -.102445483208D-07 .800000000000D+02
      .511302000000D+06 .400000000000D+01
5 15 8 22 0 0 0.0 -.203978735954D-03 .420641299570D-11 .000000000000D+00
      .160000000000D+02 -.650000000000D+01 .506735393277D-08 .130562843943D+01
      -.106170773506D-06 .430821860209D-02 .925548374653D-05 .515362569809D+04
      .518400000000D+06 .102445483208D-06 -.240024567020D+01 .987201929092D-07
      .946571307992D+00 .193156250000D+03 .392681158026D+00 -.827070165078D-08
      -.266439669710D-09 .100000000000D+01 .185800000000D+04 .000000000000D+00
      .240000000000D+01 .000000000000D+00 -.107102096081D-07 .160000000000D+02
      .511872000000D+06 .400000000000D+01
7 15 8 22 0 0 0.0 .481138937175D-03 .193267624127D-11 .000000000000D+00
      .630000000000D+02 .150312500000D+02 .434196657462D-08 -.236267532700D+01
      .718981027603D-06 .886233546771D-02 .490434467793D-05 .515370110321D+04
      .518400000000D+06 .204890966415D-07 -.272660804548D+00 -.115483999252D-06
      .969567476114D+00 .289593750000D+03 -.271900121379D+01 -.804247785863D-08
      -.778603860547D-10 .100000000000D+01 .185800000000D+04 .000000000000D+00
      .240000000000D+01 .000000000000D+00 -.111758708954D-07 .630000000000D+02
      .511218000000D+06 .400000000000D+01
      .
      .
      .

```

Figure 4.14.: RINEX navigation message file (GPS).

24.6.2). The orbits may then be converted to standard orbits using programs PRETAB and ORBGEN, see Section 5.3.1. This is the only way to convert navigation messages to standard orbits for GLONASS. The program applies the transformation from the PZ-90 coordinate system to WGS-84 using transformation parameters from file `#{X}/GEN/DATUM`.

More details on processing broadcast navigation messages with the *Bernese GNSS Software* are given in Section 5.3.

4.10.2. Export from Bernese

The program BV3RXN ("Menu>RINEX>Export RINEX from Bernese format>Navigation files") transforms one or more Bernese broadcast files to RINEX navigation message files. Normally, one RINEX output file is created for each Bernese broadcast input file. Optionally, the messages from all input files may be written to the same RINEX output file. Program BV3RXN may only be used to generate GPS RINEX navigation message files as there are no Bernese broadcast files for GLONASS.

4.10.3. Utilities

CCRINEXN ("Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GPS)") and CCRINEXG ("Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GLONASS)") may be used to cut/concatenate RINEX navigation message files from GPS or GLONASS. Consult the online help for more information.

4.11. RINEX Meteo Files

4.11.1. Definition

The RINEX meteorological data files are used to exchange weather data collected at different GNSS stations. The format description may be found in the document referenced in Section 4.2.1. Figure 4.15 shows an example for a RINEX Meteo file. The recommended file naming is `ccccddd.f.yyM`, where `M` denotes meteorological data files, `cccc` is the station identifier, and `ddd` is the session string composed of day of year (`ddd`) and session character (`f`); `yy` is the two-digit year.

4.11.2. Import to Bernese

`RXMBV3` ("Menu>RINEX>Import RINEX to Bernese format>Meteo files") transforms the RINEX meteo files into Bernese meteo files (description see Section 24.8.3). The RINEX format asks for one meteo file per site and session, in the Bernese format one meteo file per site is required (only one meteo file per site can be specified in `GPSEST`). Therefore, the program `RXMBV3` may concatenate RINEX meteo files from different sessions into one (site-specific) Bernese meteo file. Optionally, the "Station information" (Panel "RXMBV3 2: Station Name Translation") may be used for converting the station names from RINEX Meteo file to a well defined name (section `TYPE 001: RENAMING OF STATIONS`).

4.11.3. Writing RINEX Meteo Files

When extracting SLR observations from the Normal Point observation files using the programs `QLRINEXO` ("Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX") or `CRD2RXNO` ("Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX"), the meteorological measurements are extracted and stored in the RINEX meteo file format. Hence, it is possible to use `RXMBV3` (see above) to make these data available to the Bernese processing programs to model the tropospheric refraction. For more details on processing SLR data inspect Chapter 19.

2	METEOROLOGICAL DATA						RINEX VERSION / TYPE		
QLRINEXO V1.0.0 UX	AIUB	09-DEC- 3 02:08				PGM / RUN BY / DATE			
SLR QL NORMAL POINT DATA	COMMENT						COMMENT		
STATION ID: 7832	COMMENT						COMMENT		
CDP SYSNUM: 55	CDP OCCNUM: 01	SYS CONFIG: 1		COMMENT		COMMENT			
W-LENGTH 1: 532	W-LENGTH 2: 0		COMMENT			COMMENT			
EPOCH TIME SCALE REFERENCE : UTC (USNO)						COMMENT			
EPOCHS: TIME OF SIGNAL RECEPTION IN GPS TIME FRAME						COMMENT			
RANGES: 0.5 * C * FLIGHT TIME (M)						COMMENT			
7832 RIYL	MARKER NAME						# / TYPES OF OBSERV		
3	PR	TD	HR			END OF HEADER			
3 11 27 14 59 37	929.2	21.6	36.0						
3 11 27 15 3 3	929.1	21.6	37.0						
3 11 27 15 7 40	929.1	21.5	37.0						
3 11 27 15 12 42	929.2	21.4	37.0						
3 11 27 15 22 22	929.2	21.2	37.0						
3 11 27 15 27 1	929.3	21.0	38.0						
3 11 27 16 54 31	929.6	19.7	39.0						
3 11 27 17 2 10	929.6	19.6	39.0						
3 11 27 17 7 9	929.6	19.6	39.0						
3 11 27 17 12 31	929.6	19.5	39.0						
3 11 27 17 17 18	929.7	19.6	38.0						
3 11 27 17 22 60	929.6	19.7	39.0						
3 11 27 22 5 10	928.2	17.3	42.0						
3 11 27 22 6 46	928.1	17.2	41.0						
...									

Figure 4.15.: Example of a RINEX meteorological data file.

4.12. SLR Normal Point Observation Files

SLR observation file formats contain not only the measurements itself but also important information regarding the station, satellite, time, meteorologic conditions, and sometimes even geometrical observation data. For a long time, SLR normal point data have been provided in the so-called CSTG format. In March 2012 the ILRS changed the format to the new Consolidated Laser Ranging Data Format (CRD).

4.12.1. Historic CSTG Normal Point Format

The historic CSTG Normal Point format was introduced in 1990 and was revised twice in 1997 and 2004. However, as of March 2012 it is no longer used in favour of the more versatile and capable format. More details regarding this format can be found at:

http://ilrs.gsfc.nasa.gov/data_and_products/data/npt/npt_format.html.

4.12.2. Current Consolidated Laser Ranging Data Format (CRD)

To offer an adequate, flexible and extendable file format for SLR normal point measurements that can store both fullrate data and normal points as well as engineering, meteo, object and station related parameters, the ILRS introduced the CRD Format in 2012. An example is given in Figure 4.16 and an extensive documentation about the file format and all available options can be found at:

http://ilrs.gsfc.nasa.gov/data_and_products/data/npt/crd.html.

```

h1 crd 1 2012 5 30 10
h2 ZIML 7810 68 1 4
h3 lageos2 9207002 5986 0 0 1
h4 1 2012 5 30 7 39 44 -1 -1 -1 -1 -1 -1 0 0 0 0 1 0 2 0
c0 0 532.100 sys1 frq1 spad tim1
c1 0 frq1 Nd-YAG 1064.20 100.00 8.00 60.0 10.00 0
c2 0 spad CSPAD 532.100 -1.00 -1.0 -1.0 tbd -1.0 0.10 90.0 10.00 na
c3 0 tim1 TrueTime_XL-DC BVA_8607BE_10MHz A032ET 3203 0.0
40 27584.470332367346 0 sys1 -1 1487 658.711 120275.5 0.0 29.0 -1.000 -1.000 -1.0 2 0 0
50 sys1 61.1 0.000 0.000 0.0 0
11 27584.470302336424 0.042589117551 sys1 2 120 39 8.7 -1.000 -1.000 -1.0 ...
20 27584.470 916.60 289.74 50. 1
11 27662.610302334251 0.041724315731 sys1 2 120 1011 1.9 -1.000 -1.000 -1.0 ...
11 27785.040302339443 0.040519753240 sys1 2 120 900 1.9 -1.000 -1.000 -1.0 ...
20 27785.040 916.60 289.85 49. 1
11 27895.951302335674 0.039602001367 sys1 2 120 989 1.9 -1.000 -1.000 -1.0 ...
11 28025.991102337077 0.038755648014 sys1 2 120 887 2.0 -1.000 -1.000 -1.0 ...
20 28025.991 916.60 289.99 47. 1
11 28124.829102338517 0.038289689446 sys1 2 120 832 2.3 -1.000 -1.000 -1.0 ...
11 28279.657102338624 0.037884670176 sys1 2 120 690 2.5 -1.000 -1.000 -1.0 ...
20 28279.657 916.60 290.13 46. 1
11 28330.174302335185 0.037840640821 sys1 2 120 202 4.5 -1.000 -1.000 -1.0 ...
11 28522.510302336126 0.038073587588 sys1 2 120 53 9.4 -1.000 -1.000 -1.0 ...
20 28522.510 916.60 290.26 45. 1
11 28650.662702336871 0.038575373938 sys1 2 120 51 9.1 -1.000 -1.000 -1.0 ...
11 28707.637902339880 0.038884234884 sys1 2 120 308 3.3 -1.000 -1.000 -1.0 ...
20 28707.638 916.61 290.39 45. 1
h8

```

Figure 4.16.: Example of a Consolidated Laser Ranging Data Format (CRD) file.

4.12.3. Import to Bernese

Both formats are supported by the *Bernese GNSS Software*. Internally they are converted to RINEX observation and meteo file formats using the programs QLRINEXO ("Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX") and CRD2RNXO ("Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX"). In Section 19.3.2 you find a detailed description of the programs and the procedure.

4.13. External Data Sources

4.13.1. CODE Products

The Center for Orbit Determination in Europe (CODE) is one of the ACs of the IGS. CODE is a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (swisstopo), the Bundesamt für Kartographie und Geodäsie (BKG), and the Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG). CODE is located at the AIUB in Bern. It is contributing to the ultra-rapid, rapid, and final product series of the IGS with a rigorously combined GPS and GLONASS solution. With a five-systems solution (GPS, GLONASS, Galileo, Chinese GNSS (BeiDou), and QZSS) CODE is contributing to the IGS Multi-GNSS EXperiment (MGEX). An overview of the activities and the available product files (in the international file formats) is available in the annual reports of the IGS (e.g., Dach et al. 2015).

The CODE IGS products are made available on the AIUB anonymous ftp account. To access AIUB's anonymous ftp server use

```
address:  ftp.unibe.ch
login:    anonymous
password: your full e-mail address
products: cd aiub (to get to the top directory of AIUB's ftp area)
```

or direct your browser to

```
http://www.aiub.unibe.ch/download/.
```

After entering our anonymous ftp area, you will see several subdirectories. Our products are stored in two main directory trees:

- BSWUSER52 for files in formats specific to Version 5.2 of the *Bernese GNSS Software* and
- CODE for files in international formats.

As Figure 4.17 illustrates, these main trees are available on the top level for the operational products and in dedicated subdirectories for other datasets.

The CODE directory on the aftp server contains our official IGS products, whenever possible in international formats. The products include precise orbits in SP3c format, ERP files in IGS version 2 format, DCBs in Bernese format, satellite and receiver clock corrections in Clock RINEX format, station coordinates in SINEX format, troposphere zenith path delays in Troposphere SINEX format, global ionosphere maps in IONEX and Bernese format, and RINEX Navigation files containing improved Klobuchar-style ionosphere coefficients. Note that our precise orbit files should always be used together with the corresponding pole files!

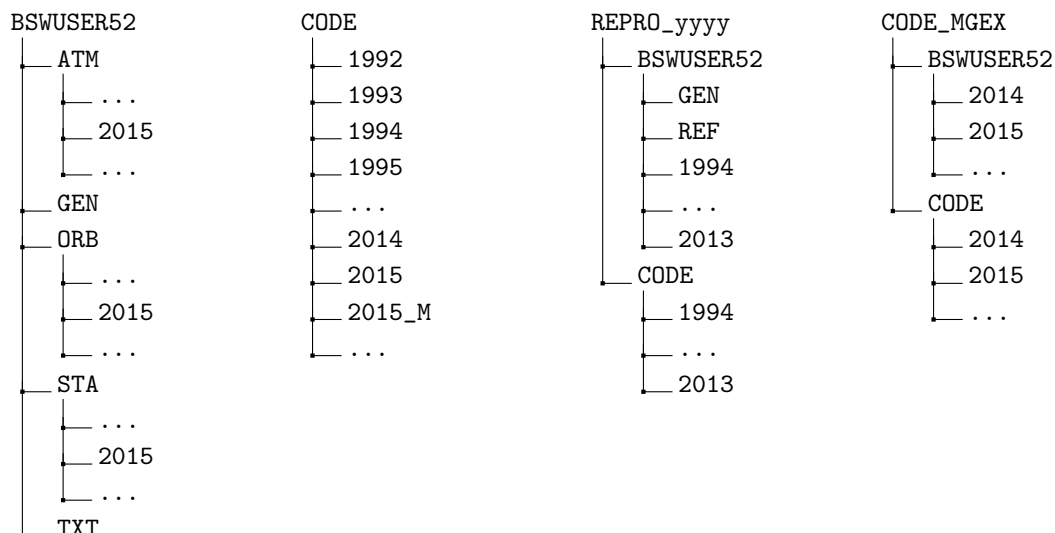


Figure 4.17.: Directory structure for CODE products at <http://www.aiub.unibe.ch/download/>.

The final products are arranged in yearly subdirectories, the rapid and ultra-rapid products are stored in the top directory until the final products for the corresponding day (or week) are available. The ultra-rapid products are overwritten several times per day. For orbits, ERPs, and ionosphere information 1-day, 2-day, and 5-day predictions are provided.

The directory `BSWUSER52` contains files specific to the *Bernese GNSS Software* Version 5.2. These can either be general Bernese files or IGS products in a format specific to the *Bernese GNSS Software*. Examples of general files in the Bernese format are the IERS pole files, the antenna phase center file, the station information files, and the satellite information files. IGS products in the Bernese file format are, for instance, daily troposphere and orbit estimates or weekly coordinate and troposphere estimates. Additional `BSWUSER` directories distinguish between the versions of the *Bernese GNSS Software*. All subdirectories contain the full set of files but in the respective format.

The top directory also contains several directories with the results of different reprocessing efforts. These directories are named `REPRO_yyyy` (`yyyy` refers here to the year of the reprocessing effort) and are sub-divided into `BSWUSER` and `CODE` directories — just like the directories for the operational products. The file naming convention is also the same as for the routine products. Note that not all products of the operational processing were recomputed in each reprocessing campaign.

The results from the CODE MGEX solution are made available in an analogue structure where the main directory is named `CODE_MGEX`. Here the precise orbits, the related ERP information, the clock corrections, and the related biases are made available.

For updated information about the content of our FTP server please at http://www.aiub.unibe.ch/download/BSWUSER52/README_AIUB_AFTP.TXT.

4.13.2. IGS Products

The products of all IGS ACs are archived at four global data centers together with the observation data. The combined official IGS products may be found at the same locations.

They consist of precise orbits, ERPs, coordinates and velocities of the ground stations, and tropospheric zenith delays. For more information please visit the website of the IGS Central Bureau

`http://www.igs.org`.

Below, we describe briefly how to access these global data centers and where to find the IGS data and products.

To access Institut national de l'information géographique et forestière (IGN) located in Paris, France, use the following commands:

```
Anonymous ftp:  address:  igs.ensg.ign.fr
                  login:    anonymous
                  password:  your full e-mail address
                  data:      cd pub/igs/data
                  products:  cd pub/igs/products
Internet browser: ftp://igs.ensg.ign.fr/pub/igs/
```

To access CDDIS located near Washington, D.C., USA, use the following commands:

```
Anonymous ftp:  address:  cddis.gsfc.nasa.gov
                  login:    anonymous
                  password:  your full e-mail address
                  data:      cd pub/gps/data
                  products:  cd pub/gps/products
Internet browser: ftp://cddis.gsfc.nasa.gov/pub/gps/
```

To access Scripps Institution of Oceanography (SIO) located in San Diego, USA, use the following commands:

```
Anonymous ftp:  address:  lox.ucsd.edu
                  login:    anonymous
                  password:  your full e-mail address
                  data:      cd pub/rinex/
                  products:  cd pub/products
Internet browser: ftp://lox.ucsd.edu/pub/
```

To access Korean Astronomy and Space Science Institute (KASI) located in Daejeon, South Korea, use the following commands:

```
Anonymous ftp:  address:  nfs.kasi.re.kr
                  login:    anonymous
                  password:  your full e-mail address
                  data:      cd gps/data
                  products:  cd gps/products
Internet browser: ftp://nfs.kasi.re.kr/gps/
```

The IGS maintains the so-called Central Bureau Information System (CBIS). The primary functions of the CBIS are to facilitate communication, coordinate IGS activities, establish and promote compliance to IGS network standards, monitor network operations, quality assurance of data, and maintenance of documentation. The CBIS is accessible on the internet by anonymous ftp. The information is mostly available in easy-to-handle ASCII files. Alternative access methods are provided as well such as third-party e-mail servers and a web site. The CBIS can be accessed in the following ways:

```
web:      http://www.igs.org
ftp:      ftp://ftp.igs.org/pub/
e-mail:   igscb@igscb.jpl.nasa.gov
```

5. Preparation of Earth Orientation, GNSS Orbit, and Satellite Clock Information

5.1. Overview

The orbits of the GNSS satellites, together with the corresponding Earth rotation parameters (ERPs) and satellite clock corrections, are essential for GNSS data analysis. Therefore, the programs related to orbit generation and transformation may be considered as the backbone of the *Bernese GNSS Software*.

Figure 5.1 shows a functional flow diagram containing all essential steps that may be performed within the orbit part of Version 5.2. To prepare the precise orbit information for GNSS data processing only a subset of the available functionality is necessary. The full functionality is exploited when improving satellite orbits (see Chapter 16).

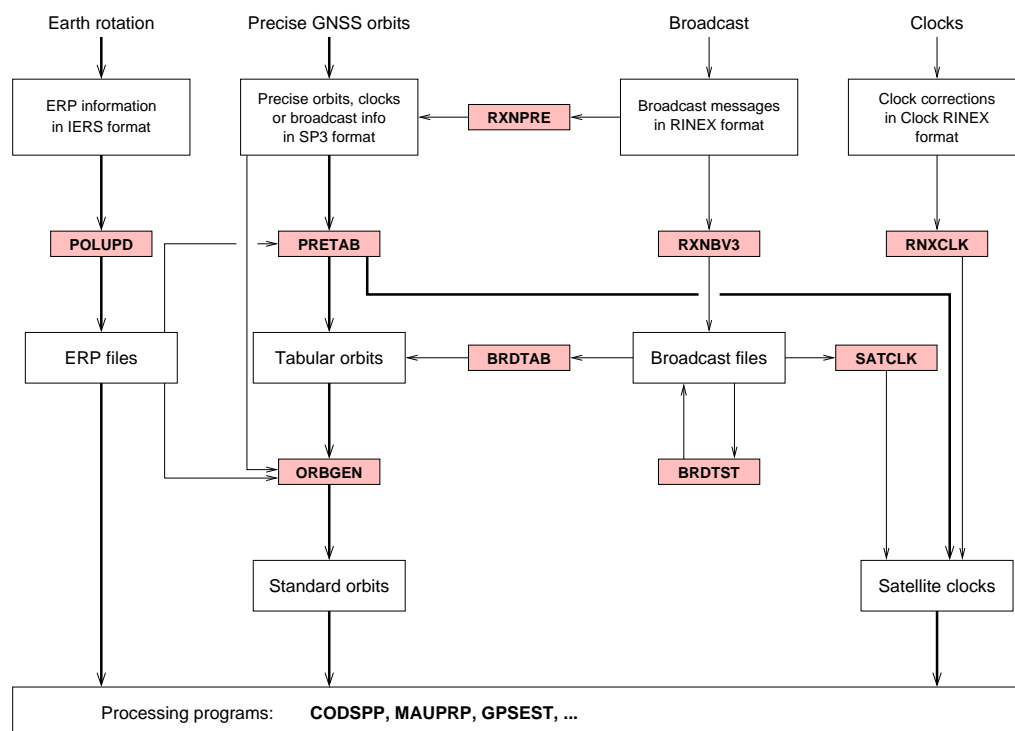


Figure 5.1.: Flow diagram of the preparation of Earth orientation parameters, GNSS orbits, and clocks in the *Bernese GNSS Software* Version 5.2. The gray boxes represent programs.

The programs related to satellite orbits may be found under the menu item "Menu >Orbits/EOP". They contain programs for checking and converting broadcast ephemerides and extracting broadcast clocks, for converting precise orbit information into the Bernese standard orbit format, and for generating precise orbit files starting from standard orbit format. Additional tools for extracting and converting Earth orientation parameters (EOPs), for the preparation of satellite clock information necessary (e.g., for receiver clock synchronization), for extracting information from the orbit integration program, and for comparing precise orbit files or standard orbit files are available.

The *Bernese GNSS Software* may handle several orbit formats (see Table 5.1). The international format for exchanging precise orbit information within the IGS is the SP3c format. Reading routines recognize the new format versions as well as older versions of the precise file format (SP3, SP2 or SP1). The precise orbit files (default extension PRE¹) contain geocentric Cartesian coordinates (in kilometers) of the satellites in an Earth-fixed frame together with satellite clock information at equidistant epochs (usually 15 minutes). For a description of the file format see <ftp://ftp.igs.org/pub/data/format/sp3c.txt> or Hilla (2010). See also Sections 4.3 and 4.13.

The internal Bernese tabular orbit files are ASCII files (default extension TAB) containing Cartesian satellite coordinates (in kilometers) in the inertial frame, tabulated at regularly spaced epochs. The so-called standard orbit files (default extension STD) are binary files specifying the positions of the satellites in a polynomial representation. They are the result of a numerical integration of the equations of motion. All programs of the *Bernese GNSS Software* that require GNSS orbit information read standard orbit files. EOPs are required for all programs accessing standard orbit files in order to perform the transformations between the Earth-fixed and the inertial frame. In addition to the file formats listed in Table 5.1, broadcast information in RINEX and Bernese format can be processed by the *Bernese GNSS Software*.

This chapter first describes how to import and prepare EOPs (next section). Section 5.3 presents the programs available for preparing broadcast information. Section 5.4 shows how to interpolate precise orbit files and to prepare the orbit information in the standard orbit format. The latter one is the standard application of the orbit programs in the *Bernese GNSS Software*. Section 5.6 describes how to extract satellite clock information from broadcast or precise orbit files, an information which is important to synchronize the receiver clocks in the data preprocessing step. In the last section the programs for orbit comparison are described. Information on how to estimate GNSS satellite orbits and EOPs is given in Chapter 16. Chapter 17 is dedicated to orbit determination of Low Earth Orbiter satellites (LEOs). For more information on estimating satellite clocks we refer to Chapter 15.

¹In most databases these files have extensions EPH or SP3.

Table 5.1.: Important orbit formats used in the *Bernese GNSS Software* (sampling is valid for GNSS satellites).

File Type	Format	Content, Reference System
PRE Precise Orbit File, SP3	International, ASCII	Tabular positions and clocks, Earth-fixed, geocentric, every 15 min
TAB Tabular Orbit File	Bernese, ASCII	Tabular positions, inertial, geocentric, every 15 min
STD Standard Orbit File	Bernese, binary	Polynomial representation, result of numerical integration, inertial, geocentric

5.2. Preparation of Earth Orientation Parameters

5.2.1. General Dataset Names

A set of Earth orientation parameters (EOPs) is required to perform the transformation from the Earth-fixed to the celestial system or vice versa. As described in the following sections, the programs PRETAB and BRDTAB compute a table of satellite positions in the inertial frame from the available orbit information (usually precise orbits in an Earth-fixed frame, e.g., IGS08). Therefore, the EOP file corresponding to the orbits used has to be specified in the appropriate input field (option “Pole file”) of all program input panels.

If no IGS precise orbits are used the corresponding EOP files are available at the global data centers (see Section 4.13.2). The Earth rotation parameters (ERPs)² associated with the IGS ephemeris files are computed using a weighted average of all available center-specific ERP files. The ERP files stemming from CODE may be downloaded via anonymous ftp, too (see Section 4.13.1). Be aware that in contrast to the naming rules of the Bernese environment all these files contain pole information in IGS format although their extension is ERP (see also Section 24.6.7)! The pole files in IGS or IERS format have to be transformed into the Bernese pole format. This task is performed by the program POLUPD with options to be discussed later.

If IGS precise orbits are not used (and no specific ERP files are available), it is recommended to use the IERS C04 pole. C04 is a continuous, slightly low pass filtered series at daily intervals and can be interpolated linearly. Oscillations in UT1 and in the length of day due to zonal tides for periods under 35 days, as well as the 14-day terms in $d\psi$ and $d\varepsilon$ are present in full size in the series (Dick and Richter 2001). In Section 4.4 sources for downloading EOP files are provided.

Nutation model and subdaily pole model coefficients are read from files located in the directory `/${X}/GEN`. To be consistent with the IERS Conventions 2010 (Petit and Luzum 2010) use IAU2000R06 as the nutation model approved by the International Astronomical Union (IAU) and IERS2010XY for the model describing the subdaily tidal variations of the pole and the rotation of the Earth. Specify these files in all program input panels for the options “Nutation model” and “Subdaily pole model”, respectively. The two models *must* be equal in the programs generating a standard orbit (PRETAB and ORBGEN) and in the programs using the standard orbit information. The names of the models are written into the headers of the ERP files, the tabular orbit files, and the standard orbit files. All programs reading standard orbit and Earth orientation information check the consistency of the nutation and subdaily models.

5.2.2. Update of Pole Information

In order to obtain the most accurate EOP information covering the time span of your GNSS data processing, it is necessary to update the file containing the ERP information, as soon as more consistent (with respect to the precise orbit data) and/or more recent values are available. The best way to perform this task is by means of the programs POLUPD (“Menu>Orbits/EOP>Handle EOP files>Convert IERS to Bernese Format”) and POLXTR (“Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files”).

²The term Earth rotation parameters (ERPs) is used for a 3-parameter subset of the Earth orientation parameters (EOPs) which comprises polar motion (x_p, y_p) and UT1.

POLUPD takes information from input files of (almost) any conventional format and converts the data to the Bernese pole format. About 20 foreign formats are supported. Pole files are located in the ORB-directory of the campaign. Usually, the extension IEP indicates a file containing pole information in a foreign format, the extension ERP denotes Bernese format. Because files in foreign format usually come with the extension ERP you have to rename them after downloading to a file name with extension IEP.

Program POLUPD requires the file GPSUTC., which is located in the directory $\${X}/GEN$ and contains a table of all leap seconds during the last several years (see option “Difference GPS-UTC” in panel “POLUPD 1.1: General Files”). The file has to be updated whenever a new leap second is announced by the IERS. You may download the file from <http://www.aiub.unibe.ch/download/BSWUSER52/GEN/>.

The file specifying pole offset information (see option “Pole offset coefficients” in panel “POLUPD 1.1: General Files”) is no longer required. This file contains the pole offset information that is used to transform C04 pole and Rapid pole information to the actual epoch (e.g., C04 ITRF 1988 to C04 ITRF 1996). Until the revision of the generation of C04 pole and Rapid pole information by the IERS in 1997, this file had to be updated every year to introduce the new “constants” given in the annual report of the IERS. Today the pole offsets are no longer required because the IERS pole series are kept consistent with the ITRF in near real-time, based on measurements provided by the space geodetic techniques. You do not need this file at all if you use IGS pole information or the C04 or the Rapid pole (Bulletin A) from <http://www.aiub.unibe.ch/download/BSWUSER52/ORB/>.

Figure 5.2 displays the settings of the relevant options for running the program POLUPD. The options “Nutation model” and “Subdaily pole model” specify the type of model you use to apply the nutation correction parameters and subdaily pole variations. The newly created ERP files may contain nutation corrections in columns DEPS and DPSI. These corrections may stem from VLBI observations (e.g., in IERS Bulletin A) or from GNSS observations processed by the *Bernese GNSS Software* primarily for research purposes. It is recommended to disable option “Include nutation offsets” and not to use these offsets. This choice prevents the use of nutation correction information. Subsequent computations are then solely based on the nutation model specified in “Nutation model”.

In case you use the values of IERS Bulletin B, the option “Use 1 or 5 day values” allows you to select the daily ERPs or the values given in five day intervals.

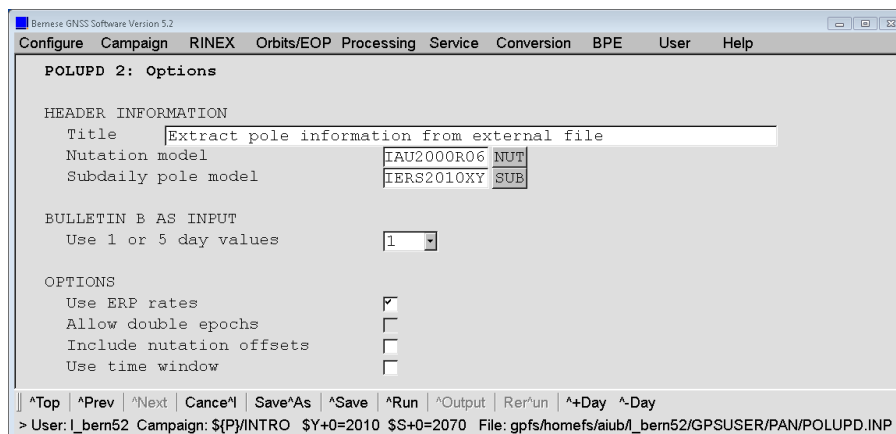


Figure 5.2.: Options in program POLUPD.

Option “Use ERP rates” may be activated in order to use the ERP rates given in the IGS format to generate additional pole records at the beginning and end of a day. The processing programs in the *Bernese GNSS Software* require a complete coverage of all processed epochs in the “Pole file”. If you are going to use pole files from the IGS (or files following the conventions of the IGS) this is usually not the case. These files only contain one record at 12:00 UT. By enabling option “Use ERP rates” you obtain a Bernese pole file with three records (at 0:00, 12:00, and 24:00 of the day) based on the ERP rates given in the 12:00 UT record. If you do not activate the option “Use ERP rates” you have the possibility to “Allow double epochs”. This option allows to extract even two entries per epoch from input files in order to convert all epochs in the input files one by one.

Program POLXTR (“Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files”) extracts ERP information from a list of consecutive pole files in the IGS format and allows to specify an a priori pole file which may be used for comparison purposes. We refer to the corresponding online help for details.

5.3. Preparation of GNSS Broadcast Information

Due to the availability of precise orbit information for GPS and GLONASS from CODE (or from IGS), broadcast information does not need to be considered for normal GNSS data processing. Even the needs of near real-time applications are covered by the predicted part of the high-quality Ultra-Rapid product line from IGS which is also supported by CODE with a rigorously combined GPS and GLONASS orbit product. Nevertheless, the *Bernese GNSS Software* contains programs to concatenate, convert, and analyze broadcast navigation messages.

Broadcast messages from individual receivers only contain messages for the observed satellites. In order to obtain a full set of RINEX messages, the messages from globally distributed receivers need to be concatenated. This can be accomplished using the programs CCRINEXN (“Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GPS)”) for GPS and CCRINEXG (“Menu>RINEX>Cut/concatenate RINEX files>Navigation files (GLONASS)”) for GLONASS.

5.3.1. Standard Procedure

The standard procedure for introducing broadcast orbit information for GPS and GLONASS into the *Bernese GNSS Software* Version 5.2 is the conversion of the navigation messages into the precise file format (SP3c, default extension PRE within the *Bernese GNSS Software* environment). For this purpose, a program called RXNPRE (“Menu>RINEX>Import RINEX to Bernese format>Navigation files to SP3”) is used. The program can either convert a list of GPS RINEX navigation files or a list of GLONASS RINEX navigation files. A third possibility is to merge GLONASS and GPS RINEX navigation message files before conversion. In this case it is recommended to process one pair of files in one program run. Each input file (or pair of input files) will be converted into one output precise file. An interface for potential RINEX navigation files for Galileo is also available (on an experimental stage due to the lack of real Galileo RINEX navigation files).

In the resulting SP3 file the Earth-fixed positions of each satellite and its clock values are stored in time intervals specified by the user. Normally, a time interval of 15 minutes is appropriate. The program checks the broadcast information for plausibility using the criteria explained in Section 5.3.3.

The program RXNPRE allows to exclude GLONASS satellites showing a shift in the navigation messages (e.g., due to a maneuver) from being written to the output precise orbit file. Shifted GPS satellites are skipped in any case (see Section 5.3.3).

In order to process GPS and GLONASS data simultaneously, the orbit and clock information need to refer to the same reference system and to the same time scale. The GLONASS broadcast ephemerides are therefore transformed to ITRF and GPS system time. For the transition from the current PZ-90.02 (GLONASS reference system) to WGS-84 (GPS reference system which is consistent with the parameters of the ITRF), translations on the decimeter level are applied to the positions of the GLONASS satellites, see Habrich (1999) and Ineichen et al. (2000). The transformation values for the transition from PZ-90.02 to WGS-84 (resp. ITRF) have to be specified in file `$_X}/GEN/DATUM`.

After having transformed the broadcast RINEX files into SP3 format, a standard orbit file in Bernese format may be created using programs PRETAB ("Menu>Orbits/EOP>Create tabular orbits") and ORBGEN ("Menu>Orbits/EOP>Create/update standard orbits"). The further processing follows the procedure described in Section 5.4.

For more information on the computation of GLONASS satellite positions using broadcast ephemerides we refer to Habrich (1999).

5.3.2. Alternative Procedure for GPS

An alternative way to introduce GPS broadcast navigation messages into the *Bernese GNSS Software* is available for compatibility purposes to earlier versions of the software: GPS RINEX navigation messages may be converted into the internal broadcast format (default extension BRD, see Section 24.6.1) using the program RXNBV3 ("Menu>RINEX>Import RINEX to Bernese format>Navigation files", description in Section 4.10). This file format may only hold broadcast messages for GPS but *not* for GLONASS or any other of the upcoming GNSS.

Let us mention that it is easy to edit the Bernese broadcast files with any text editor: files may be concatenated, separated, and even individual messages may be deleted from a file. In this context it is important to know that the messages do not have to be sorted according to satellites or time. The message number which is given for each message is ignored by the access routine.

Bernese broadcast message files may be checked for consistency and plausibility using the program BRDTST ("Menu>Orbits/EOP>Broadcast orbits>Check broadcast orbits"), which is described in the following section. Program BRDTAB ("Menu>Orbits/EOP>Broadcast orbits>Create tabular orbits") must then be used to transform the orbit information from the broadcast message into a set of tabular ephemerides in the inertial system (we recommend to use the system J2000.0). A pole file (option "Pole file" in panel "BRDTAB 1: Filenames"; description in Section 24.6.8) with information concerning the EOPs has to be used (and — according to the remark at the end of Section 5.2.1 — in all subsequent programs). Probably, information originally coming from the IERS Bulletin A or B will be used. The ERP file has to be in the Bernese format, see Section 5.2.2. The file BULLET_A.ERP may be retrieved by anonymous ftp from <http://www.aiub.unibe.ch/download/BSWUSER52/ORB/> (see Section 4.13.1).

Starting from tabular orbit files the program ORBGEN is used to generate standard orbits. The procedure is described in Section 5.4.

5.3.3. Checking GNSS Broadcast Messages

The program RXNPRE ("Menu>RINEX>Import RINEX to Bernese format>Navigation files to SP3") checks the broadcast messages of GPS and GLONASS satellites, eliminating bad messages and identifying satellite shifts (maneuvers). Alternatively, the program BRDTST ("Menu>Orbits/EOP>Broadcast orbits>Check broadcast orbits") may be used to check GPS broadcast messages in Bernese format.

Programs RXNPRE and BRDTST are able to process more than one file in the same run. For each file and each satellite the broadcast messages and the satellite clock parameters are checked for two different types of errors and one type of event:

1. If a message or a clock parameter is obviously wrong (e.g., an inclination of 2 degrees) the status in the display is set to **BAD A** (bad semimajor axis), **BAD E** (bad eccentricity), **BAD I** (bad inclination), etc.
2. If a message or a clock parameter has a reasonable value but the difference to the corresponding element of the previous message is unreasonably large, the status is set to **BAD DA**, **BAD DE**, etc.
3. If the orbital elements in the messages show big jumps between two subsequent epochs but are consistent before and after this jump, it is assumed that the satellite was repositioned or maneuvered. If such a jump is detected, the satellite number, the precise epoch, etc., will be listed at the end of the program run and all the messages of this satellite after the jump will obtain a new satellite number which is equal to the old satellite increased by 50 (PRN'= PRN+50). This "artificial" satellite will then be treated like all other satellites (see also end of Section 5.4.3).

The thresholds for identifying bad messages are hard-wired in subroutines `$_{LG}/CHKBR1.f` and `$_{LG}/CHKBR2.f`. Figure 5.3 shows an extraction of the output produced by program BRDTST for a particular program run. A similar output is written by program RXNPRE.

```

EPHEMERIS PARAMETERS FOR SATELLITE 3
-----
NUM  STATUS  WEEK  TOE      A          E          ...  PER
 1      1244  169200. 26560287.9 0.01169876 ... 149.332
 2  BAD A    1244  172800. 296.1 0.01169863 ... 149.330
 3      1244  176400. 26560295.5 0.01169862 ... 149.330
 4      1244  255600. 26560328.6 0.01170016 ... 149.328
 5  BAD DE   1244  259200. 26560341.2 0.01969999 ... 149.324
 6      1244  262800. 26560336.0 0.01169990 ... 149.326
 .      ...  .....  .....  .....  .....  .....

CLOCK PARAMETERS FOR SATELLITE 3
-----
NUM  STATUS  WEEK  TOE      TOC      AO          A1          A 2
 1      1244  169200. 169200. -0.721770D-07 0.100000D-11 0.000000D+00
 2      1244  172800. 172800. -0.703150D-07 0.100000D-11 0.000000D+00
 3      1244  176400. 176400. -0.684520D-07 0.100000D-11 0.000000D+00
 .      ...  .....  .....  .....  .....

SUMMARY:
-----
SAT.  #MSG  #OK  #BAD  #JUMPS
 3     9    7    2     0
 6     6    6    0     0
 9    12   12    0     0
11    13   13    0     0
12    15   15    0     0
13    11   11    0     0
NO JUMPS DETECTED

```

Figure 5.3.: Sample output produced by programs BRDTST or RXNPRE.

5.4. Preparation of Precise Orbit Information

Precise GNSS orbits are a prerequisite for all precise applications of GNSS. Today, highest precision and fully consistent GPS and GLONASS satellite orbits are available through CODE, the IGS³ or from other Analysis Centers. For more information on available orbits and the estimated prediction of the different products we refer to Table 2.6 in Section 2.2. This section describes the steps needed to make precise orbit information available for GNSS data processing within the *Bernese GNSS Software*.

The satellite orbits are distributed by the IGS and its Analysis Centers in the SP3c format (Hilla 2010) as Earth-fixed, geocentric positions tabulated every 15 minutes. In order to have access to the satellite positions at any epoch, the tabular positions have to be interpolated. This may be achieved by adjusting a polynomial of sufficiently high degree to a subinterval of the table. The drawback of this approach is a decreasing accuracy of the orbit representation at the borders of the time interval covered by the table.

The optimum way of interpolation is the adjustment of the tabulated positions by an orbit fulfilling the equations of motion based on a physical model of the forces acting on the satellites as described in Section 2.2. This approach is used in the *Bernese GNSS Software* to generate the so-called standard orbits, an orbit representation in binary format used by all programs requiring satellite positions. It is important to note that Earth orientation information is necessary in this context because precise orbit positions are given in the Earth-fixed system while the equations of motion are formulated in the inertial system. The same Earth orientation information *must* be used in all programs that access GNSS orbits. How to prepare the Earth orientation information is described in Section 5.2.

5.4.1. Center of Mass Corrections

Apart from the EOPs also the displacement of Earth's center of mass from the origin of the coordinate system due to tidal loading effects (ocean and atmosphere) may be considered for the transformation from the Earth-fixed to the inertial system. This selection should be done consistently with the decision whether or not you want to correct the station positions for these effects during the processing and depending on the reference systems for the tidal corrections. The purpose is to keep the origin of the Earth-fixed system stable in time (even if the station coordinates are corrected for this effect). On the other hand, the satellites are flying around the instantaneous center of mass because the orbit modeling is based on the theory of gravitational forces.

To consider this problem, the transformation between the Earth-fixed and the inertial system has to be extended by translations related to the location of the instantaneous center of mass with respect to the origin of the Earth-fixed system. For tidal loading models, center of mass corrections (CMC) are provided for the transformation. These CMC have to be given in the header of the tidal loading file (default extensions BLQ for ocean and ATL for atmospheric tidal loading corrections; description in Section 24.7.9 and 24.7.10, respectively). If CMC are given, checkboxes become active "Apply OTL CMC correction" and "Apply ATL CMC correction" in the programs PRETAB and ORBGEN if the satellite positions

³The GLONASS orbits are currently combined separately from the GPS orbits within the IGS. For that reason the consistency is limited and the orbits from the different GNSS need to be merged before processing.

are read from a precise orbit file. The decision, whether or not the CMC should be applied is stored in the header of the generated standard orbit files. Hence, if it was decided to consider the CMC they must be provided to all subsequent programs that use the orbit files to allow for the correct transformation back from the inertial to the Earth-fixed system. For that reason, the corresponding ocean and atmospheric tidal loading correction files must be selected in several of the orbit related programs.

5.4.2. Conversion of Precise Orbit Information to Tabular Format

To generate a standard orbit the program ORBGEN reads so-called tabular orbit files or precise orbit files (see next section). The program PRETAB ("Menu>Orbits/EOP>Create tabular orbits") may be used to generate the intermediate tabular orbit files (default extension TAB) but it allows, in addition, to extract clock information from the precise orbit files and write it to a Bernese satellite clock file (see Section 5.6).

Program PRETAB converts the satellite positions from the Earth-fixed system to the inertial system J2000.0. For this transformation the EOPs (or ERPs) delivered in the form of a pole file together with the precise orbit file should be used in order to guarantee maximum consistency. Using a different pole file will in general result in a orbital fit of lower quality.

In any program reading orbit information it is *mandatory* to always use the standard orbit (based on a tabular file) together with the pole file and the nutation and subdaily Earth rotation information which were used in PRETAB to create the tabular orbit. Only in this way it is assured that the transformation from Earth-fixed to inertial system (to generate tabular and standard orbit files) is fully consistent with the transformation back to the Earth-fixed system (e.g., in program GPSEST).

Potentially problematic satellites may have been flagged in the SP3c files using an accuracy code. Within the IGS the accuracy code zero is used to indicate that less than three Analysis Centers have contributed in that satellite's orbit determination. Such satellites may easily be excluded from your processing by enabling the option "Use accuracy codes from SP3-file" in conjunction with the options "Exclude sat. with accuracy code 0" and "Exclude sat. with acc. code exceeding" in panel "PRETAB 2: General Options". All observations to satellites excluded here will not be processed later on because the corresponding orbit information is not included in the standard orbit file.

5.4.3. Generation of Standard Orbit Information

The orbit information in standard orbit format is generated by program ORBGEN based on one of the following input files (see panel "ORBGEN 1: Input Files"):

- Tabular orbit files generated by programs PRETAB or BRDTAB.
- Precise orbit files. In this case the ERP files accompanying the orbits must have the same name as the precise orbit files (but different extension). The same pole files have to be used by all programs and in all cases where the resulting standard orbits are used.
- Element files. This input is only required if orbits are improved (further details in Chapters 16 and 17 for GNSS and LEO precise orbit determination, respectively).

It is important to know that for the second option listed above, the Earth orientation information for transforming the satellite positions to the inertial system is *not* taken

from the file specified in option “Pole file”, but from an ERP file with the same name as the precise orbit file. To avoid confusion it is safer to work with the first of the above options (i.e., using program PRETAB for orbit transformation). Note that satellite clock information can only be extracted from precise orbit files by program PRETAB. This is an additional reason to work with intermediate tabular orbit files.

For its standard application, the program is executed once for each precise or tabular orbit input file. The time window specified in panel “ORBGEN 5: Orbital Arc Definition” covers the time interval for which the input satellite positions are defined (in general one day). Program ORBGEN may, however, also be used to extrapolate satellite orbits beyond the time interval covered by the input tabular positions, by specifying the time window accordingly. Care has to be taken if extrapolating backwards. In this case the number of iterations may have to be increased in panel “ORBGEN 3.2: Options”.

The output of the program ORBGEN is a standard orbit file (default extension STD), containing the satellite orbit information, and a so-called radiation pressure file (default extension RPR) containing the derivatives of the satellite positions with respect to the initial conditions and the dynamical parameters. The second file is only needed if orbits are to be improved with program GPSEST (or ADDNEQ2). For details we refer to Chapters 16 and 17, respectively.

The standard orbit may be composed of one or more arcs, each with its individual start and end time. Each standard arc is a solution of the equations of motion, Eqn. (2.5), characterized by six initial conditions and a user-specified number of dynamical parameters. A maximum of nine deterministic parameters per satellite are possible. The multi-arc option of the program is not recommended (panel “ORBGEN 5: Orbital Arc Definition”) and not necessary because a multi-day solution may be produced using ADDNEQ2. In case a multi-day solution with GPSEST is indispensable, several arcs may be generated, each covering one day. It is recommended to always generate standard orbits covering one day (or a multiple thereof) even if the data to be processed covers a shorter time interval. The only exception is the PPP where shortening the length of the orbital arcs improves the capability to recover the orbits from software packages using slightly different orbit models than ORBGEN.

All standard orbits and all partial derivatives (variational equations) are computed by numerical integration of the equations of motion in program ORBGEN (see Section 2.2). No other program in Version 5.2 performs numerical integration. If tabular or precise orbit files are selected as input the program uses the satellite positions as pseudo-observations in an orbit determination process (one process per arc and satellite). The orbit always refers to the center of mass of the satellite. The satellite antenna phase center correction is applied in every program that reads the orbit file. No antenna offset has, therefore, to be applied when generating the standard orbit (see panel “ORBGEN 3.1: Options”, option “Apply antenna offset”, see Figure 5.4). The only exception is the processing of broadcast orbits because they refer to the satellite antenna phase center.

The different models for the orbit generation have to be selected in panel “ORBGEN 1.1: General Files”, e.g., EGM 2008 for the “Coeff. of Earth potential”. For GNSS satellites a maximum degree and order of 12 for the Earth potential is sufficient (panel “ORBGEN 3.1: Options”, option “Earth potential degree”, displayed in Figure 5.4). For interpolating GNSS orbits at the one day level even a maximum degree and order of 8 is appropriate.

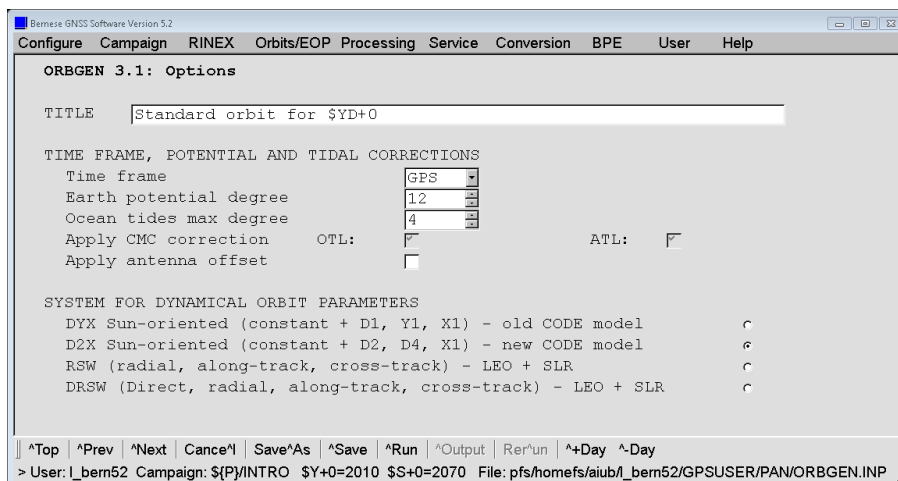


Figure 5.4.: Orbit model options in program ORBGEN.

Based on the DE405⁴ development ephemeris file from the Jet Propulsion Laboratory (JPL) (Standish 1990, specified in “Planetary ephemeris file”), the gravitational attraction of Sun, Moon and the major planets (Jupiter, Venus, and Mars) are taken into account. Apart from general relativistic corrections, also elastic Earth tidal corrections according to the IERS 2010 conventions (Petit and Luzum 2010) are applied. All step 1 corrections and the step 2 corrections for the seven largest frequency dependent corrections of C_{21} and S_{21} , the pole tide, and the permanent tide corrections (subroutine $\text{\$}\{\text{LG}\}/\text{TIDPT2.f}$), as well as ocean tide corrections up to degree 4 (subroutine $\text{\$}\{\text{LG}\}/\text{OTIDES.f}$) are taken into account.

Up to nine radiation pressure parameters may be adjusted per satellite and satellite arc. Depending on the type of satellite (GNSS, LEO, or spheric) different dynamic orbit parameters become relevant. The related group must be pre-selected in panel “ORBGEN 3.1: Options” (see Figure 5.4). For GNSS satellites, the parameters in the DYX- or D2X-system have to be chosen — we refer to Eqn. 2.6 in Section 2.2.2.3 for the detailed description. According to the selection the dynamical parameters (constant and periodic terms) can be chosen in a subsequent panel “ORBGEN 4: Parameter Selection” (displayed in Figure 5.5). We will give different recommendations below for different types of tabular positions (broadcast or precise).

The a priori radiation pressure model is defined by the radiation pressure file descriptor in the header of the satellite information file (e.g., $\text{\$}\{\text{X}\}/\text{GEN}/\text{SATELLIT.I08}$, see Section 24.3.4). The first character of this indicator is used to specify the a priori model. The ROCK4/42 model (Fliegel et al. 1992) is specified by the corresponding file descriptor T950101. The alternative model developed by Springer et al. (1999) is indicated by the descriptor C980101 (as in $\text{\$}\{\text{X}\}/\text{GEN}/\text{SATELLIT.I08}$).

The representation by the standard orbits may be improved by the introduction of stochastic pulses (panel “ORBGEN 4: Parameter Selection”, Figure 5.5). These parameters are described in detail in Section 2.2.2.4. These empirical velocity changes are useful to improve the representation of given orbits constructed with different orbit models. Let us add two remarks regarding these pulse parameters in ORBGEN:

- If you would like to improve orbits in a subsequent step you cannot set up stochastic pulses in ORBGEN because GPSEST is not yet able to handle these stochastic pulses as a priori information when estimating orbit parameters.

⁴The DE200 ephemeris series from previous versions of *Bernese GNSS Software* is not supported anymore.

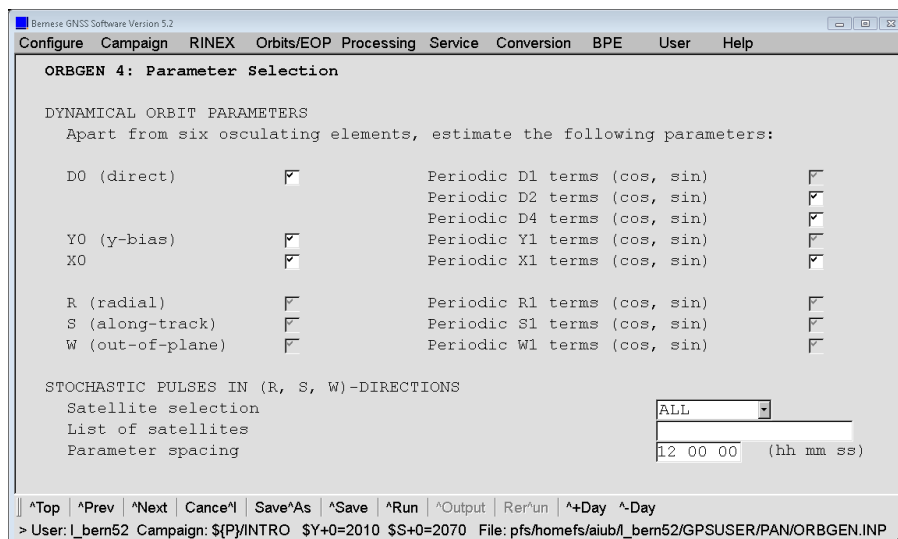


Figure 5.5.: Selection of radiation pressure parameters and setup of stochastic pulses in program ORBGEN.

- Pulses can also be set up for specific satellites and epochs in the satellite problem file:

SATELLITE	PROBLEM	ACTION	FROM	TO
***	*	*	YYYY MM DD HH MM SS	YYYY MM DD HH MM SS
...				
20	4	4	2013 01 16 06 00 00	
20	4	4	2013 01 16 18 00 00	
...				
PROBLEM DESCRIPTION	PROBLEM	ACTION DESCRIPTION	ACTION	
-----	-----	-----	-----	
...				
SATELLITE MODELING	4	ADD PULSES IN ORBGEN	4	
...				

The standard options for the numerical integration of GNSS orbits (see Section 2.2.3) are displayed in Figure 5.6. In general, three iterations are needed. In the case of GPS and GLONASS satellites, a subinterval length of 1 hour and a polynomial degree (or integration order) of $q = 10$ results in an accumulated approximation error in the satellite position, which, after three days, is still below 1 mm.

ORBGEN Program Output

Program ORBGEN produces a summary concerning the fit of the tabular orbit positions. If you were using tabular or precise orbit files stemming from broadcast messages, the summary (in the third iteration step) will look as in Figure 5.7. The table shows that the internal consistency of the broadcast orbits is around 1 meter (the actual accuracy is around three meters). It was produced by adjusting only two radiation pressure parameters, namely D0 (direct) and Y0 (y-bias) in panel “ORBGEN 4: Parameter Selection” (see Figure 5.5) which is sufficient to accommodate broadcast orbits. Bulletin A Earth orientation information was used.

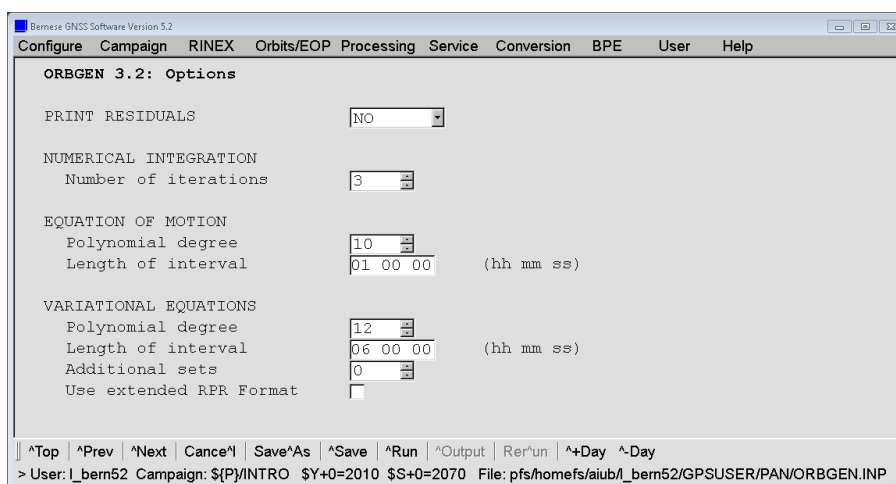


Figure 5.6.: Options for numerical integration in program ORBGEN.

Figure 5.8 shows that the fit of the standard orbit is of the order of several millimeters if a precise IGS ephemerides file is used together with the corresponding EOPs assuming that all nine radiation pressure parameters are selected and stochastic pulses are set up at noon. This means that the force models implemented in program ORBGEN allow to reconstruct the IGS precise orbits below the 1 cm level. If orbits from the CODE analysis center were used this consistency would be even higher (as shown in Figure 5.9) because at CODE a similar orbit model is used.

The satellite 55 that appears in the output example (see Figures 5.9) is related to a repositioning event detected and estimated in the CODE processing for GPS satellite PRN 05. If precise orbit information from CODE is used together with the related satellite problem file (see Section 5.4.4) you can use manoeuvring satellites without any problems for your processing.

It is *absolutely mandatory* to use the same Earth orientation information used to generate the tabular orbit or the standard orbit in every program where this orbit information is needed. The standard orbit together with the Earth orientation information define the orbits in the terrestrial reference frame.

For an automated processing the “Summary file for IGS-ACC” is well suited. It may be specified in panel “ORBGEN 2: Result and Output Files”. The summary file contains the RMS of the tabular orbit positions in millimeters for all satellites. Eclipsing satellites are flagged. For compatibility reasons, also the “Summary file” as it was used in previous versions (with RMS in centimeters) is available.

Program DEFXTR may be used to extract information from an output file generated by ORBGEN. The summaries contain the total number and the number of eclipsing satellites, the largest RMS of the orbit fit as well as a compact list of the RMS for all satellites. Furthermore, an arc split summary may list satellites with high RMS. See the corresponding on-line help for more details.

Orbit Modeling at CODE Analysis Center and Compatibility with Version 5.2

CODE generates long-arc orbit solutions over three days to ensure the optimal quality of GNSS orbits in the middle day. To support the long-arc solution stochastic pulses are

```

-----
RMS ERRORS AND MAX. RESIDUALS      ARC NUMBER: 1                      ITERATION: 3
-----
SAT  #POS  RMS (M)      QUADRATIC MEAN OF O-C (M)      MAX. RESIDUALS (M)
      -----      -----      -----      -----
      TOTAL  RADIAL  ALONG  OUT      RADIAL  ALONG  OUT
-----
  1   88   0.762      0.751   1.103  0.646  0.236      1.343  1.362  0.387
  2   88   0.375      0.369   0.154  0.615  0.083      0.360  1.447  0.224
  3   88   0.718      0.707   1.006  0.676  0.171      1.632  1.420  0.373
  4   88   0.664      0.654   0.845  0.707  0.263      1.089  1.678  0.507
  5   53   0.385      0.375   0.113  0.631  0.104      0.253  1.145  0.160
  6   88   0.709      0.698   0.971  0.695  0.193      1.426  1.681  0.392
  ..  ..  .....      .....  .....  .....  .....      .....  .....  .....
 32   88   0.642      0.632   0.860  0.668  0.120      1.073  1.509  0.214
-----

```

Figure 5.7.: Output produced by program ORBGEN with two radiation pressure coefficients using precise orbit positions stemming from broadcast messages; example from January 10, 2013.

```

-----
RMS ERRORS AND MAX. RESIDUALS      ARC NUMBER: 1                      ITERATION: 3
-----
SAT  #POS  RMS (M)      QUADRATIC MEAN OF O-C (M)      MAX. RESIDUALS (M)
      -----      -----      -----      -----
      TOTAL  RADIAL  ALONG  OUT      RADIAL  ALONG  OUT
-----
  1   96   0.003      0.003   0.001  0.002  0.004      0.004  0.005  0.008
  2   96   0.003      0.003   0.002  0.002  0.004      0.003  0.004  0.014
  3   96   0.004      0.004   0.005  0.003  0.004      0.015  0.007  0.007
  4   96   0.003      0.003   0.001  0.001  0.005      0.004  0.003  0.010
  5   61   0.001      0.001   0.001  0.001  0.001      0.003  0.003  0.002
  6   96   0.005      0.005   0.007  0.004  0.005      0.019  0.010  0.009
  ..  ..  .....      .....  .....  .....  .....      .....  .....  .....
 32   96   0.003      0.003   0.002  0.001  0.004      0.004  0.005  0.006
-----

```

Figure 5.8.: Output produced by program ORBGEN with an IGS precise orbit and Earth orientation file as input and adjusting all nine radiation pressure parameters and stochastic pulses at noon; example from January 10, 2013.

```

-----
RMS ERRORS AND MAX. RESIDUALS      ARC NUMBER: 1                      ITERATION: 3
-----
SAT  #POS  RMS (M)      QUADRATIC MEAN OF O-C (M)      MAX. RESIDUALS (M)
      -----      -----      -----      -----
      TOTAL  RADIAL  ALONG  OUT      RADIAL  ALONG  OUT
-----
  1   96   0.001      0.001   0.000  0.001  0.000      0.001  0.003  0.001
  2   96   0.000      0.000   0.000  0.001  0.000      0.001  0.001  0.001
  3   96   0.000      0.000   0.000  0.001  0.000      0.001  0.001  0.001
  4   96   0.001      0.000   0.000  0.001  0.000      0.001  0.002  0.001
  5   61   0.000      0.000   0.000  0.001  0.000      0.001  0.002  0.001
  6   96   0.000      0.000   0.000  0.001  0.000      0.001  0.001  0.001
  ..  ..  .....      .....  .....  .....  .....      .....  .....  .....
 32   96   0.000      0.000   0.000  0.001  0.000      0.001  0.001  0.001
 55   35   0.000      0.000   0.000  0.001  0.000      0.001  0.001  0.001
101   96   0.001      0.003   0.001  0.004  0.000      0.003  0.010  0.001
102   96   0.001      0.002   0.001  0.004  0.000      0.002  0.010  0.001
103   96   0.001      0.001   0.001  0.002  0.000      0.001  0.004  0.001
104   96   0.001      0.001   0.000  0.002  0.000      0.001  0.005  0.001
105   96   0.001      0.002   0.001  0.004  0.000      0.002  0.009  0.001
106   96   0.001      0.002   0.001  0.004  0.000      0.002  0.008  0.001
  ..  ..  .....      .....  .....  .....  .....      .....  .....  .....
120   96   0.000      0.003   0.001  0.006  0.000      0.003  0.013  0.001
121   96   0.001      0.013   0.004  0.022  0.000      0.011  0.050  0.001
122   96   0.001      0.005   0.002  0.008  0.001      0.004  0.016  0.002
123   96   0.001      0.007   0.002  0.011  0.000      0.005  0.023  0.001
124   96   0.001      0.002   0.001  0.003  0.000      0.002  0.008  0.001
-----

```

Figure 5.9.: Output produced by program ORBGEN with a CODE precise orbit and Earth orientation file as input and adjusting all nine radiation pressure parameters and stochastic pulses at noon; example from January 10, 2013.

SAT	#POS	RMS (M)	QUADRATIC MEAN OF O-C (M)				MAX. RESIDUALS (M)		
			TOTAL	RADIAL	ALONG	OUT	RADIAL	ALONG	OUT
1	96	0.001	0.002	0.001	0.003	0.001	0.002	0.007	0.002
2	96	0.001	0.001	0.001	0.001	0.001	0.005	0.002	0.002
3	96	0.003	0.003	0.004	0.003	0.002	0.009	0.008	0.004
4	96	0.002	0.002	0.002	0.001	0.002	0.004	0.003	0.003
..
32	96	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002
101	96	0.001	0.001	0.001	0.002	0.000	0.002	0.005	0.001
102	96	0.001	0.001	0.001	0.001	0.000	0.004	0.003	0.001
...
109	96	0.002	0.007	0.003	0.012	0.001	0.008	0.028	0.003
110	96	0.002	0.005	0.002	0.008	0.002	0.006	0.017	0.005
...
123	96	0.002	0.011	0.004	0.018	0.001	0.011	0.042	0.005
124	96	0.001	0.006	0.003	0.010	0.001	0.007	0.024	0.004

Figure 5.10.: Output produced by program ORBGEN with a CODE precise orbit and Earth orientation file as input and adjusting all nine radiation pressure parameters (according to orbit model "System DYX") and stochastic pulses at noon; example from January 10, 2014.

SAT	#POS	RMS (M)	QUADRATIC MEAN OF O-C (M)				MAX. RESIDUALS (M)		
			TOTAL	RADIAL	ALONG	OUT	RADIAL	ALONG	OUT
1	96	0.004	0.004	0.005	0.004	0.003	0.019	0.012	0.011
2	96	0.012	0.011	0.017	0.008	0.003	0.029	0.018	0.007
3	96	0.003	0.003	0.001	0.001	0.004	0.003	0.003	0.012
4	96	0.009	0.008	0.012	0.007	0.004	0.024	0.018	0.010
..
32	96	0.005	0.005	0.005	0.002	0.006	0.009	0.006	0.015
101	96	0.005	0.005	0.005	0.002	0.006	0.008	0.008	0.015
102	96	0.003	0.003	0.003	0.002	0.005	0.005	0.005	0.015
...
109	96	0.012	0.012	0.018	0.008	0.003	0.030	0.029	0.009
110	96	0.014	0.013	0.021	0.009	0.002	0.034	0.025	0.006
...
123	96	0.008	0.008	0.012	0.007	0.001	0.022	0.016	0.003
124	96	0.008	0.008	0.011	0.008	0.001	0.023	0.017	0.004

Figure 5.11.: Output produced by program ORBGEN with a CODE precise orbit and Earth orientation file as input and adjusting all nine radiation pressure parameters (according to orbit model "System D2X") and stochastic pulses at noon; example from January 10, 2015.

SAT	#POS	RMS (M)	QUADRATIC MEAN OF O-C (M)				MAX. RESIDUALS (M)		
			TOTAL	RADIAL	ALONG	OUT	RADIAL	ALONG	OUT
1	96	0.002	0.003	0.002	0.004	0.002	0.008	0.012	0.003
2	96	0.001	0.001	0.002	0.001	0.001	0.006	0.003	0.003
3	96	0.001	0.001	0.000	0.002	0.001	0.001	0.006	0.001
4	96	0.001	0.001	0.002	0.001	0.001	0.004	0.002	0.002
..
32	96	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.001
101	96	0.001	0.001	0.000	0.001	0.000	0.001	0.002	0.001
102	96	0.001	0.002	0.001	0.003	0.000	0.002	0.007	0.001
...
109	96	0.002	0.004	0.002	0.006	0.002	0.007	0.010	0.004
110	96	0.002	0.004	0.003	0.005	0.002	0.006	0.016	0.004
...
123	96	0.002	0.015	0.006	0.026	0.001	0.015	0.058	0.002
124	96	0.002	0.007	0.003	0.012	0.001	0.008	0.023	0.002

Figure 5.12.: Output produced by program ORBGEN with a CODE precise orbit and Earth orientation file as input and adjusting all nine radiation pressure parameters (according to orbit model "System D2X") and stochastic pulses every two hours; example from January 10, 2015.

introduced every 12 hours: at noon (and at midnight for the three–days orbits). To allow for the best possible consistency, it is recommended to set up pulses in ORBGEN every 12 hours for all satellites in panel “ORBGEN 4: Parameter Selection” when integrating the orbits for your processing (as displayed in Figure 5.5).

When the *Bernese GNSS Software*, Version 5.2, was released in December 2012, the orbit modeling in this version and the operational version running at CODE for the IGS activities have been fully consistent as confirmed by the perfect fit in Figure 5.9. Out of the set of available dynamical orbit parameters, the three constant components D , Y , and X as well as the periodic terms (once–per–revolution) in the X component were estimated. The orbits generated at that time can be reconstructed perfectly by the orbit model in ORBGEN of Version 5.2 ($\text{RMS} \leq 1 \text{ mm}$) if the same dynamic and stochastic orbit parameters are defined.

Since that time the following changes in the orbit modeling have taken place at the CODE Analysis Center:

GPS week 1749 (July 14, 2013): Albedo modeling according to Rodriguez-Solano et al. (2012) and the effect of antenna thrust⁵ were enabled. At the same time the a priori solar radiation pressure model was switched off — all coefficients in PART 3: PRP PARAMETERS in the satellite information file were set to zero, the RADIATION PRESSURE MODEL was set to NONE. This orbit model was used for the CODE contribution to the IGS reprocessing campaign “REPRO2”, where the results are available at http://www.aiub.unibe.ch/download/REPRO_2013.

As shown by Figure 5.10, this orbit can be represented with a RMS in the order of 1...5 mm using ORBGEN in Version 5.2 if all nine dynamical orbit parameters (constant and once–per–revolution in all three components) are enabled in panel “ORBGEN 4: Parameter Selection” as it is displayed in Figure 5.5.

GPS week 1826 (January 04, 2015): In addition to the five dynamical orbit parameters traditionally estimated, twice– and four–times per revolution parameters in the D component are estimated. This significantly improves the quality of the resulting orbits (see Arnold et al. 2015b).

Depending on the orbital plane, the RMS of the orbit fit with ORBGEN of Version 5.2 increases up to 30 mm. That is why we have provided a dedicated update for ORBGEN with release date “2015-02-05” that allows the estimation of the new components in the orbit model (twice– and four–times per revolution in D). It can be enabled with the “System D2X” model in “ORBGEN 3.1: Options” (see Figure 5.4). With this selection, the orbits can be represented with a RMS of about 5...15 mm mainly because of the missing albedo modeling capability (see Figure 5.11). As confirmed by Figure 5.12, this deficiency can be compensated by additional stochastic pulses (e.g., at 2 hour intervals instead of 12 hour intervals, resulting in a RMS of about 1...2 mm).

For the other background models, there is no significant difference between Version 5.2 and the operational orbit generation at CODE as it is confirmed by Table 5.2 (the difference in the planetary ephemeris file can be neglected).

⁵Antenna thrust was enabled according to <http://acc.igs.org/orbits/thrust-power.txt> for GPS– and with an assumed power of 100 W for GLONASS–satellites.

Table 5.2.: Input file selections for the important orbit models.

Model	Version 5.0	Version 5.2	CODE
Planetary ephemerides	DE200	DE405	DE421
Geopotential model	EGM96.	EGM2008.	EGM2008.
Ocean tides file	OT_CSRC	OT_FES2004	OT_FES2004
Solid Earth tides file	TIDE2000	TIDE2000	TIDE2000

5.4.4. Use of the Satellite Problem File

Programs PRETAB and ORBGEN allow to specify a satellite problem file (see Section 24.3.5). Satellite data marked as bad in this file (problem type 3 – bad data) may be excluded also from the orbit generation. They are excluded directly after reading the precise orbit file:

- When creating the tabular orbits using the program PRETAB, the corresponding satellite(s) are excluded if the option “Remove bad satellites” in panel “PRETAB 2: General Options” is enabled.
- When ORBGEN is used with precise orbit files the indicated satellite will not be used for the orbital fit. If a satellite is marked as bad for the entire interval its orbit will not be contained in the standard orbit generated by ORBGEN.

It is not mandatory to exclude the satellite already during orbit generation because the measurements can also be excluded later in the processing programs (see Section 6.7.2). On the other hand it may be helpful to cure “problematic” orbits (that cause ORBGEN to print a message like ORBIT NO ELLIPSE).

As described above, stochastic pulses may be introduced using the satellite problem file. A satellite for which an orbital maneuver is indicated in the satellite problem file for the time period covered by the orbital fit may appear two times in the standard orbit file (unless the data is removed as bad):

1. with its actual PRN-number. The orbit fits the tabular positions available before the epoch of the maneuver.
2. with the PRN-number $PRN' = PRN + 50$. The orbit fits the tabular positions available after the epoch of the maneuver.

Both orbits cover the entire time period contained in the standard orbit. All programs accessing the standard orbit get their information on the maneuver epoch from the satellite problem file and they switch from the first to the second orbit of the satellite for all epochs following the maneuver epoch. It is, therefore, important to use the same satellite problem file throughout all processing steps.

The CODE Analysis Center maintains a satellite problem file. The file `SAT_yyyy.CRX` (where yyyy denotes the 4-digit year) is updated daily and may be downloaded from <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>. Files from earlier years are available back to 1992.

5.5. Service Programs for Orbit Files

Service programs that are only relevant for orbit estimation are discussed separately in the related context (see Section 16.2.3).

5.5.1. Concatenation of Precise Orbit Information

Let us briefly introduce the program CCPREORB ("Menu>Orbits/EOP>Concatenate/merge precise orbit files"). This program allows to merge two orbit files in precise orbit format: all satellites found in the first file are written into the resulting orbit file. If the second file contains further satellites (e.g., GLONASS satellites), they are added to the new orbit file. In this way it is possible, for instance, to merge the separate precise orbit files provided by the IGS for GPS (labelled IGS) and for GLONASS (labelled IGL) into one combined precise orbit file. It is important that the orbit files selected for the merge are sufficiently consistent, if no further orbit estimation is planned.

Several options are available to control the merging of two precise orbit files. Priority of individual satellites in the two input files may be resolved based on the prediction flags in the precise orbit files. Satellites with predicted positions will get lower priority. The priority may also be controlled by the satellite-specific accuracy code specified in the precise orbit file headers. The program selects the satellite with lower accuracy code (better accuracy). The accuracy code of satellites merged into the file may be set to zero (unknown). These options are particularly useful to merge satellite positions extracted, e.g., from broadcast ephemeris files into precise orbit files which do not contain all satellites. For details we refer to the help panel of the program.

The program also allows to cut a precise orbit file to a specific time interval, or session, selecting the option "Concatenate files" and specifying a single input precise orbit file. Because satellite numbers in the output precise orbit file are always stored in ascending order, the same option allows to reorder the satellite entries. It is not recommended to concatenate successive daily precise orbit files. They should be processed independently with program ORBGEN. If concatenation is necessary, more than one precise orbit file may be specified as input for program ORBGEN.

5.5.2. Comparison of Satellite Orbits

Two programs are available to compare satellite orbits. The program ORBCMP ("Menu>Orbits/EOP>Compare orbits>Precise orbits") compares satellite orbits in different precise ephemeris files. If you specify more than two files, the orbits from each file will be compared with the orbits in all other files. A set of Helmert parameters between the orbits in different files may be estimated. The comparison may be performed in the Earth-fixed system, in the inertial system or in the RSW (radial, along-track, out-of-plane) decomposition. The orbit positions in the precise orbit files are compared at common epochs.

The program STDDIF ("Menu>Orbits/EOP>Compare orbits>Standard orbits") is used to create a table of coordinate differences between two standard orbit files. The coordinate differences are listed in radial, along-track, and out-of-plane directions. Both programs ORBCMP and STDDIF are very straightforward to use, the handling is exhaustively explained in the corresponding help panels.

A third program, STDELE ("Menu>Orbits/EOP>Compare orbits>Osculating elements"), may be used to compute orbit position differences at the middle epoch of the orbit overlap time interval. The program provides differences between osculating elements, the position difference in radial, along track and cross track directions, as well as the absolute values of the position and velocity difference vectors. Depending on the option "Use pole file accompanying the standard orbit" the meaning of the orbit differences change: either the ERP files are omitted and inconsistencies in the ERP information are visible in the orbit differences (orbit

differences as seen in the Earth-fixed frame) or the consistent ERP files are introduced resulting in orbit differences as seen in the celestial frame. The program compares successive orbits if more than two input orbit files are specified. Consult the on-line help for further information.

5.6. Preparation of Satellite Clock Corrections

Apart from Precise Point Positioning (PPP) applications that are discussed in Section 10.6, external satellite clock corrections are necessary for the synchronization of the receiver clocks. The synchronization is performed in the data preprocessing step using program CODSPP, see Section 6.3. The satellite clock corrections with respect to GPS time may be extracted from three sources, namely from broadcast messages, from IGS precise orbit files, or from IGS clock RINEX files (see Chapter 4).

In general, a satellite clock file is produced in PRETAB when converting precise orbit information into tabular format (see Section 5.4.2). The satellite clock information from the precise orbit files is fitted within intervals of several hours (12 hours are recommended in panel "PRETAB 3: Options for Clocks") by low degree polynomials (the recommended degree is $q = 2$) and, thus, a satellite clock file is created which may be used to compute satellite clock corrections for each observation epoch. This way of handling the clocks in the precise orbit files is the normal case.

It is also possible to extract the unaltered satellite clock corrections from the precise orbit files (usually given at 15 minute intervals) by asking for a polynomial degree and an interval length of "zero". In this way, the very precise IGS satellite clock information may be accessed for observations made exactly at the time of the tabular epochs in the precise orbit file (e.g., in case that Selective Availability, SA is enabled). Program CODSPP may profit from this special case for handling precise clock information, if there the corresponding option is selected. The option may also be used to perform a PPP with program GPSEST (see Section 10.6). In general, this option is, however, rather harmful due to the significant data reduction (one epoch every 15 minutes instead of, e.g., every 30 seconds). Therefore, this special option has to be used with care.

A satellite clock file for use in CODSPP or GPSEST may also be generated from Clock RINEX files using program RNXCLK ("Menu>RINEX>RINEX utilities>Extract satellite clock"). The satellite clock corrections are simply extracted and provided in the Bernese internal format without further operations. The resulting Bernese GNSS satellite clock file will have the same name as the introduced clock RINEX file, it is located in the ORB instead of the OUT directory of the campaign. Clock RINEX files available from the IGS contain clock values for every 5 minutes instead of every 15 minutes as for the IGS precise orbit files. From CODE, precise clock information at a rate of 30 seconds is available since March 2004 and at a rate of 5 seconds since May 2008 (see Section 4.13.1).

To transfer broadcast satellite clock corrections into Bernese format, the program SATCLK ("Menu>Orbits/EOP>Broadcast orbits>Extract satellite clocks") is available. It extracts the satellite clock information from broadcast files generated by program RXNBV3 (after checking with the program BRDTST) and writes it into a satellite clock file in the Bernese format (see Section 24.6.10).

6. Data Preprocessing

6.1. Overview

In this chapter the first group of processing programs of the *Bernese GNSS Software* is discussed. These programs do not produce final results but check and prepare the data for the main estimation program (GPSEST). The programs are

Program RNXSMT ("Menu>RINEX>RINEX utilities>Clean/smooth observation files") detects cycle slips and outliers on RINEX level using simultaneous code and phase observations from both frequencies to each satellite. Code observations are smoothed using the phase measurements. The program is also used for the observation type and GNSS selection from RINEX3 observation files.

Program CODSPP ("Menu>Processing>Code-based clock synchronization") computes the corrections for synchronizing the receiver clocks with respect to GPS time. Only code observations are used for this step. The program may be used to screen code data, too.

Program SNGDIF ("Menu>Processing>Create baseline files") forms baselines from zero-difference observation files. The output are single-difference observation files.

Program MAUPRP ("Menu>Processing>Phase preprocessing") detects and resolves cycle slips, removes outliers, and adds multiple ambiguities for the phase observation files. It works with station observation files (zero-difference mode) and with baseline observation files (single-difference mode).

Program RESRMS ("Menu>Service>Residual files>Create residual statistics") screens the post-fit residuals produced in a GPSEST run to identify outliers.

Program RESCHK ("Menu>Service>Automated processing>Detect misbehaving stations/satellites") is a tool to detect misbehaving stations and satellites by analyzing the summary file of the program RESRMS. This program is mainly intended for automated processing.

Program SATMRK ("Menu>Service>Bernese observation files>Mark/delete observations") marks the observations identified as outliers by RESRMS in the Bernese observation files.

Figure 6.1 shows the different possibilities to preprocess the code and phase observation files available in the *Bernese GNSS Software* Version 5.2. The usual way for a double-difference solution is to perform the receiver clock synchronization (program CODSPP, description in Section 6.3), form baselines from phase observation files (program SNGDIF, description in Section 6.4), and clean the single-difference phase observation files (program MAUPRP, description in Section 6.5). If you are going to use the Melbourne-Wübbena linear combination for ambiguity resolution (see Section 8.5) you should use RNXSMT to smooth the code observations (description in Section 6.2).

For zero-difference solutions, e.g., to estimate receiver or satellite clock corrections, usually the program RNXSMT is used to screen code and phase observations and to smooth the code data. The receiver clock synchronization (program CODSPP) is used to prepare

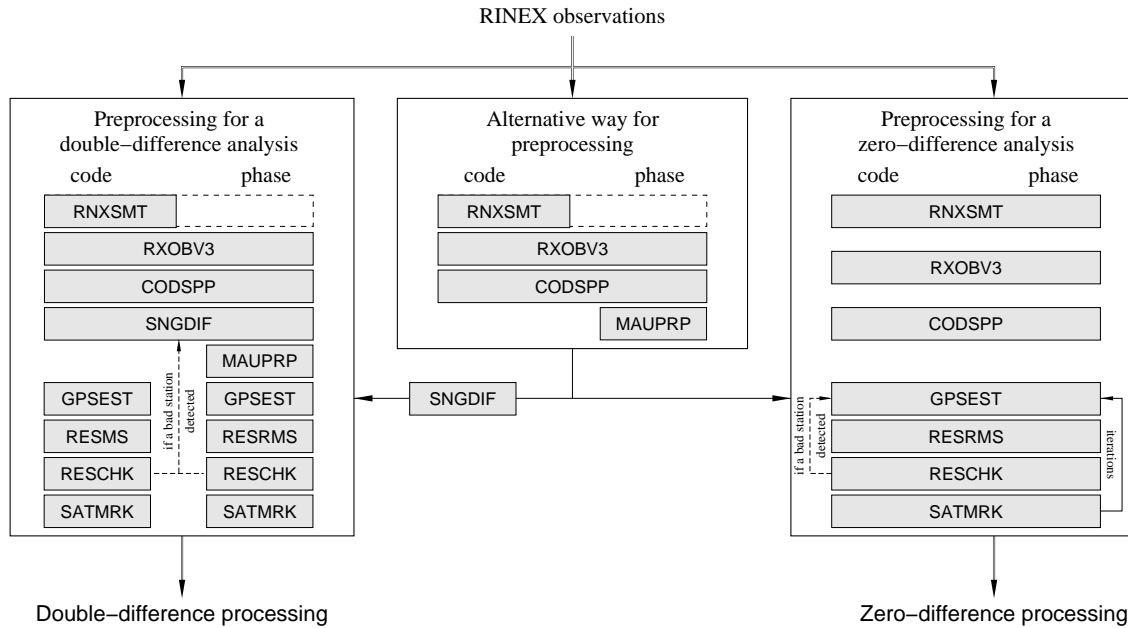


Figure 6.1.: Functional flow diagram for the preprocessing part in the *Bernese GNSS Software*. Gray boxes indicate programs, applied to code and phase in a single run or in separate runs.

a priori station clock corrections that are stored in the observation files. The disadvantage of cleaning phase observations using RNXSMT is that the phase data can only be cleaned with code measurement accuracy. If you have excellent high rate satellite clocks available you may use the program MAUPRP instead of (or in addition to) the program RNXSMT to clean the phase observation files.

The program SNGDIF removes marked observations and may keep the phase ambiguities from the zero-difference observation files while generating baseline files. If you form baselines after a zero-difference preprocessing you can perform a double difference solution with the same observations as for a zero-difference analysis. In some cases (e.g., LEO data) this preprocessing procedure may be preferable also for a double-difference analysis.

Independent from the chosen preprocessing strategy an additional post-fit residual screening (see Section 6.6) is highly recommended (in double-difference case) or even mandatory (in zero-difference case when applying RNXSMT). The procedure involves the following steps (that may be iterated):

1. GPSEST to store normalized residuals (from a zero-difference or double-difference solution),
2. RESRMS to detect outliers in the residuals, to write an edit information file, and to generate a summary file,
3. RESCHK to detect misbehaving stations in the RESRMS summary file (restart the processing without the corrupted station), and
4. SATMRK to mark outliers in observation files according to the content of the edit information file.

6.2. Preprocessing on the RINEX Level (RNXSMT)

The program RNXSMT ("Menu>RINEX>RINEX utilities>Clean/smooth observation files"), which stands for RiNeX SMooThing, is the RINEX preprocessing tool in the *Bernese GNSS Software*. It processes RINEX observations file by file without using any geometry information. The program requires dual frequency code and phase observations. The output is again a RINEX-style file, which should be free of outliers and cycle slips and contains smoothed code measurements. RNXSMT is normally used to clean RINEX files for zero-difference processing. Since *Bernese GNSS Software* Version 5.2, the program is also capable to create a statistics on the available observation types. When importing RINEX3 observation files one has typically to select which of the observations shall be processed in the dual-frequency chain of *Bernese GNSS Software*. For that reason this statistics is indispensable for importing RINEX3 observation files (see also Section 4.2.3.7). In this case the preprocessing might be turned off (i.e., the output RINEX files will contain the original observations).

The actions taken by the program are summarized in the output. Each RINEX file is processed arc by arc, where an arc is usually a satellite pass. The observations of each satellite arc are processed in five steps:

1. Checking for potential inconsistencies between code and phase measurements regarding the receiver clock.
2. Screening of the Melbourne–Wübbena linear combination, Eqn. (2.28), for outliers and cycle slips.
3. If cycle slips are detected, the geometry-free linear combination, Eqn. (2.27), is checked in order to determine the size of the cycle slips in both frequencies. This information can be used to connect the smoothed code observations before and after the cycle slip. Phase cycle slips are not repaired but a new ambiguity is set up at the corresponding epoch.
4. Screening of the difference between the ionosphere-free linear combinations of code and phase, Eqns. (2.22) and (2.23), i.e., $L_3 - P_3$, to remove bad observations which were not detected during the Melbourne–Wübbena based screening (step 1).
5. Smoothing the code observations using code and carrier phase data of the clean observation arcs.

In the following sections, each of these steps are discussed in detail. Additional information may also be found in Springer (2000).

6.2.1. Checking the Receiver Clock Consistency

In the first step, the epoch-differences of the ionosphere-free linear combination between the phase and code measurements are evaluated. They are of course expected to be zero within the noise level of the observations. If the discrepancy exceeds the threshold given in the option "Minimum size of a clock event" (panel "RNXSMT 2.1: Options"), an inconsistency in the receiver clock, as it is seen by the code and phase data, was detected. If the discrepancy is a multiple of a millisecond (within the uncertainty range given by option "Tolerance for the ms-jump detection"), the event is fixed as a millisecond jump. Otherwise the arc for all satellites is interrupted, which means at the end, that a new phase ambiguity will be introduced for all satellites to recover the consistency between the code and phase measurements for the clock estimation. The number of events handled in the second way is limited by the input option "Maximum number of events with unknown size". If more events

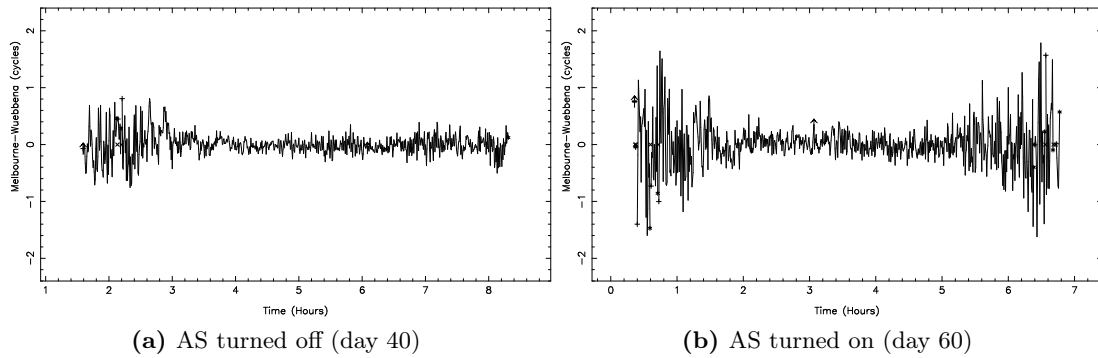


Figure 6.2.: Noise of the Melbourne–Wübbena linear combination under different AS conditions. Data of one station (Wetzell, Germany) and one satellite pass collected during two days in 1997 is shown.

are detected then no SMT result file is provided, i.e., the station is excluded from further processing.

6.2.2. Data Screening Based on Melbourne–Wübbena Linear Combination

The Melbourne–Wübbena linear combination eliminates the effects of the ionosphere, geometry, clocks, and the troposphere (see Eqn. (2.28)). Apart from the wide-lane ambiguity, the remaining signal should be pure noise with a RMS error of approximately 0.7 times the RMS of the code observations on the L_1 frequency. If the noise of the Melbourne–Wübbena linear combination has an RMS below 0.5 wide-lane cycles (43 cm) it is almost trivial to detect all cycle slips and outliers. Only very few epochs are needed to estimate the wide-lane ambiguity; jumps and outliers can easily be detected. Of course, only the difference between the cycle slips on the two frequencies is detected ($n_5 = n_1 - n_2$), see Eqn. (2.28). Note that in the very unlikely case where the integer number of cycle slips on the two frequencies is identical (i.e., $n_1 = n_2$), no cycle slip will be detected ($n_5 = 0$).

However, under AS the noise of the Melbourne–Wübbena linear combination for most geodetic receivers exceeds the RMS of 0.5 wide-lane cycles. Figure 6.2 shows a single pass of a single satellite (PRN 18) for the same station on two different days. On the first of the two days AS was not activated. The different noise level is obvious. The beginning and the end of the observation arc illustrate that for low elevations a much more pronounced increase of the noise level is observed for “AS on” as compared to “AS off”. For low elevations it will thus be more difficult to detect small outliers and cycle slips, and it is almost impossible to detect outliers of one or two wide-lane cycles (86 – 172 cm) under AS conditions.

It is also interesting to note the time shift of the observation arc of this satellite. On day 40 the satellite was first tracked at approximately 1:30 hours, whereas on day 60 the first data of the satellite were received at approximately 0:10 hours. This is caused by the 4 minute shift per day of the satellite–station geometry.

The only way to improve the data screening reliability is to generate the longest possible arcs for a station. We make, therefore, the attempt to use all observations within one satellite pass. An arc is defined by specifying a “Minimum number of observations per arc” and

a “Maximum gap before starting a new arc” in panel “RNXSMT 2.1: Options”. Typical values are a minimum of 10 data points per arc and a maximum of 3 minutes without observations before starting a new arc.

After defining the arcs, the RMS error of the observations within the arc is computed. If this RMS exceeds a user-specified maximum (option “RMS of a clean arc for Melbourne-Wuebbena” in panel “RNXSMT 3: Screening Options”) the observation arc is screened for cycle slips. The cycle slip detection algorithm splits the observation arc into two equally long parts. It is assumed that the part with the larger RMS contains the cycle slip(s). The arc splitting step is repeated until the epoch of the cycle slip is found. Both parts, before and after the cycle slip, are edited for outliers, using an outlier level of four times the RMS (4σ) of the observations in the arc with a maximum RMS value specified by the user. Outliers are only temporarily removed in this step. The difference between the two (clean) parts is estimated and the arcs are connected using the estimated cycle slip. All points that were considered to be outliers during the cycle slip detection are included again. The RMS is recomputed to check whether there are more cycle slips in this observation arc.

After the detection of all cycle slips, the observations are screened for outliers. Outliers are removed (using a 4σ -threshold) until the RMS of the observation arc is below the specified maximum. The specified maximum RMS is typically 0.4–0.6 wide-lane cycles (34 – 52 cm). If an outlier is detected, all four observation types (code and phase on two frequencies) are rejected.

6.2.3. Data Screening Based on the Geometry-Free Linear Combination

Only those observation arcs in which cycle slips have been detected are screened using the geometry-free combination of the phase observations (see Eqn. (2.27)). At this stage the size of the wide-lane cycle slip ($n_1 - n_2$) is known. The geometry-free linear combination (L_4) allows us to compute the size of the n_1 and n_2 cycle slips because it gives us: $L_4 = L_1 - L_2$. To determine the size of the cycle slip on the L_4 linear combination two linear polynomials are fitted through m points (m is defined by the user in option “Number of L4 observations for fit” in panel “RNXSMT 3: Screening Options”) before and after the cycle slip. The difference between the two polynomials at the time of the cycle slip is computed. If the fractional part of the difference is smaller than a user specified limit (option “RMS of L4 for fit and cycle slip correction” in panel “RNXSMT 3: Screening Options”) the n_4 cycle slip is accepted and the cycle slips n_1 and n_2 are computed. Typically, a value of $m = 10$ is used and a difference smaller than 10 mm. This procedure is executed to be able to connect the code observations during the code smoothing step. Because cycle slips occur rarely, no attempt is made to connect the phase observations. For the phase observations a new ambiguity is set up at the epoch of the detected cycle slip.

6.2.4. Data Screening Based on the Ionosphere-Free Linear Combination

Sometimes the described procedure cannot fully clean the data due to systematic errors in the Melbourne-Wübbena linear combination. These systematic errors are most likely caused by the filtering and smoothing procedures employed in the receivers. Therefore, an additional data screening step is necessary.

The difference between ionosphere-free linear combinations of the phase and code observations, Eqns. (2.22) and (2.23), i.e., $L_3 - P_3$, is used in this step. As in the case of

the Melbourne–Wübbena linear combination this linear combination should also consist of noise only. The disadvantage is an amplified noise (about 3 times the noise of the P_1 observations), which is about 4 times larger than the noise of the Melbourne–Wübbena linear combination. Nevertheless, the check is useful for removing errors caused by systematic effects. It consists of an outlier rejection scheme very similar to the one used for screening the Melbourne–Wübbena linear combination. The starting value for the maximum RMS is larger (typically 1.6–1.8 meters for option “RMS of an arc in ionosphere free LC (L3-P3)” in panel “RNXSMT 3: Screening Options”) to account for the higher noise of these observations.

6.2.5. Code Smoothing

The final step consists of the smoothing of the code observations. The previous program steps have cleaned both, code and phase observations. This allows us to smooth the code observations for the continuous data arcs using the carrier phase observations. For code smoothing the code observations in a clean observation arc are actually replaced by the phase observations shifted by the mean difference code minus phase in the arc. Of course we have to account for the opposite sign of the ionospheric effect for the code and phase observations. The smoothed code at epoch t may then be written as:

$$\begin{aligned}\tilde{P}_1(t) &= \phi_1(t) + \bar{P}_1 - \bar{\phi}_1 + 2 \cdot \frac{f_2^2}{f_1^2 - f_2^2} \cdot \left((\phi_1(t) - \bar{\phi}_1) - (\phi_2(t) - \bar{\phi}_2) \right) \\ \tilde{P}_2(t) &= \phi_2(t) + \bar{P}_2 - \bar{\phi}_2 + 2 \cdot \frac{f_1^2}{f_1^2 - f_2^2} \cdot \left((\phi_1(t) - \bar{\phi}_1) - (\phi_2(t) - \bar{\phi}_2) \right)\end{aligned}$$

where:

- $\tilde{P}_F(t)$ Smoothed code measurement at epoch t and frequency $F = 1, 2$.
- $\phi_F(t)$ Carrier phase measurement at epoch t and frequency $F = 1, 2$.
- $\bar{P}_F - \bar{\phi}_F$ Mean difference between all the accepted code and phase measurements in the current observation arc on frequency $F = 1, 2$.

Figure 6.3 shows the effect of code smoothing. Shown are the residuals of a point positioning procedure, estimating only the receiver clock offset for each observation epoch and

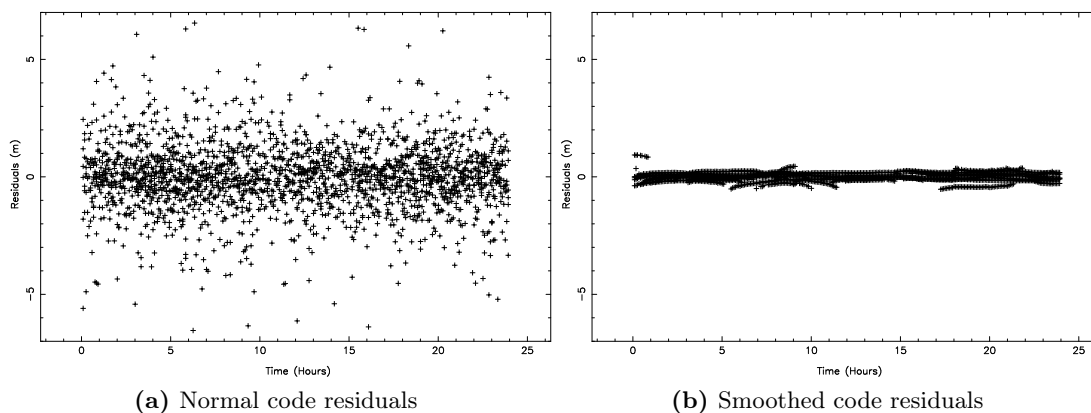


Figure 6.3.: Code residuals from point positioning. Data from a receiver installed at USNO was used for day 133 of 1999.

using the CODE final orbit and satellite clock estimates. The RMS error of the residuals in Figure 6.3 is 1.53 and 0.17 meters for the raw code residuals and the smoothed code residuals, respectively. The smoothed code residuals show systematic errors of up to one meter. The size of these biases is a function of the noise of the code observations and of the number of observations used in the smoothing interval. One may consider smoothed code observations as ambiguity-fixed phase observations where the ambiguities were fixed only approximately.

6.2.6. Resulting Smoothed RINEX Files

The limitations of RNXSMT are due to the use of code observations, which implies that small outliers in the phase cannot be detected safely. With a typical RMS of 0.5 cycles for the Melbourne–Wübbena linear combination the 4σ outlier detection level is about 160 cm. All carrier phase outliers below this level will not be detected. They will have to be detected by screening the post-fit residuals after a first parameter estimation step (see Section 6.6.2).

The code observations from different receiver types may have a significantly different noise such that a station specific weighting of the observations usually becomes necessary. Because the smoothed code is derived from the phase measurements it is much more homogeneous and a station specific weighting of the code data is not necessary. The smoothed code observations may be introduced for ambiguity resolution using the Melbourne–Wübbena linear combination because they no longer contain large outliers.

One big advantage of the program RNXSMT is its complete independence of the satellite orbits and of the position and velocity of the receiver. This means that this data cleaning method can also be used for kinematic applications and even for very fast moving objects such as LEOs. The only condition is the availability of dual frequency data for code and phase.

RNXSMT sets the signal-to-noise ratio for bad observations to 1 and it sets cycle slip flags at those epochs where a cycle slip was detected. If you disable the option “Preprocess phase observations” in panel “RNXSMT 4: Output Options” the signal-to-noise ratio for bad phase observations is set to 2. All observations considered as good have a signal to noise ratio of 9. From this convention you can derive the options in panel “RXOBV3 4: Input Options 2” for converting smoothed RINEX files into Bernese observation file format using the program RXOBV3 (see Figure 6.4). All other settings and checks in the program RXOBV3 are identical for original and smoothed RINEX files. They are described in Section 4.2.3.

The output RINEX files may be stored with the original instead of the preprocessed observations by unchecking the options “Preprocess phase observations” and “Use smoothed code instead of raw code)” in panel “RNXSMT 4: Output Options”. This might be useful, in particular, when RNXSMT is intended to be used only for the selection of observation types and GNSS from RINEX3 observation files. The RINEX3 data import is explained in detail in Section 4.2.3.7.

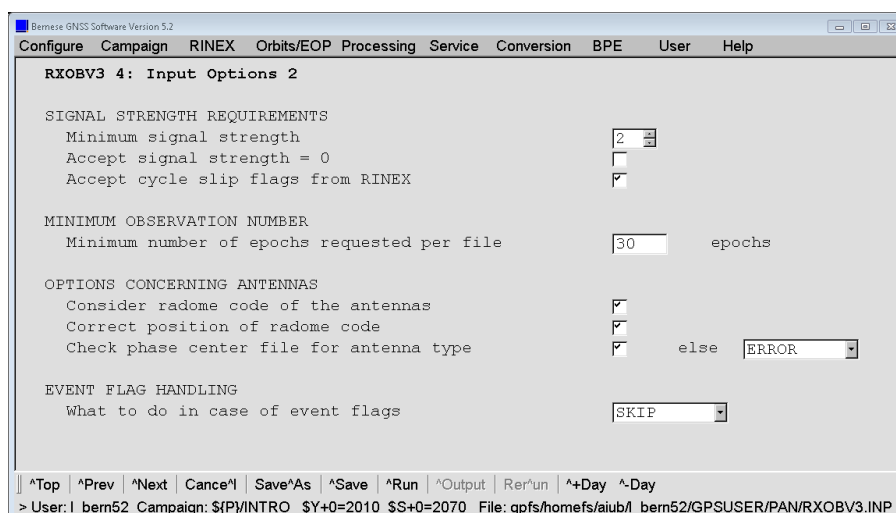


Figure 6.4.: “Minimum signal strength” in RXOBV3 to import smoothed RINEX files into Bernese formatted observation files.

6.2.7. Special Modes in RNXSMT

Besides the screening of the RINEX files RNXSMT offers two modes for special applications:

1. “Verify GLONASS frequency number”

If you are not sure whether the frequency number for the GLONASS measurements in the satellite information file is correct you may enable the related option in panel “RNXSMT 4: Output Options”. The program runs through the screening procedure trying all GLONASS frequency numbers from -7 to 24 . It assumes that the frequency number with the largest number of valid observations after the screening procedure has been used by the receiver. It is compared in the program output to the default frequency number given in the satellite information file.

In the example below it is clearly visible that all observations are detected as bad if the wrong frequency number is used. Only if the frequency number is zero (FRQ: 0) (nearly) all observations are accepted by the preprocessing algorithm. In that case the estimated frequency number is identical with the frequency number in the satellite information file, given in FRQ0:

FREQUENCY ESTIMATION FOR PRN:115						
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -7	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -6	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -5	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -4	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -3	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -2	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: -1	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1	FRQ: 0	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: 1	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: 2	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: 3	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: 4	FRQ0: 0	NARC: 3	
PRN: 115	NOBS: 1100	NBAD: 1100	FRQ: 5	FRQ0: 0	NARC: 3	
...						

Independent from the result of the frequency estimation, the resulting smoothed RINEX file is generated in any case with the default frequency number from the satellite information file.

2. "Estimate DCB values"

If a RINEX observation file contains both P1 and C1 observations at the same time, the related Differential Code Bias (DCB) P1–C1 can be directly derived. In this case, the DCB in the receiver and satellite is contained in the difference of the two measurements. The DCB of each satellite is averaged over all RINEX files, whereas the remaining part of the direct difference between the two observations is assumed to be the receiver DCB.

This description makes it clear that the procedure can only be successful if a sufficient number of receivers from different manufacturers is included in the procedure at the same time. All RINEX files have to include both P1 and C1 measurements to the same satellites.

The advantage of this procedure is that it allows to derive receiver DCBs and even DCBs for GLONASS because they are typically absorbed by the inter-system/inter-frequency biases that have to be estimated when computing clock corrections (see Section 15.2.2).

When enabling the related option in panel "RNXSMT 1: Filenames" no smoothed RINEX file is generated.

6.3. Receiver Clock Synchronization and Preprocessing of Code Observations (CODSPP)

6.3.1. Receiver Clock Synchronization

In Section 2.3.5 we have seen that the receiver clock has to be synchronized with GPS time even for a double-difference analysis. The receiver clock error δ_k has to be known with an accuracy better than $1\ \mu\text{s}$. It would be possible to introduce δ_k as unknown parameters during the final least-squares adjustment in the program GPSEST but this would increase the number of parameters considerably. Fortunately, it is possible to compute δ_k a priori with sufficient accuracy ($< 1\ \mu\text{s}$) using zero-difference code measurements. This is the main task of program CODSPP ("Menu>Processing>Code-based clock synchronization"), the second important result from this program are the receiver coordinates. Looking at Eqn. (2.18) we conclude that if we want to reach an accuracy of $1\ \mu\text{s}$ in δ_k it is necessary to have the code measurements available with an RMS error smaller than

$$c (\delta_k)_{max} = c (1\ \mu\text{s}) \approx 300\ \text{m}$$

(c is the velocity of light). Obviously, even C/A-code measurements are sufficient for this purpose. CODSPP will process P-code or smoothed code if available.

For the zero-difference analysis of the data in the parameter estimation program GPSEST the results of the receiver clock synchronization are introduced as a priori values for the station clock estimation. Because the dependency of the observation on the clock parameters is almost linear, the a priori values for the clock parameters are not very important. On the other hand, the receiver clock synchronization on the $1\ \mu\text{s}$ level is necessary in

the zero-difference case, too. In addition, the numerical stability in program GPSEST is improved when the estimates for the clocks are not too big.

The program CODSPP uses the standard least-squares adjustment to compute the unknown parameters. The observables are the zero-difference code measurements. Usually, the L_3 (ionosphere-free) linear combination is used. The most important parameters computed by CODSPP are the receiver clock corrections δ_k . These parameters will be estimated in any case. The resulting receiver clock corrections are written directly into the Bernese observation files. This may be suppressed if the option “Save clock estimates” in the panel “CODSPP 2: Input Options” is disabled. This may be useful for test purposes. In normal processing this option has to be BOTH which is indicated in the program output file by the line:

```
CLOCK OFFSETS STORED IN CODE+PHASE OBSERVATION FILES
```

for each station. Otherwise, a warning message is issued.

The procedure requires satellite clock corrections. These may be obtained from broadcast navigation messages or, better, from precise IGS orbit files or from combined IGS clock files (see Section 5.6). Specify the clock file in option “Satellite clocks” in panel “CODSPP 1: Filenames”.

The user may also estimate the coordinates of the receivers. The model used in the program is represented by Eqns. (2.20c) and (2.20d). The unknown parameter δ_k appears implicitly in the term ϱ_k^i , too. Therefore, CODSPP estimates the parameters iteratively (using a least-squares adjustment). The second reason for iterations is that the a priori coordinates may not be accurate enough. In fact, if you do not have any a priori coordinates for your new points, you might simply start with “0/0/0”.

If GPS and GLONASS data are processed simultaneously and the satellite clock file contains clock corrections also for the GLONASS satellites, one additional parameter for each station and session is estimated by the program CODSPP, namely the difference between GPS and GLONASS system time. An additional section appears in the CODSPP program output listing this estimated system time difference and its RMS value for the combined receivers:

```
*****
GLONASS/GPS TIME OFFSETS
*****
```

FILE	STATION NAME	TIME OFFSET (NS)	RMS ERROR (NS)
1	WHIT 40136M001	NO RESULTS AVAILABLE	
2	WTZR 14201M010	NO RESULTS AVAILABLE	
3	WTZZ 14201M014	-149.403	0.356
4	YELL 40127M003B	NO RESULTS AVAILABLE	
5	YIBL 25001M001	NO RESULTS AVAILABLE	
6	YSSK 12329M003	NO RESULTS AVAILABLE	
7	ZAMB 34601M001	NO RESULTS AVAILABLE	
8	ZIMJ 14001M006	-150.042	0.371
9	ZIMM 14001M004	NO RESULTS AVAILABLE	

2	TOTAL	-149.709	0.257

From the nine stations in this program run only two are combined GPS/GLONASS receivers (WTZZ and ZIMJ). Therefore, the time offset is only available for these two receivers.

Processing the data from different receivers leads to different estimated time offsets for each individual receiver (Ineichen et al. 2000). The reason is that the estimated time offset contains not only the pure difference between GPS and GLONASS system time but also a receiver-specific measurement bias — the so-called ISB. In the case of GLONASS there is an additional bias depending on the individual frequency of the received signal (Dach et al. 2006a). It is important to note, however, that for *all* relevant receiver types the estimated system time difference does not exceed $1\ \mu\text{s}$. Using the estimated GPS receiver clocks for subsequent processing steps is therefore sufficient and results in a GLONASS orbit error smaller than 1 mm. For more information about the ISB and the GLONASS-specific IFB we refer to Section 15.2.2.

6.3.2. Preprocessing of Code Observations

The program CODSPP processes the observation files epoch by epoch. The term observed minus computed (O–C) is calculated for each observation of an epoch introducing the satellite orbits, satellite clocks, and the a priori position of the station (or the position that resulted from the previous iteration). Based on these O–C values the receiver clock correction for this particular epoch is obtained by a majority voting. After correcting the O–C values for all observations for the receiver clock correction the residuals are analyzed for outliers. If the outlier detection is disabled or if the biggest residual is smaller than a user specified threshold (option “Max. residual allowed”), all observations of this epoch are accepted and will contribute to the coordinates and/or the GPS/GLONASS time offset.

If the residual of at least one observation of an epoch exceeds the threshold specified, the outlier detection procedure starts (if enabled). From all residuals of the epoch a noise level (RMS without the worst satellite) is then computed. Either this noise level or the RMS of unit weight from the previous iteration (the smaller value is selected) is scaled by the user defined “Confidence interval” to get a threshold for the biggest residual of the epoch. In case that the threshold is exceeded, the observation corresponding to the biggest residual is flagged and the majority voting to compute the receiver clock correction is repeated without the flagged observations.

When the receiver clock corrections are written to the observation files, observations identified as outliers may be marked as well in the code, phase, or both observation files (see option “Mark outliers in obs. files”). Usually, only the code observations should be marked because the outlier detection is done for this observation type only. If you don’t use the code observation files in further processing, marking of bad observations is not necessary.

Because the noise level of the raw code measurements may vary considerably between different receiver types, the use of station observation sigma factors (station weighting) is highly recommended to scale the outlier threshold. A file with station-specific sigma values might be specified in the field “Station sigma factors” in panel “CODSPP 1: Filenames”. The threshold (option “Max. residual allowed”) is then multiplied with the station specific sigma factor to obtain the effective outlier rejection threshold for the respective station. A sigma factor below 1.000 is set to 1.000. If you are using smoothed code from program RNXSMT then the use of the sigma factors for the rescaling of the outlier rejection threshold is not required. See Section 24.7.14 for the definition and Section 6.6.3 for the creation of a station observation sigma file.

If you use CODSPS to obtain receiver clock synchronization for an intended phase-only based baseline processing, you should choose a high outlier rejection threshold (e.g., 30 m). You have to keep in mind that an epoch for which CODSPS could not compute a receiver clock value for a given station will be lost for all further processing.

CODSPS summarizes the detected outliers at the end of the program output file:

```

*****
SUMMARY OF BAD OBSERVATIONS
*****
MAXIMUM RESIDUAL DIFFERENCE ALLOWED :      50.00 M
CONFIDENCE INTERVAL OF F*SIGMA WITH F:      5.00
OUTLIERS MARKED IN THE CODE OBSERVATION FILES

NUMBER OF BAD OBSERVATION PIECES      :      11

NUMB FIL  STATION          TYP SAT          FROM          TO          #EPO
-----
  1  1  KIRO  10422M001      OUT 26  03-12-12 06:49:30  03-12-12 08:27:30  197
  2  1  KIRO  10422M001      OUT 26  03-12-12 08:28:30  03-12-12 08:34:00   12
  3  1  KIRO  10422M001      OUT 26  03-12-12 08:35:00  03-12-12 08:41:30   14
  4  1  KIRO  10422M001      OUT 26  03-12-12 08:42:30  03-12-12 08:44:30    5
  5  1  KIRO  10422M001      OUT 26  03-12-12 08:46:00  03-12-12 08:49:30    8
  6  1  KIRO  10422M001      OUT 26  03-12-12 08:50:30  03-12-12 08:51:00    2
  7  1  KIRO  10422M001      OUT 26  03-12-12 08:52:00  03-12-12 08:53:30    4
  8  1  KIRO  10422M001      OUT 26  03-12-12 08:56:30  03-12-12 08:57:30    3
  9  1  KIRO  10422M001      OUT 26  03-12-12 08:58:30  03-12-12 08:58:30    1
 10  1  KIRO  10422M001      OUT 26  03-12-12 08:59:30  03-12-12 09:00:00    2
 11  1  KIRO  10422M001      OUT 26  03-12-12 09:03:30  03-12-12 09:04:00    2
-----

```

The above example reports that outliers were marked in the code observation files. The complete list of reasons (column TYP) why CODSPS could not use the listed observations includes:

- OUT rejected by outlier detection algorithm described above,
- ORB no orbit or satellite clock information available,
- CRX satellite excluded in the "Satellite problems" file (description in Sections 6.7.2 and 24.3.5),
- KIN the minimum redundancy for the outlier detection in the kinematic mode was not reached (see below).

6.3.3. Kinematic Stations

CODSPS is able to handle kinematic stations (select KINEMATIC in option "Estimate coordinates" in panel "CODSPS 2: Input Options"). A new set of coordinates is then estimated independently for each epoch. Each epoch solution is computed iteratively; the a priori coordinates may be set to "0/0/0" if unknown. Only epoch parameters can be estimated in this case. In particular, the time offset between GPS and GLONASS cannot be set up. Therefore, in case of mixed GPS/GLONASS files only GPS observations are considered for the estimation of kinematic coordinates.

In the kinematic mode outlier detection is performed epoch by epoch. The algorithm is slightly different from that used in the static mode: in a first step an epoch solution is computed iteratively. If the RMS of this solution is larger than a threshold (option "Max. RMS of kin. solution" in panel "CODSPS 4: Screening Options"), a search for the worst satellite is initiated. Each satellite is excluded in turn, allowing to identify the satellite for which the maximum improvement of the solution is realized if its observation is not contributing.

This procedure is repeated until an acceptable solution is found or until the redundancy becomes too small (option “Min. degree of freedom”). In the latter case no epoch–solution is computed and all observations of the corresponding epoch are marked. These observations are indicated by the flag KIN in the summary of the bad observations in the CODSPP program output.

If kinematic coordinates are introduced for a station these positions are used as a priori information for the epoch solutions. All positions in the kinematic coordinate file are used if epoch–wise kinematic coordinates are estimated in the program run. If a kinematic coordinate file is introduced and no kinematic positions are estimated (e.g., the accuracy of the introduced kinematic coordinates is better than expected from the estimation in program CODSPP) then only those epochs are used as a priori which have the flag K (indicating a good kinematic position) in the input kinematic coordinate file. For other flags all observations of the epoch are marked.

In the case of LEO processing, a standard orbit can be introduced instead of a kinematic coordinate file. A receiver on board of a LEO must be labeled in any case with the marker type SPACEBORNE in the station information file.

6.3.4. Extraction (CODXTR)

CODXTR (“Menu>Processing>Program output extraction>Code-based clock synchronization”) is the extraction program for the CODSPP program output. It produces a short summary of all CODSPP output of the following form:

```
### PG CODXTR: RMS LARGER THAN 999. M FOR STATION: BRMU 42501S004
FILE: ${P}/IGSRAPID/OBS/BRMU3390.CZO
RMS : 1629.07 M

69 FILES, MAX. RMS: 1629.07 M FOR STATION: BRMU 42501S004
MAX. BAD: 7.21 % FOR STATION: OHI3 66008M006
```

The summary file contains at least two lines. They give the number of code files that were processed, the maximum RMS, and the station for which this maximum occurred. The RMS value should be around 25 meters under SA conditions, whereas with SA off the maximum RMS value is expected to be about 2.5 meters. Using smoothed code obtained with RNXSMT we can expect a RMS value below 1 meter. The next line indicates the station with the largest number of bad code observations. The percentage is usually below 10%.

In the above example the RMS of the station BRMU 42501S004 exceeds the user specified option “RMS limit for a good station” in panel “CODXTR 2: Options”. The big RMS indicates that the receiver clock synchronization failed and that successful further processing of the data is not guaranteed. The observation filenames of such stations may be listed in a deletion file which may be used to remove the files in an automatic processing.

Furthermore, the CODXTR summary output shows one line for each station–satellite combination where more than 50 epochs are considered as outliers or marked for any other reason. The first two numbers of these lines reflect the internal CODSPP numbering and are not important. Station name, outlier identification, and satellite PRN follow. The outlier identification is most commonly OUT. Other possible entries are listed in Section 6.3.2. The line terminates with the start and end epochs of the outlier interval and the number of observations in this interval.

2	1	ALBH	40129M003	OUT	31	03-12-05	06:47:00	03-12-05	10:18:00	423
7	1	ALBH	40129M003	OUT	31	03-12-05	16:00:00	03-12-05	16:59:30	120
9	2	ALGO	40104M002	OUT	31	03-12-05	15:30:30	03-12-05	15:58:30	57
10	3	ALIC	50137M001	OUT	31	03-12-05	01:26:00	03-12-05	05:02:00	433
11	3	ALIC	50137M001	OUT	31	03-12-05	05:07:30	03-12-05	05:54:30	95
103	4	AMC2	40472S004	OUT	31	03-12-05	07:27:00	03-12-05	10:03:00	313
108	4	AMC2	40472S004	OUT	31	03-12-05	15:13:00	03-12-05	16:59:30	214
.....										
116	8	ZAMB	34601M001	OUT	31	03-12-05	00:00:00	03-12-05	03:14:30	390
117	8	ZAMB	34601M001	OUT	31	03-12-05	03:21:00	03-12-05	04:00:00	79
### SATELLITE REPOSITIONING OR CLOCK RESET DETECTED!										
# SATELLITES : 1										
SATELLITE NUMBER: 31										

If the same station is listed for many satellites, something is probably wrong with its data. If the same satellite is listed for many stations there is something wrong with the satellite. In the above example satellite 31 was marked for many sites. As the marked time intervals are distributed over the day and do not concentrate towards the end of the day, the outliers are not caused by a maneuver. In fact, on this particular day satellite 31 was scheduled for maintenance. Usually, the satellite clock is reset in such cases. The outlier detection of CODSPS handles such problems and no action is required by the user. If such an event is detected the clock values for the corresponding satellite can be removed from the satellite clock file containing, e.g., broadcast clock. This action is reported in the summary by the line:

```
1 SATELLITE(S) REMOVED FROM BROADCAST CLOCK FILE.
  SATELLITE NUMBER(S): 31
```

6.4. Forming Baselines (SNGDIF)

The *Bernese GNSS Software* uses double-differences as basic observables. The single-differences (between receivers, see Section 2.3.4) are stored in files while the double-differences are created in program GPSEST. Program SNGDIF ("Menu>Processing>Create baseline files") creates the single-differences and stores them in files. The program may create single-differences for both phase and code measurements. Usually, only the phase single-differences are used for further computations. An important exception is the ambiguity resolution using the Melbourne-Wübbena linear combination. In that case the code single-differences have to be formed, too.

The ambiguities from both zero-difference phase observation files are merged when forming a single-difference observation file if the option "Merge ambiguities from input files" in the panel "SNGDIF 3: Options" is enabled. It is, however, possible to set up an additional ambiguity parameter if an observation gap is larger than the value specified in the field "Set new ambiguity after a gap in the observations larger than" or if a cycle slip flag is found in one of the zero-difference observation files ("If cycle slip flag set in input file(s)"). These options are of interest only if your zero-difference observation files are already cleaned by the program MAUPRP in the zero-difference mode or by RNXSMT. Usually, however, the ambiguities are redefined when the single-difference phase observation files are screened with the program MAUPRP (see Section 6.5).

If the zero-difference observation files contain satellite-specific observation type information in RINEX3 notation in their header part then this information will be considered in the following way: if signals of different frequencies are selected for a satellite in both zero-difference files the observations of this satellite will be skipped for the baseline. If the

observation type is specified only in the header of one zero-difference file, the satellite will be skipped, too. If observation types are specified for the satellite in both zero-difference observation file headers and if they refer to the same frequency, the satellite-specific observation type information of both stations will be saved in the header of the single-difference observation file.

6.4.1. Algorithm for Baseline Selection

Let us assume that m receivers are used simultaneously. Let us further assume that the same satellites are tracked by all receivers (these assumptions are true in local campaigns). We have thus m zero-difference measurements to each satellite at each epoch (and each carrier). If we use single-difference observations then only $m - 1$ independent single-differences may be formed.

If the assumption that the same set of satellites is tracked by all receivers is not correct (global campaigns), it would be better to optimize forming of single-differences for each epoch. However, the data handling would be tremendous in such a case. We use a compromise in the *Bernese GNSS Software*. We create only one set of $m - 1$ baselines for the entire session (and store the observations into the single-difference files — each single-difference file corresponding to one baseline and one session) but we optimize the selection of these independent baselines. The algorithm used is known as maximum (or minimum) path method. First, all possible baselines are ordered according to a user-defined criterion (either baseline length or the number of available single-difference observables — see Section 6.4.2). Then, all the receivers active in the current session are given the initial flag 0. We take the “best” baseline into the optimal set, the two corresponding stations receive both the flag 1. The variable “maximum flag” is set to 1. Now, we proceed to the second baseline. If the corresponding stations have flag 0, we change them to 2, and 2 is the value of the “maximum flag”, too. If one station has flag 0 and the other one 1, both flags will be set to 1 and the “maximum flag” remains 1. From now on we proceed as follows: we select the next baseline according to our criterion and distinguish between the following four cases:

1. Both stations of the new baseline have flags 0:
in this case, the two station flags are set to “maximum flag +1” and we have to increment the “maximum flag” accordingly.
2. One station has flag 0 and the flag of the other station is not equal to 0:
in this case, the station with flag 0 receives the (non-zero) flag of the other station. The “maximum flag” is not changed.
3. The two flags are not equal and no flag is 0:
let us assume that the first station has a lower flag than the second one. We have to change the flags of all stations which have the same flag as the first station. The station flags are set to the flag of the second station.
4. The two flags are equal and different from 0:
this means that the baseline is dependent and can not be added to the set.

This procedure is repeated until $m - 1$ independent baselines have been formed.

6.4.2. Strategies for Baseline Definition

A simple criterion is to use the baseline length to create the set of shortest baselines (SHORTEST in option "Processing strategy"). This could be useful if you want to create the same set of baselines for each session (assuming that the same stations are observing in each session). The strategy can only be used if the observations from all stations cover the same time interval and the same GNSS. As Figure 6.5b demonstrates also baselines between GPS-only stations (e.g., between WSRT and PTBB) are created which means a loss of GLONASS tracking information. On the other hand, the baseline length is an important criterion for ambiguity resolution. If the number of observations is used as a criterion, the program will not create very long baselines either.

Usually, we use the number of observations as optimization criterion (OBS-MAX in option "Processing strategy"). The baselines are created taking into account the number of common observations for the associated stations. From all possible combinations, a set of baselines

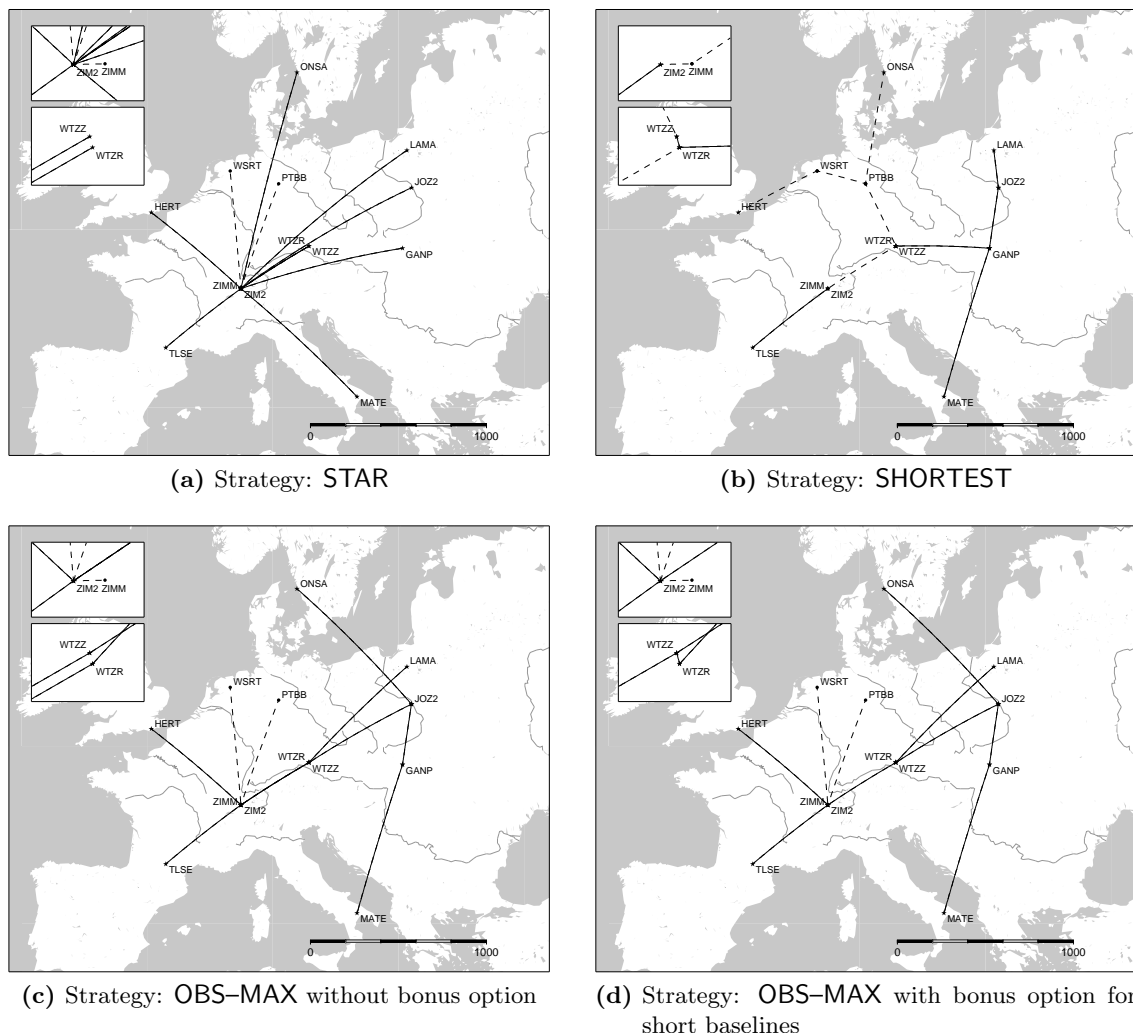


Figure 6.5.: Effect of different strategies on the resulting network of baselines for selected stations in Europe. The stations WSRT, PTBB, and ZIMM are equipped with GPS-only receivers resulting in GPS-only baselines indicated by dashed lines whereas combined GPS/GLONASS baselines are plotted with solid lines.

with maximum common observations is chosen (see Figure 6.5c for an example). The number of observations is scaled to a sampling rate of one minute and to one frequency when the set of baselines is selected in order to treat all zero-difference files in the same way.

Counting the observations may be speeded up for short baselines (the limit is defined in option “Maximum distance for fast observation count” in panel “SNGDIF 3.1: Options for Strategy OBS-MAX”) where it can be assumed that both sites do observe the same satellites. In that case, only the number of observations in the header of the observation file is checked instead of reading through the entire observation file.

To force the creation of shorter baselines, where the ambiguity resolution is expected to be more successful, you may use the group of options “ADD BONUS DEPENDING ON BASELINE LENGTH” in panel “SNGDIF 3.1: Options for Strategy OBS-MAX”. The number of counted observations is increased by a “bonus” factor according to the length of a baseline. In this way, you may combine the strategies OBS-MAX and SHORTEST if you have a network with regional densifications. As a result of the extended strategy, the short baseline from WTZR to WTZZ is created in the example of Figure 6.5d instead of connecting both stations with ZIM2 (as in Figure 6.5c).

For both strategies you have the possibility to specify “Predefined baselines” from a baseline definition file (see Section 24.7.17 for a description). The predefined baselines are then created in any case. Additional baselines are built using the selected strategy to complete the set of baselines.

Using the STAR strategy the baselines are built by connecting one reference station with all remaining stations (e.g., ZIM2 in Figure 6.5a). You may select the reference station manually in the input panel (option “Reference station for STAR (P)” in panel “SNGDIF 1: Input File Selection”). Otherwise, the reference station will be selected automatically in a way that the sum of the length of all baselines is minimized. Alternatively, the stations of a baseline may be selected manually in the input panel.

SNGDIF may create a list of the formed baselines in a file (enter a filename in the field “Listing of formed baselines” in panel “SNGDIF 2: Filenames”). The resulting file may be introduced as the baseline definition file in another run of the program (enter the file name in the input field “Predefined baselines” and choose the “Processing strategy” “DEFINED”). This allows, e.g., to recreate the same baselines at another day or to create the same baselines from phase and code observations. The latter is necessary if you use the Melbourne–Wübbena linear combination, e.g., for the ambiguity resolution. In this case, the baselines for the phase measurements are created in a first step, optimizing the number of phase observations, and are then stored in a baseline definition file. In the second step the same baselines are formed for the code observations (choose “Measurement type” “CODE”) by introducing this file as “Predefined baselines”.

6.4.3. Special Options for Poorly Observed Satellites

Some GNSS satellites might be poorly observed, e.g., because they are temporarily set unhealthy during an orbit repositioning maneuver or not yet declared operational after launch. In these cases the corresponding satellites might not be tracked by all receivers resulting in a lower number of observations.

If orbits of poorly observed satellites shall be determined and the OBS-MAX strategy is used, the number of observations for such satellites might be increased by using redundant

baselines. In this case the observations of selected stations are assigned to additional baselines. When activating the checkbox “Add redundant baselines” in panel “SNGDIF 3.1: Options for Strategy OBS-MAX”, a new input panel “SNGDIF 3.2: Options for redundant Baselines” will show options for the definition of redundant baselines. Note that the list of redundant baselines is always stored in the cluster with the number 00 (added to the filename defined in the field “Cluster/baseline assignment” in “SNGDIF 2: Filenames”). While for all “normal” clusters with the numbers 01 . . . 99 the “Correlation strategy” “CORRECT” must be chosen in GPSEST, the “Correlation strategy” has to be “BASELINE” for the baselines of the redundant cluster. We recommend to use redundant baselines with care and only for global networks.

When processing data from the early days of GLONASS tracking with only a very limited number of stations tracking a small number GLONASS satellites, the network creation algorithm might not be optimal: if these stations are widely spread in your network the counting of the remaining satellites (e.g., GPS) will dominate the baseline creation algorithm and you will probably not get optimal orbit results for the GLONASS satellites. The same situation may be expected nowadays with the new Galileo system, e.g., in the frame of the MGEX project of the IGS.

In such cases, you may focus the baseline selection on a certain GNSS by specifying this system in the option “Stations must contain observ. from a GNSS” in panel “SNGDIF 1: Input File Selection”. Baselines will only be created between stations that observe the specified GNSS. The baselines defined in a first program run can be re-introduced as pre-defined baselines (option “Predefined baselines” in panel “SNGDIF 2: Filenames”) in a second run in which the option “Stations must contain observ. from a GNSS” is set to ANY (or GPS to exclude stations that do not provide GPS data). All remaining stations are then assigned to the network — now considering the observations from all GNSS. This approach may be combined with the use of redundant baselines as well.

6.5. Preprocessing Phase Observations (MAUPRP)

It was stated in Section 2.3 that the receivers can measure the difference between the phase of the satellite transmitted carrier and the phase of the receiver generated replica of the signal. This measurement yields a value between 0 and 1 cycle (0 and 2π). After turning on the receiver an integer counter is initialized. During tracking, the counter is incremented by one whenever the fractional phase changes from 2π to 0. Thus, for every epoch the accumulated phase is the sum of the directly measured fractional phase and the integer count. The initial integer number n_{Fk}^i of cycles between the satellite i and receiver k is unknown and has to be estimated (see Eqn. (2.20)). This initial phase ambiguity remains the same as long as no loss of signal lock occurs. A loss of lock causes a jump in the instantaneous accumulated phase by an integer number of cycles. If there is a difference

$$n_{Fk}^i(t_2) - n_{Fk}^i(t_1) \neq 0$$

we say that a cycle slip occurred between epochs t_1 and t_2 . There are several possible causes for cycle slips:

- obstruction of the satellite signal due to trees, buildings, etc.,
- low signal-to-noise ratio due to rapidly changing ionospheric conditions, multipath, high receiver dynamics, or low satellite elevation,
- failure in the receiver software, and
- malfunctioning of the satellite oscillator.

In Version 5.2 of the *Bernese GNSS Software* the detection of cycle slips may be carried out at the RINEX level using the program RNXSMT (see Section 6.2). The limitations are given by the requirement of dual-frequency data and by the accuracy of the code observation as both observation types are used together.

Using the program MAUPRP ("Menu>Processing>Phase preprocessing") cycle slips in the phase observations can be identified more reliably¹. The program does not need code observations to screen the phase measurements. It is able to preprocess zero-difference as well as single-difference observation files, forming and analyzing different linear combinations of phase observations. In the case of zero-difference observation files it is necessary to introduce excellent high-rate satellite clocks (accuracy < 0.1 ns; same sampling as observations to be processed) to obtain reliable results. In any case, precise satellite orbits and sub-meter-accuracy station coordinates are required.

The program MAUPRP either assumes that the wide-lane combination is not corrupted by cycle slips (this is true if the preprocessing program RNXSMT was used before) or it looks for wide-lane cycle slips, too.

The following tasks are accomplished by program MAUPRP:

1. Mark observations due to the following reasons in order to exclude them from the preprocessing and from the data analysis (options in panel "MAUPRP 4: Marking of Observations"):
 - observations at low satellite elevation,
 - epochs with unpaired observations (L_1 without L_2 or vice versa),
 - small pieces of observations.
2. Perform a non-parametric screening to identify big outliers.
3. Compute an epoch-difference solution as a reference for the cycle slip detection.
4. Check all the observations and find the time intervals $[t_1, t_2]$ which are corrupted by cycle slips.
5. If possible, repair the cycle slips. For this purpose the difference $n_{F_k}^i(t_2) - n_{F_k}^i(t_1)$ is estimated for each slip and all observations following the epoch t_1 are corrected accordingly. If the size of the cycle slip cannot be estimated reliably, the observation at time t_2 has to be marked as outlier or a new unknown ambiguity parameter $n_{F_k}^i(t_2)$ must be introduced.
6. Check for clock events if zero-difference phase files are preprocessed.

6.5.1. Non-Parametric Screening

The goal of the non-parametric screening is to identify time intervals in which no cycle slips occur with utmost certainty. Usually, a fair amount of such data (not corrupted by cycle slips) can be found. The observed minus computed (O-C) values are calculated from the phase observations and the input a priori information. The O-C values are checked (on satellite difference level: one station, two satellites, one epoch for zero-difference files, and two stations, two satellites, one epoch for single-difference files) whether they are values of a smooth function of time and whether they may be represented within an interval of a few minutes by a polynomial of low degree, say q , by computing the $(q+1)$ -st derivative and by checking whether or not this quantity is zero within the expected RMS error.

¹Although MAUPRP stands for Manual and AUtomatic PReProcessing the manual mode is no longer available in Version 5.2.

Algorithm

It is expected that the satellite–differences of O–C are values of “smooth” time functions with random errors of the order of a few centimeters. The program checks whether or not the $q + 2$ subsequent O–C values may be represented within an interval of a few minutes by a low degree polynomial of degree q . This is done by computing the $(q + 1)$ –st derivative by numerical differentiation of the O–C values time series and by checking whether or not this quantity is zero (within 3 times its RMS error). The RMS error of the $(q + 1)$ –st derivative is computed from the RMS error of the O–C values which is specified in the option “Discontinuity level” in panel “MAUPRP 5: Non-Parametric Screening”. If the condition is met, the interval considered is shifted by one epoch, if not, the last observation of the current interval is marked and replaced by the following one. If the current interval gets longer than a maximum length specified in the option “Maximum time interval for polynomial fit”, all observations of the current interval are dropped, and the process is reinitialized. After successful reinitialization the program tests backwards to recover erroneously marked observations. The initialization works as follows: the condition is tested using the first $q + 2$ O–C values (for reinitialization the next $q + 2$ observations not yet checked). If it is not fulfilled, the first observation is marked, the condition is tested using value $2, 3, \dots, q + 3$. The process is terminated as soon as the above mentioned condition is fulfilled.

If in this screening procedure more than 25% of the observations from a particular satellite are indicated as bad, all measurements from this satellite are marked and excluded from the further processing. This is reported in the program output by an additional << `deleted` in the corresponding section (see Section 6.5.7). The limit of 25% is hardwired in the subroutine `LG/PREPHA.f`.

6.5.2. Epoch–Difference Solution

With the data identified as “clean” in the first step, an epoch–difference solution (Section 2.3.4) is performed using the standard least–squares adjustment for each baseline or station. In the case of baselines the coordinates of the first receiver are kept fixed on their a priori values while the coordinates of the second receiver are estimated.

This epoch–difference solution is not as accurate as the result of the least–squares adjustment in the final parameter estimation program GPSEST (using either zero–differences for stations or double–differences for baselines) but it is a fair approximation of the final solution. The main advantage has to be seen in the fact that an undetected cycle slip corrupts one epoch–difference only (and not all zero–differences or double–differences after the slip). Therefore, this solution may be used as reference for the automatic cycle slip detection in the next step.

The epoch–difference residuals are computed and stored in a scratch file (the residuals are computed for *all* observations not only for those identified as “clean” in the first step).

6.5.3. Automatic Cycle Slip Detection

The algorithms described in the following are specific to GPS. Specific modifications for GLONASS (due to the FDMA) are described in Habrich (1999).

First, the program corrects big jumps on the single–difference level when screening baseline files. Such jumps usually originate from the receiver clock and are common to all satellites. Therefore, these clock jumps are only relevant for the receiver clock synchronization for double difference processing algorithms. This step is replaced by the clock event handling (described in Section 6.5.4) if zero–difference files are preprocessed because in this case receiver clock corrections may be estimated later in the parameter estimation program GPSEST.

Then the results of the previous two steps are used to detect the cycle slips in the following way: The epoch–difference residuals stemming from the second step (they have been stored in an auxiliary file — see Section 6.5.2) are inspected. We assume that we have observations in two carriers L_1 and L_2 and write

r_1 the epoch–difference L_1 –residuum
 (we do not explicitly indicate the one or two receivers, two satellites, and two epochs pertaining to this epoch–difference) and
 r_2 the epoch–difference L_2 –residuum.

According to the baseline length or the available dataset, either the dual or the single frequency algorithm is applied.

Cycle Slip Detection: Dual Band Algorithm

If the COMBINED method is used, MAUPRP interprets the residuals as follows:

$$r_1 = b_1 \lambda_1 + \left(I_{k\ell}^{ij}(t_2) - I_{k\ell}^{ij}(t_1) \right), \quad r_2 = b_2 \lambda_2 + \frac{f_1^2}{f_2^2} \left(I_{k\ell}^{ij}(t_2) - I_{k\ell}^{ij}(t_1) \right). \quad (6.1)$$

where $I_{k\ell}^{ij}(t)$ is the ionospheric refraction “as seen” by the L_1 carrier at time t , see Eqns. (2.21). If zero–difference files are preprocessed the change of the receiver clock must be considered in addition:

$$\begin{aligned} r_1 &= b_1 \lambda_1 + \left(I_k^{ij}(t_2) - I_k^{ij}(t_1) \right) + \left(\delta_k(t_2) - \delta_k(t_1) \right), \\ r_2 &= b_2 \lambda_2 + \frac{f_1^2}{f_2^2} \left(I_k^{ij}(t_2) - I_k^{ij}(t_1) \right) + \left(\delta_k(t_2) - \delta_k(t_1) \right). \end{aligned} \quad (6.2)$$

The change of the receiver clock ($\delta_k(t_2) - \delta_k(t_1)$) is computed using the linear combination selected in option “Frequency for the solution” (usually the ionosphere–free combination L_3) for each epoch–difference.

Now, we check whether the *no-cycle slip hypothesis* $b_1 = b_2 = 0$ holds. The residual in the L_3 (ionosphere–free) linear combination is computed as

$$r_3 = \beta_1 r_1 + \beta_2 r_2, \quad \text{where} \quad \beta_1 = \frac{f_1^2}{f_1^2 - f_2^2} \quad \text{and} \quad \beta_2 = -\frac{f_2^2}{f_1^2 - f_2^2}.$$

The following condition should be met:

$$|r_3| \leq 3g \sqrt{(\beta_1 \sigma_1)^2 + (\beta_2 \sigma_2)^2}. \quad (6.3)$$

When screening baseline files the factor $g = \sqrt{8} = \sqrt{2^3}$ is due to triple–differencing (two receivers, two satellites, two epochs). When screening zero–difference files the factor is $g = \sqrt{4} = \sqrt{2^2}$ instead (one receiver, two satellites, two epochs).

Eqns. (6.1) resp. (6.2) allow us to compute the change of ionospheric refraction between the epochs t_1 and t_2

$$I_{k\ell}^{ij}(t_2) - I_{k\ell}^{ij}(t_1)$$

independently for both carriers (we assume $b_1 = b_2 = 0$ at present). The mean value m is computed as

$$m = \frac{1}{2} \left(r_1 + \frac{f_2^2}{f_1^2} r_2 \right) .$$

We check whether the condition

$$m \leq M_{ion} \tag{6.4}$$

is met. The value of M_{ion} (option “Maximum ionospheric change from epoch to epoch”) and the a priori RMS errors of the zero difference observables σ_1 and σ_2 (options “Sigma for L1 observations” and “Sigma for L2 observations”) are input parameters in panel “MAUPRP 8: Cycle Slip Detection/Correction”. If conditions (6.3) and (6.4) hold, the no-cycle-slip hypothesis is accepted as true. In the opposite case a search over the values b_1 and b_5 is performed. All combinations

$$\begin{aligned} b_{1p} &= \text{NINT} \left(\frac{r_1}{\lambda_1} \right) + p , & p &= -J_1, \dots, -1, 0, 1, \dots, J_1 \\ b_{5q} &= \text{NINT} \left(\frac{r_1}{\lambda_1} - \frac{r_2}{\lambda_2} \right) + q , & q &= -J_5, \dots, -1, 0, 1, \dots, J_5 \end{aligned}$$

(NINT = nearest integer) are formed and the “corrected” residuals

$$\begin{aligned} r_{1p} &= r_1 - b_{1p} \lambda_1 , \\ r_{2pq} &= r_2 - (b_{1p} - b_{5q}) \lambda_2 \end{aligned}$$

are tested in the same way as the original residuals r_1 and r_2 . The user has to specify the search ranges J_1 and J_5 (see “Search width to find L1 cycle slip correction” and “Search width to find L5 cycle slip correction” in panel “MAUPRP 8: Cycle Slip Detection/Correction”). If one combination of r_{1p} , r_{2pq} meets the no-cycle-slip hypothesis as defined by Eqns. (6.3) and (6.4), this pair is assumed to be the cycle slip correction.

If no combination for r_{1p} , r_{2pq} is found that meets the no-cycle-slip hypothesis, a new ambiguity parameter should be introduced. But introducing too many ambiguity parameters would result in large RMS errors of the other parameters estimated in GPSEST. There is still the chance that the problem is actually not a cycle slip but an outlier and that only one or a few observations are corrupted. If the cycle slip problem appears in the epoch-difference between the epochs t_1 and t_2 , the first corrective action is usually to mark (i.e., not use) the observation stemming from epoch t_2 (“Enable outlier rejection” in panel “MAUPRP 9: Outlier Rejection / Ambiguity Setting”) and to try the same tests using the epoch-difference between the epochs t_1 and t_3 and possibly t_1 and t_4 , etc. Of course, there is a parameter which limits the length of the interval $[t_1, t_x]$. It is specified by option “Mark consecutive outliers up to a time interval”.

Small cycle slips in the data (up to about 10 cycles) might not be real but rather a consequence of a high noise level (e.g., for low elevation data). To reduce the probability that such cycle slips are corrected, the user may specify a minimum slip size in option “Minimum size of accepted cycle slip correction”. If b_{1p} , b_{2pq} , and b_{5q} are all smaller than this value the cycle slip is considered as an outlier and is marked. With the option “Do not accept cycle slip corrections” the correction of cycle slips may generally be suppressed. This is recommended when processing zero-difference files because the introduction of the satellite clocks adds additional noise.

If you have to rerun MAUPRP for a set of observation files and you had cycle slip correction enabled, you have to rebuild the observation files first using SNGDIF for single-difference files or RXOBV3, CODSP for zero-difference files.

Cycle Slip Detection: Single Band Algorithm

If the screening mode L1, L2, or BOTH is selected in option “Screening mode, frequency to check” of input panel “MAUPRP 3: General Options”, MAUPRP does not create any linear combination of the measurements. The residuals are directly evaluated as follows:

$$b_1 = \text{NINT} \left(\frac{r_1}{\lambda_1} \right) \quad \text{or} \quad b_2 = \text{NINT} \left(\frac{r_2}{\lambda_2} \right) .$$

If $b_{1/2}$ is zero no cycle slip is assumed otherwise $b_{1/2}$ represents the potential candidate for the cycle slip correction.

The values m_1 and m_2 are computed as

$$m_1 = b_1 \cdot \lambda_1 - r_1 \quad \text{and} \quad m_2 = b_2 \cdot \lambda_2 - r_2 .$$

Only the condition (6.4) is tested (but *not* the condition (6.3)). In that context the parameter M_{ion} becomes a limit for the accepted fraction of a wavelength (e.g., 30%). Of course this parameter is still related to the change of the ionospheric refraction from one epoch to the next. If this limit is exceeded, the outlier detection algorithm as described above for the COMBINED mode is applied.

Cycle Slip Detection: Algorithm Selection

For short baselines (< 20 km) the method BOTH is preferable because of the higher noise level of the ionosphere-free linear combination L_3 used in the COMBINED mode for the cycle slip detection. For longer baselines the COMBINED mode is mandatory since only then the ionosphere-free linear combination L_3 of the L_1 and L_2 observations is used.

The user may select either the COMBINED or BOTH method in option “Screening mode, frequency to check” of input panel “MAUPRP 3: General Options” and select the related baselines. Of course, it is more convenient if the program adjusts the algorithm selection according to the baseline length. This feature is available if you specify AUTO for the option “Screening mode, frequency to check”. In the input field “Max. baseline length for BOTH (else COMBINED)” you have to select the baseline length where to make the switch between the BOTH and COMBINED mode processing. In that case you have to specify the two values for the “Maximum ionospheric change from epoch to epoch”: one related to the single frequency and a second one for the combined mode.

For short baselines processed in BOTH mode, the value for the short baselines is used. When processing the baselines in a combined mode, the value for “Maximum ionospheric change from epoch to epoch” is adjusted by a linear interpolation between both values until the baseline length of “Maximum ionospheric change from epoch to epoch” is achieved. For longer baselines the value for the COMBINED mode is used as it is given in the panel.

When processing zero-difference files, the COMBINED mode is selected automatically for dual-frequency data because the computation of the epoch-difference solution is based on a point positioning. For single frequency preprocessing, only the BOTH mode actually can be applied, performing a single frequency preprocessing for L_1 and L_2 independently.

6.5.4. Clock Events in Preprocessing of Zero-Difference Files

In principle, jumps in the receiver clock are uncritical. This is true if such events are treated in a consistent way in the RINEX files. They affect the observation epoch, the code, and the phase measurements in a similar way. To synchronize the receiver clocks program CODSPP needs to run before MAUPRP is executed.

The epoch-differences of the receiver clock values estimated in program MAUPRP ($\delta_k(t_2) - \delta_k(t_1)$ in Eqn. (6.2)) using the phase observations have to confirm the code based receiver clock values from the program CODSPP within a user specified limit (option “Minimum size of a clock event” in panel “MAUPRP 7: Clock Events”). If the two clock values are different then MAUPRP reports a *clock event*, identifies it and, if possible, corrects it. This is important if code and phase observations will be introduced together into the program GPSEST for the estimation of clock corrections.

Some receivers generate jumps with the size of a multiple of one millisecond. If such ms-jumps are not correctly handled by the receiver or the RINEX converter, they may be repaired by MAUPRP in an analogous way like the clock jumps. Otherwise, a new ambiguity needs to be inserted for each satellite.

If several clock events occur within a short time interval (specified in option “Mark observations up to a time interval”), the magnitude of all these events are summed up. If this sum is below the detection limit for clock events then the receiver clock problem affects only the few epochs between the two events. All observations of these epochs are marked to eliminate the clock event. In this way the number of additional ambiguities may be reduced.

6.5.5. Kinematic Stations

In analogy to the change of the receiver clock between epochs ($\delta_k(t_2) - \delta_k(t_1)$) needed in Eqn. (6.2) for the screening of zero-difference files, the change of the position between epochs t_1 and t_2 needs to be estimated for kinematic stations. This step is performed for zero-difference as well as for single-difference files if the option “Kinematic coordinate estimation” in panel “MAUPRP 6: Epoch-Difference Solution” is enabled. Usually, the ionosphere-free linear combination L_3 is used for this estimation (see option “Frequency for the solution”).

Because four parameters must be estimated for each epoch-difference, the redundancy is small if, e.g., only five or six satellites are observed. This will have, of course, an effect on the reliability of the cycle slip detection. The situation may be improved by introducing good kinematic positions as a priori information from a “Kinematic input coordinates” file to be specified in panel “MAUPRP 1: Input Files”. In this case the epoch-difference estimates for the change of the positions may be constrained using the “A priori coordinate/baseline vector sigmas” in panel “MAUPRP 6: Epoch-Difference Solution”.

If a kinematic coordinate file is introduced and the “Kinematic coordinate estimation” is disabled (e.g., if the accuracy of the introduced kinematic coordinates is better than expected from the epoch–difference solution in program MAUPRP), then only those epochs are used as a priori for which the file gives the flag K (indicating a good kinematic position). For any other flag all observations of the epoch are marked.

6.5.6. Screening of LEO Data

In the case of preprocessing data from a LEO, either a standard orbit or a kinematic coordinate file may be introduced. In both cases a receiver on board of a LEO must be labeled with the marker type SPACEBORNE in the station information file.

Screening of phase observations from spaceborne receivers may be done with the program MAUPRP in zero–difference mode if high–rate precise GPS clock corrections are introduced (e.g., from CODE, see Section 4.13.1). Due to the rapidly changing GPS satellite geometry as seen by the LEO, several time interval options may have to be reduced with respect to the default values (e.g., “Minimum time interval accepted for continuous observations” and “Maximum gap accepted within continuous observations” in panel “MAUPRP 4: Marking of Observations” and “Mark consecutive outliers up to a time interval”, “After an observation gap larger than” and “Minimum observed time interval per ambiguity” in panel “MAUPRP 9: Outlier Rejection / Ambiguity Setting”). You may divide the recommended values given in the online help by about a factor of 2.

As a priori information either a kinematic coordinate file or a standard orbit file may be introduced. The screening may be iterated when an improved orbit from GPSEST gets available. Unless the a priori information is very reliable the estimation of kinematic coordinates should be enabled (option “Kinematic coordinate estimation” in panel “MAUPRP 6: Epoch-Difference Solution”). Adapt the constraints to be assigned to the estimated coordinates to the accuracy of the a priori information (option “RMS limit for epoch solution”). If no reliable a priori information is available you may have to relax or disable the screening option “Maximum observed-computed value”.

6.5.7. Program Output Examples

Example 1

The first example stems from the preprocessing of the baseline Brest–Brussels (BRST–BRUX; day of year 063 in 2015) from our regular processing for the IGS. The baseline length is about 693 km. The options have been set according to the recommendations in the help panels. The strategy AUTO has been used.

At the beginning of the preprocessing report some information on the baseline is provided. In addition, the baseline screening mode COMBINED is confirmed (indicated by CHECK FREQUENCIES: 3) as well as the value for M_{ion} that has been computed by 158% of L_1 cycles according to the length of the baseline to be used for the option “Maximum ionospheric change from epoch to epoch”.

```

*****
DATA SCREENING: IGSRAPID                                05-MAR-15 01:57
*****
STATION 1: BRST 10004M004          YEAR: 2015          SESSION: 0630
STATION 2: BRUX 13101M010          DAY :    63          FILE   :    0

BASELINE LENGTH (M) :    693542.514
OBSERVAT. FILE NAME :  ${P}/IGSRAPID/OBS/BTB00630.PSH

BASELINE DEPENDENT OPTIONS:
-----
CHECK FREQUENCIES (L1=1, L2=2, L1&L2=3, L1,L2=4) --> :    3
MAX. IONOS.DIFF. BETW. EPOCHS (o/o OF L1 CYCLES) --> :   158

```

In the next section of the MAUPRP output file, marked measurements are reported. Three reasons may be responsible for the rejection of an observation: low elevation of the satellite, unpaired observations, and small pieces of measurements (options from panel “MAUPRP 4: Marking of Observations”).

```

-----
MARK UNPAIRED L1/L2 OBSERVATIONS: SUMMARY
-----

```

SATELLITE	#L1 MARKED	#L2 MARKED
11	22	0
14	9	0
17	5	0
19	7	0
20	3	0
22	18	0
23	12	0
24	13	0
28	9	0
31	3	0
32	26	0
102	2	1
111	6	0
112	1	0
113	1	0
...		
TOTAL	457	6

```

-----

```

```

-----
MARK OBSERVATIONS WITH SMALL ELEVATION: SUMMARY
-----

```

SATELLITE	#L1 MARKED	#L2 MARKED
11	170	170
14	16	16
17	38	38
19	93	93
20	7	7
22	68	68
23	42	42
24	195	195
28	58	58
31	40	40
32	0	0
102	82	82
111	64	64
112	80	80
113	50	50
...		
TOTAL	3465	3465

```

-----

```



```

-----
MARK OBSERVATIONS WITHIN SMALL PIECES: SUMMARY
-----
SATELLITE      #L1 MARKED    #L2 MARKED
-----
  11             9             9
  14             6             6
  17             5            12
  19             3             5
  20            13            13
  22            12            18
  23             8             9
  24             6             6
  28             3             4
  31             0             0
  32            11            11
 102             1             1
 111             5             6
 112             0             1
 113             0             0
  ...
-----
TOTAL           262           340
-----

```

The first screening part of program MAUPRP checks the O–C differences between satellites (exceptionally also the original observations) by smoothing (using the so-called non-parametric screening options in panel “MAUPRP 5: Non-Parametric Screening”, see Section 6.5.1). The program produces the following output:

```

-----
CHECK SATELLITE DIFFERENCES: SUMMARY (WITH RESPECT TO REF.SATELLITE)
-----
SATELLITE      #OBS.   MARKED   SLIPS   INIT.SLIPS
-----
  11           551       0        1        2
  14          1015      12        2        5
  17           728       2         1         5
  19           946       1         5         6
  20           776       4         2         4
  22           930       3         6         5
  23           771       1         0         4
  24           755       0         1         4
  28           989       3         5         5
  31          1036       3         3         6
  32           786       0         0         4
 102          1062       0         7         7
 111           323       206        0         1 << deleted
 112          1083       0         3         6
 113          1119       1         4         5
  ...
-----
TOTAL         45121      103       225      249
-----

```

For GLONASS satellite R11 about two third of the observations have been identified as problematic. According to the criteria described at the end of Section 6.5.1, the satellite is excluded from the further processing by marking all its observations.

The second part of the program performs the epoch-difference solution (options in panel “MAUPRP 6: Epoch-Difference Solution”, see Section 6.5.2):

```

-----
EPOCH DIFFERENCE SOLUTION
-----
FREQUENCY OF EPOCH DIFF. SOLU.:           3
#OBS. USED FOR EPOCH DIFF. SOLU.:       44541
RMS OF EPOCH DIFF. SOLUTION (M):       0.012

COORDINATES  NEW-A PRIORI X (M):          -0.029 +-      0.021
                                           Y (M):           0.003 +-      0.022
                                           Z (M):           0.027 +-      0.014
-----

```

In this example the a priori coordinates were very accurate. The difference between the a priori coordinates and the new values computed using the triple differences indicates the accuracy of the epoch–difference solution. The RMS error of the epoch–difference solution should not be much larger than 2 cm. A higher value indicates

- bad or inconsistent input data (e.g., satellite orbits),
- data problems in an observation file (mark all observations of the time interval with bad data manually in this observation file or make use of the option “Maximum observed-computed value” in panel “MAUPRP 6: Epoch-Difference Solution”), or
- improper settings of the input options (e.g., constraints in the “A priori coordinate/base-line vector sigmas” are not appropriate).

Now, the epoch–difference residuals are screened. MAUPRP detects a total of 43 cycle slips in this run (using the default settings in panel “MAUPRP 8: Cycle Slip Detection/Correction”, see Section 6.5.3):

CYCLE SLIPS ACCEPTED IN THIS RUN										
NUMBER OF SLIPS IN L1:		14								
NUMBER OF SLIPS IN L2:		27		7 CYCLE SLIPS REMOVED FROM LIST						
NUMB	TYP	N	EPOCH	SAT	FRQ	WLF	SLIP	FRAC	RES.L3 (M)	IONOS (M)
1	DUA	*	331	17	1	1	-12.	0.37	0.040	0.004
2	DUA	*			2	1	-24.	0.37		
					5	1	12.	0.09		
3	DUA	*	562	20	2	1	21.	-0.16	-0.017	0.021
					5	1	-21.	-0.07		
4	DUA	*	857	13	1	1	61.	0.27	0.029	0.004
5	DUA	*			2	1	75.	0.27		
					5	1	-14.	0.06		
6	DUA	*	1285	108	2	1	-60.	0.11	0.012	-0.010
					5	1	60.	0.04		
7	DUA	*	1392	101	1	1	27.	-0.33	-0.034	-0.149
8	DUA	*			2	1	13.	-0.33		
					5	1	14.	0.14		
...										
35	DUA	-	519	17	2	1	-29.	-0.13	-0.014	0.077
36	DUA	-	520	17	2	1	29.	-0.13	-0.014	0.072
37	DUA	-	522	17	2	1	-29.	-0.29	-0.031	0.055
38	DUA	-	523	17	2	1	29.	0.15	0.016	0.031
39	DUA	-	524	17	2	1	-29.	-0.21	-0.023	0.060
40	DUA	-	525	17	2	1	29.	-0.39	-0.042	0.054
41	DUA	-	526	17	2	1	-29.	-0.16	-0.017	0.068
...										

The possible types of cycle slip flags are the following:

- DUA means that the cycle slip was found by the dual band algorithm using the conditions (6.3) and (6.4),
- SNG means that the cycle slip was found by the single frequency algorithm using the condition (6.4) only,
- CLK indicates a so-called clock jump (jumps on the single–difference level, see Section 6.5.3), and
- JMP indicates a clock event: a ms–jump has been corrected (only when pre-processing zero–difference files).

The items which were changed in the most recent run are marked by an asterisk in the column N.

The lower part of this example contains cycle slip corrections indicated with a - in the column N. They are related to a sequence where that the algorithm did find cycle slip corrections for (nearly) each epoch during a certain interval. Because a receiver tracking

problem is very likely in such a case, the corresponding cycle slip corrections are removed from the list and marked in the observation files to exclude them from further processing.

A long list of the pieces of measurements marked or changed follows:

```

-----
NEW OR MODIFIED MARKED AREAS IN THIS RUN
-----
NUMBER OF MARKED AREAS IN L1: 753
NUMBER OF MARKED AREAS IN L2: 624
NUMB  TYP N      EPOCHS      SAT  FRQ  #EPOCHS
-----
   1  USR *      1 - 2880    37   1   2880
   2  USR *      1 - 2880    37   2   2880
...
  10  ELV *     143 - 144    12   1     2
  11  ELV *     143 - 144    12   2     2
  12  ELV *     146 - 148    12   1     3
  13  ELV *     146 - 148    12   2     3
...
  14  GAR *     117 - 117     4   1     1
  15  GAR *     117 - 117     4   2     1
...
  16  UNP *     158 - 163    12   1     6
  17  UNP *     172 - 174    12   1     3
...
  18  O-C *     248 - 249    11   1     2
  19  O-C *     248 - 249    11   2     2
...
  20  GAR *     303 - 314     2   1    12
  21  GAR *     303 - 314     2   2    12
  22  GAR *     315 - 320     2   1     6
  23  GAR *     315 - 320     2   2     6
...
 131  DUA *      10 - 10    31   1     1
 132  DUA *      10 - 10    31   2     1
 133  DUA *      14 - 18    28   1     5
 134  DUA *      14 - 18    28   2     5
 135  DUA *      20 - 21    28   1     2
 136  DUA *      20 - 21    28   2     2
 137  DUA *      64 - 70    14   1     7
 138  DUA *      64 - 70    14   2     7
...
 139  GAR *      71 - 74    14   1     4
 140  GAR *      71 - 74    14   2     4
...
 141  DUA *      94 - 96    13   1     3
 142  DUA *      94 - 96    13   2     3
...

```

The possible marking types are:

- DUA dual band algorithm, see Section 6.5.3,
- SNG single band algorithm, see Section 6.5.3,
- USR defined in the “Satellite problems” file (description in Section 6.7.2 and 24.3.5), or no valid position for an epoch in the “Kinematic input coordinates” file (other than flag K) if the “Kinematic coordinate estimation” is disabled, see Section 6.5.5,
- UNP marked epochs with unpaired observations (L_1 without L_2 or vice versa),
- ELV observations at low elevation,
- GAR small pieces of observations (garbage),
- O-C observations marked due to large observed–computed values during the epoch difference solution (see option “Maximum observed-computed value” in panel “MAUPRP 6: Epoch-Difference Solution”), and
- CLK observations marked because no satellite clock value was available when preprocessing zero–difference files, or observations marked because of a clock event, see Section 6.5.4.

MAUPRP also gives information on the ambiguities setup. Each satellite has one initial ambiguity corresponding to the first epoch. All other ambiguities are called multiple. Here only the multiple ambiguities are listed. The ambiguities which were introduced in the most recent run are marked by an asterisk.

----- MULTIPLE AMBIGUITIES -----			
NUMB	TYP	SATELLITE	EPOCH

1	*GAP	11	2436
2	*GAP	14	1316
3	*GAP	14	1370
4	*GAP	14	2510
5	*GAP	17	1045
6	*GAP	17	2758
7	*GAP	19	2212
8	*GAP	19	2267
9	*GAP	20	2677
10	*GAP	23	1938
11	*GAP	23	2849
12	*GAP	28	750
13	*GAP	28	2585
14	*GAP	28	2689
15	*GAP	32	2562
16	*GAP	24	2536
17	*GAP	31	1609
18	*GAP	31	1655
...			

The following types of multiple ambiguities are defined:

- FIL ambiguity which was already set in the observation file header,
- CYC ambiguity which was introduced due to a cycle slip flag in the observation (see option "If a cycle slip flag in observation file" in panel "MAUPRP 9: Outlier Rejection / Ambiguity Setting"),
- GAP ambiguity which was introduced due to a gap in the observations,
- PRP ambiguity which was introduced due to the detection of a cycle slip that could not be corrected (and outlier rejection was not possible), and
- CLK ambiguity which was introduced due to a clock event, see Section 6.5.4.

At the end MAUPRP writes the very important message

```
FILE SAVED
```

which means that all the changes were written into the observation file. If FILE NOT SAVED is printed, *no* changes were made to the original observation file(s) (see option "Save screened observation files" in panel "MAUPRP 3: General Options").

Example 2

The second example is based on the very short baseline (only 11 meters) between the two stations in Matera (MAT1–MATE). Since AUTO is selected for the option "Screening mode, frequency to check" the program switches automatically into the BOTH mode for this short baseline (indicated by CHECK FREQUENCIES: 4). The limit $M_{ion} = 30\%$ was directly taken from the "Maximum ionospheric change from epoch to epoch" for short baselines in panel "MAUPRP 8: Cycle Slip Detection/Correction".

```

*****
DATA SCREENING: IGSRAPID                                05-MAR-15 01:57
*****

STATION 1: MAT1 12734M009          YEAR: 2015          SESSION: 0630
STATION 2: MATE 12734M008          DAY :    63          FILE   :    0

BASELINE LENGTH (M) :           10.724
OBSERVAT. FILE NAME : ${P}/IGSRAPID/OBS/OAMT0630.PSH

BASELINE DEPENDENT OPTIONS:
-----

CHECK FREQUENCIES (L1=1, L2=2, L1&L2=3, L1,L2=4) --> :    4
MAX. IONOS.DIFF. BETW. EPOCHS (o/o OF L1 CYCLES) --> :   30

```

The output from the program is similar to that of Example 1. The only difference is the cycle slip detection flag used: here it is SNG (instead of DUA in Example 1).

```

-----
CYCLE SLIPS ACCEPTED IN THIS RUN
-----

NUMBER OF SLIPS IN L1:    719
NUMBER OF SLIPS IN L2:    777

NUMB  TYP  N  EPOCH  SAT  FRQ  WLF          SLIP  FRAC      RES.L3      IONOS
      (M)  (M)
-----
  1  SNG *   27   31  1   1           40.   0.07
  2  SNG *   27   31  2   1           70.  -0.04
  3  SNG *   70   19  2   1           23.   0.10
  4  SNG *   76   19  1   1          143116. -0.04
  5  SNG *   76   19  2   1          108136. -0.09

  6  CLK *  121  ALL  1   1        -11027940.
  7  CLK *  121  ALL  2   1        -8593200.

  8  SNG *  126   15  2   1           -11.   0.12
  9  SNG *  183   22  2   1          1474853. -0.00
 10  SNG *  235   21  2   1          42457541. 0.02

 11  CLK *  241  ALL  1   1        -11027941.
 12  CLK *  241  ALL  2   1        -8593201.
...

```

You can see in this example clock events (reported by CLK * in the program output sequence) appearing every 120 epochs indicating inconsistencies between the receiver clock as seen by the code and phase measurements. When these receiver clock events occur every hour, they are likely related to the generation or merging of hourly RINEX observation files. For a double-difference processing these events can simply be corrected by adding a reasonable number of cycles to the measurements of each satellite because no receiver clock can be estimated. In this example there are 31 GPS satellites measured in this baseline (MATE does not support tracking of GLONASS satellites). This means that $23 \times 31 = 713$ out of the 719 and 777 corrected cycle slips reported for L_1 and L_2 , respectively, are related to these clock inconsistency events.

Example 3

The third example demonstrates the program output of the MAUPRP for screening zero-difference files. The station Zwenigorod (ZWE2) is used. Additionally, a satellite clock file produced by the program CLKEST was introduced. To preprocess zero-difference observation files we have used the COMBINED mode as confirmed by CHECK FREQUENCIES: 3. The option "Maximum ionospheric change from epoch to epoch" is automatically adjusted to 400%.

```
*****
DATA SCREENING: RCLKGNSS                                05-MAR-15 16:09
*****

STATION   : ZWE2 12330M003          YEAR:   2015          SESSION: 0630
              DAY :    63              FILE   :    0

OBSERVAT. FILE NAME : ${P}/RCLKGNSS/OBS/ZWE20630.PZH

STATION DEPENDENT OPTIONS:
-----

CHECK FREQUENCIES (L1=1, L2=2, L1&L2=3, L1,L2=4) --> :    3
MAX. IONOS.DIFF. BETW. EPOCHS (o/o OF L1 CYCLES) --> :   400
```

The report on the quality of the epoch-difference solution is the same, independently of whether zero- or single-difference files are processed. In the case of zero-difference files the coordinate correction is related to a single-point positioning instead of a correction to a baseline vector.

```
-----
EPOCH DIFFERENCE SOLUTION
-----

FREQUENCY OF EPOCH DIFF. SOLU.:          3
#OBS. USED FOR EPOCH DIFF. SOLU.:       24717
RMS OF EPOCH DIFF. SOLUTION (M):        0.010

COORDINATES NEW-A PRIORI X (M):         -0.004 +-      0.006
                                   Y (M):          0.010 +-      0.006
                                   Z (M):          0.042 +-      0.006
-----
```

As mentioned in Section 6.5.3 the change of the receiver clock correction is estimated epoch-wise before the residuals for the cycle slip detection are computed (Eqns. (6.2)). The program output contains a summary of these epoch solutions:

```
-----
SUMMARY OF EPOCH SOLUTIONS
-----

NUMBER OF EPOCH SOLUTIONS WITHOUT PROBLEMS:      2879
NUMBER OF EPOCH SOLUTIONS WITH A BIG RMS:        0
NUMBER OF EPOCH SOLUTIONS WITH TOO FEW OBS.:    0
NUMBER OF EPOCH SOLUTIONS WITH "BAD" FLAG:      0

TOTAL NUMBER OF EPOCH SOLUTIONS:                 2879

MEAN RMS OF THE EPOCH SOLUTIONS:                 0.0082 M

MAXIMUM RMS FOR AN EPOCH SOLUTION:              0.0293 M   EPOCH: 2682
MAX. CLOCK CORR. FOR AN EPOCH SOLUTION:        -0.1900E+08 NS  EPOCH: 1702
MIN. DEG OF FREEDOM FOR AN EPOCH SOLUTION:      4           EPOCH: 2
-----
```

As indicated already by the huge value of MAX. CLOCK CORR. FOR AN EPOCH SOLUTION, there are clock events in this observation files. In fact, four clock jumps with a size

of 19 ms have been detected and repaired as “cycle slips” to the phase measurements:

```

-----
CYCLE SLIPS ACCEPTED IN THIS RUN
-----
NUMBER OF SLIPS IN L1:    120
NUMBER OF SLIPS IN L2:    120

NUMB  TYP  N   EPOCH SAT  FRQ  WLF          SLIP   FRAC      RES.L3      IONOS
-----
      1  JMP *   434  ALL  1   1    29932980.000 (EQUIVALENT TO 19. MS)
      2  JMP *   434  ALL  2   1    23324400.000 (EQUIVALENT TO 19. MS)
      3  JMP *  1067  ALL  1   1    29932980.000 (EQUIVALENT TO 19. MS)
      4  JMP *  1067  ALL  2   1    23324400.000 (EQUIVALENT TO 19. MS)
      5  JMP *  1702  ALL  1   1    29932980.000 (EQUIVALENT TO 19. MS)
      6  JMP *  1702  ALL  2   1    23324400.000 (EQUIVALENT TO 19. MS)
      7  JMP *  2343  ALL  1   1    29932980.000 (EQUIVALENT TO 19. MS)
      8  JMP *  2343  ALL  2   1    23324400.000 (EQUIVALENT TO 19. MS)
-----

```

Because the correction of cycle slips is switched off when preprocessing zero-difference files this section should only contain JMP-entries (or nothing).

The handling of detected clock events is reported in a part of the program output which appears only when preprocessing zero-difference files:

```

-----
CLOCK EVENT SUMMARY FOR ZERO-DIFFERENCE FILES
-----
NUMBER OF CLOCK EVENTS:    4

NUMB  EPOCH      CLOCK(PHASE)      CLOCK(CODE)      ACTION
-----
      1    434      19000000 NS      -18970405 NS      CYC
      2   1067      19000000 NS      -18970064 NS      CYC
      3   1702      19000001 NS      -18970311 NS      CYC
      4   2343      19000000 NS      -18970427 NS      CYC
-----

```

The following actions are defined corresponding to the settings in the panel “MAUPRP 7: Clock Events” for the handling of clock events:

CYC indicates a millisecond-jump that was repaired as a cycle slip,

MRK indicates that the corresponding observations are marked because the clock event may bias the common clock estimation from code and phase observations, and

AMB reports the setting up of a new ambiguity for all satellites because of a clock event.

6.5.8. Extraction (MPRXTR)

Program MPRXTR ("Menu>Processing>Program output extraction>Phase preprocessing") extracts information from the output of the program MAUPRP and produces a summary of the following form:

SUMMARY OF THE MAUPRP OUTPUT FILE															

SESS	FIL	OK?	ST1	ST2	L(KM)	#OBS.	RMS	DX	DY	DZ	#SL	#DL	#MA	MAXL3	...
0630	1	OK	GODZ	HNPT	77	41104	14	25	-38	38	7	409	78	48	...
0630	2	OK	LHAZ	NTUS	3365	29470	9	-99	344	-37	5	99	50	19	...
0630	3	OK	MAT1	MATE	0	17496	12	8	7	22	777	356	33	0	...
0630	4	OK	STR2	TID1	10	30853	13	21	-3	6	72	427	80	0	...
0630	5	OK	UNBJ	VALD	862	40322	11	-27	78	-106	1	268	56	7	...
0630	6	OK	UNB3	UNBJ	0	47551	6	0	1	-2	39	297	62	0	...
0630	7	OK	CONZ	CRAR	6379	20631	17	6	37	-189	45	601	55	50	...
0630	8	OK	CONZ	KOUR	4976	24893	20	617	-944	189	85	839	78	49	...
0630	9	OK	CRAR	DAV1	2687	44891	16	106	109	-102	55	1069	269	50	...
0630	10	OK	JOZ2	MOBJ	1078	39575	13	7	40	95	14	429	83	50	...
0630	11	OK	JOZ2	ONSA	830	36258	11	-69	-20	-87	73	2960	234	49	...
...															
0630	43	OK	BRMU	KOUR	3212	36052	20	427	-486	-140	86	2004	116	51	...
0630	44	OK	BRST	BRUX	694	47120	14	-92	-4	-4	22	683	78	47	...
0630	45	OK	BRST	MAS1	2467	39370	16	-265	21	-364	24	766	90	49	...
...															
0630	100	OK	SUTV	WIND	1146	39430	15	473	47	-123	6	462	63	49	...
0630	101	OK	GUUG	PIMO	2548	22547	19	-11	-4	-32	54	744	61	45	...
0630	102	OK	GUUG	TOW2	3576	34601	18	-629	159	-301	45	1180	119	49	...
0630	103	OK	XMIS	YARR	2279	38668	16	43	-407	-232	66	828	66	50	...
0630	104	OK	MIZU	USUD	413	17674	12	21	-43	4	3	80	25	45	...
0630	105	OK	MIZU	WHIT	5766	28752	17	-47	-133	189	11	474	66	44	...
...															
Tot:	105				2080	50753	20	617	-944	189	777	3295	407	51	...

The summary file contains one line per baseline processed. The line starts with the session, a file sequence number, the "OK" flag, the first four characters of the station names, and the length of the baseline. The line continues with some information concerning the epoch-difference solution: the number of observations, RMS, baseline change in the Cartesian X, Y, and Z components. The next three fields contain the number of corrected cycle slips, the number of deleted observation intervals, and the number of multiple ambiguities. Finally, the maximum residual for the ionosphere-free linear combination is given followed by the smallest corrected cycle slip.

The last line of the summary gives the number of files, the mean baseline length, the maximum number of observations, the biggest epoch-difference RMS, the longest vector of coordinate improvements, and the maximum number of corrected cycle slips, deleted observation intervals, and multiple ambiguities. In this way, this summary line reports the "worst case" for each criterion.

The summary listing in the zero-difference case contains the RMS and coordinate corrections from the epoch-difference solution for each individual station. All other parameters are identical to the baseline case. If millisecond-jumps were detected in MAUPRP the events are reported below the main table.

If a station or baseline was not successfully cleaned, the flag would be different from "OK" and the station/baseline should be removed. Apart from the summary file, MPRXTR may also create a deletion list file (in the case of preprocessing baseline files also a new baseline definition file). This file is intended to be used for removing bad observation files in an automated processing. When preprocessing zero-difference files, the corresponding observation files may be added to the deletion list. If preprocessing single-difference files the extraction program will also (try to) identify which of the two stations of the baseline

was causing the problems. The bad zero-difference file(s) may optionally be added to the “bad” single-difference file(s) in the deletion list file.

If a baseline file was removed, a new baseline should be created to make sure that the network is complete. MPRXTR defines a new baseline that is listed in the output baseline definition file. This file may then be used by the program SNGDIF to create the new baseline. Make sure that you do not forget to run MAUPRP for the newly created baseline. When preprocessing zero-difference files the deletion of an observation file does not require any other action.

6.6. Screening of Post-Fit Residuals

In the *Bernese GNSS Software* Version 5.2 residual files may be created by the programs GPSEST, MAUPRP, CODSPP, ORBGEN, and IONEST. These residual files are unformatted binary files containing all the residuals of one program run. There are three different types of residual files:

- Only linear combinations of L_1 and L_2 residuals are stored and may be displayed.
- L_1 and L_2 residuals are stored and may be displayed separately or in any linear combination (only for residuals from program MAUPRP).
- Instead of observation residuals, the radial, along-track, and out-of-plane components of orbit residuals are contained in residual files generated by ORBGEN.

The residual files may contain residuals

- on the zero-difference level (GPSEST, CODSPP, and IONEST),
- on double-difference level (GPSEST: two stations and two satellites resp. MAUPRP: two satellites, two epochs), or
- on triple-difference level (MAUPRP: two stations, two satellites, two epochs).

Residual files may be analyzed in the *Bernese GNSS Software* Version 5.2 by the two programs REDISP and RESRMS.

6.6.1. Browsing the Residual Files (REDISP)

The panel “REDISP 2: Display Characterization” of program REDISP (“Menu>Service>Residual files >Display residual file”) asks to select the units of the residual representation and the frequency to be displayed (one of the frequencies processed). Additionally, for each residual file, you need to choose:

- for observation residuals: the station name(s), reference epoch, measurement type, difference level, and a list of frequencies in the residual file.
- for satellite arc residuals: arc number, reference epoch, and the components RADial, aLONG track, resp. OUT of plane of the residuals.

An example of a REDISP output for zero-difference residuals:

```

GENERAL INFORMATION:
-----
Program that created the file:      CODSPP
Difference level of observations:    0 sta.      0 sat.      0 epo.
Number of parameters:              0

File: 1  ZAMB 34601M001      2003-09-03 00:00:00      CODE zero-diff.      L3
TIME |   6   14   15   16   18   25   2   23   30   3   20   ...
-----|-----
1 |  2.1 -0.4  1.3 -0.1 -0.3 -2.2
2 |  2.1 -0.3  1.3 -0.2 -0.3 -2.2
3 |  2.1 -0.3  1.3 -0.2 -0.3 -2.2

```

For each epoch one line is written. The epoch number indicates the number of epochs elapsed since the reference epoch reported in the header of the table. The residuals are listed in the column of the satellite they refer to in user selected units. The column remains blank if no residual for the corresponding satellite is available. Empty lines indicate missing epochs either due to the sampling during processing or due to a lack of data in the observation file.

Example of an output for double-difference residuals:

```

GENERAL INFORMATION:
-----
Program that created the file:      GPSEST
Difference level of observations:    1 sta.      1 sat.      0 epo.
Number of parameters:              314

File: 1  CONZ 41719M002      RI0G 41507M004      2003-10-09 00:00:00      PHASE dble-diff.      L3
TIME |   1   2   2 13 13 20 20 24 24 27 27  4  4 16 16  8  8 10 10 17 17 29 29 28 28 26  ...
-----|-----
1 |   0       1       1      -1       0
2 |   0       1       0      -2       0       2
3 |   0       *      -1       1      -1       1       0
4 |   2       *       0      -1       0       2       0
5 |   1       0       0      -1       0       5

```

For each epoch one line is written. Each column refers to the double-difference residuals of two satellites: satellites 1 and 2 in the first column of the example, satellites 2 and 13 in the second column, satellites 13 and 20 third column, and so on. In the example above, satellite 2 was not available for epochs 3 and 4. It is, therefore, not possible to report double-difference residuals between satellites 1 and 2 and between 2 and 13 (first and second columns). But it is possible to display the double difference residual between the satellites 1 and 13. To indicate this situation the value of the residual is written into the first column and the *-character into the second column. Analogously, the residual of 5 millimeters at the fifth epoch is the double-difference residual between the satellites 27 and 17.

6.6.2. Generating Residual Statistic (RESRMS)

Program RESRMS ("Menu>Service>Residual files>Create residual statistics") analyzes a set of selected residual files. It provides statistical information on the residuals, and optionally writes the following output files:

- A summary file (default extension **SUM**) gives a compact overview of the residual's RMS per station or baseline and per satellite.

- A histogram of the residuals for each station or baseline may be stored in another file (default extension `LST`).
- The edit information file (default extension `EDT`) contains the list of observations identified as outliers.
- Station observation sigma factors for the station weighting (default extension `SOS`) may be derived from the residuals.

The frequency to be analyzed is given by the linear combination of the residuals in the input file. For that reason, you may simply specify `AS_IS` for option “Frequency to check” in panel “RESRMS 2: Options”. The only exception are residuals provided by the program MAUPRP where the residuals for L_1 and L_2 are provided in a way that RESRMS is able to create linear combinations that may be selected in this input field.

The program output of RESRMS provides statistical information for the residuals of the stations or baselines. An example is given in Figure 6.6. The stations or baselines are identified by their names, the measurement type (`ObsTyp`), and the session (`Session`) — some of these columns are not shown in the example above. For each station or baseline one line of program output is providing:

<code>Total RMS</code>	the total RMS for all satellites,
<code>med.Resi</code>	the median of all residuals (first a median of the residuals from all satellites is computed per epoch, the reported value is the median of this value from all epochs),
<code>Sigma</code>	the width of the histogram (see options “Size of the histogram” in panel “RESRMS 3: Residual Statistics and Sigma Factors”) containing two thirds of all observations (The option “Bin width for histogram” has a direct impact on the accuracy of this value.),
<code>numObs</code>	the number of observations,
<code>nSat</code>	the number of satellites, and
<code>nDel</code>	the number of observation pieces rejected based on the thresholds specified in options “Detect large residuals: phase measurements” in panel “RESRMS 2: Options” and added to the edit information file.

FILE INFORMATION AND STATISTIC:										
Num	Station 1	Station 2	Total RMS	med.Resi	Sigma	numObs	nSat	nDel	...	...
1	GANP 11515M001	JOZ2 12204M002	1.3	0.8	1.1	7640	50	9	...	...
2	HERT 13212M010	ZIM2 14001M008	1.2	0.7	1.0	7446	51	0	...	...
3	JOZ2 12204M002	LAMA 12209M001	1.2	0.7	1.0	7858	50	4	...	...
4	JOZ2 12204M002	ONSA 10402M004	1.3	0.7	1.0	7472	50	11	...	...
5	JOZ2 12204M002	WSRT 13506M005	1.3	0.7	1.0	4403	30	6	...	...
6	JOZ2 12204M002	WTZR 14201M010	1.5	0.8	1.2	7697	50	16	...	...
7	MATE 12734M008	ZIM2 14001M008	1.3	0.7	1.1	6805	51	11	...	...
8	PTBB 14234M001	ZIM2 14001M008	1.4	0.8	1.2	3823	32	8	...	...
9	TLSE 10003M009	ZIM2 14001M008	1.5	0.8	1.2	7634	52	13	...	...
10	WTZR 14201M010	WTZZ 14201M014	1.6	0.6	1.0	8095	51	55	...	...
11	WTZR 14201M010	ZIM2 14001M008	1.6	0.9	1.3	7749	51	13	...	...
12	ZIM2 14001M008	ZIMM 14001M004	0.9	0.5	0.8	4532	31	1	...	...

NUMBER OF EDIT REQUESTS: 147

Figure 6.6.: Example for a program output from RESRMS.

In general, the unit for the residuals in program RESRMS is millimeters. The residuals for code measurements are rescaled with respect to the residuals of phase measurements using a factor of 100 (specified in the file $\${X}/\text{GEN}/\text{CONST.}$), i.e., the unit for code residuals is decimeter.

All other weights applied in the parameter estimation process when computing the residuals (e.g., “Elevation-dependent weighting”, or “Observation sigma factors” in program GPSEST) cannot be taken into account in program RESRMS. It is strongly recommended to save normalized residuals in GPSEST to assure a reliable and homogeneous outlier detection by RESRMS. Normalized residuals are defined as $r_{\text{norm}} = r/\sigma_r$ where r is the real residual and σ_r is the a priori (NORM_APR) or the a posteriori (NORMALIZED for option “Type of computed residuals” in panel “GPSEST 3.1: General Options 1”) RMS of the residual (see Section 7.4.4). In contrast to real residuals, normalized residuals are always converted to one-way L_1 carrier phase residuals.

One of the major purposes of the program RESRMS is the screening of post-fit residuals for outliers. The residual file from a GPSEST solution is analyzed for outliers and an edit information file (description in Section 24.11.12) is written. Using this file, program SATMRK (description in Section 6.7.1) can mark the corresponding measurements in the observation files. These steps are highly recommended when processing baseline files and are mandatory when processing zero-difference observation files. When the observation files are preprocessed by the program RNXSMT (zero-difference case) the screening of the post-fit residuals should be done iteratively by lowering the outlier detection thresholds (option “Detect large residuals: phase measurements”).

If you applied a sampling rate to the GPSEST run when you have generated the residual file, it is necessary to specify the same sampling rate in “Sampling interval of residual files” in panel “RESRMS 2: Options” again. The value is used to mark/remove also observations adjacent to a bad observation in a range corresponding to the specified sampling rate.

The steps of searching for outliers and marking the corresponding observations are intentionally separated. Please check the edit information file before you are going to apply the marking requests to your observation files. If you have a baseline (or station) with huge outliers, it may lead to bigger residuals for all observations (according to the principle of least squares adjustment). The limit to identify outliers (“Detect large residuals: phase measurements”) possibly has to be adjusted. In an automated processing scheme this may be realized by looping from big to small thresholds. Typically, only the program RESRMS needs to be repeated in each loop because no new residuals need to be computed by GPSEST as long as no observations are marked with a big threshold. The line **NUMBER OF EDIT REQUESTS: 147** in the program output (see Figure 6.6) is intended to be used as the indicator.

Station Observation Sigma Factors

For each individual station a measurement noise may be computed from the residuals of their observations. Station observation sigma factors are then derived from this measurement noise. The conversion of measurement noise to sigma factors may be defined by the options “New sigma factor Noise larger than” in panel “RESRMS 3: Residual Statistics and Sigma Factors”. The station sigma factors may be stored in a file which is described in Section 24.7.14.

The purpose of these station observation sigma factors is the following: as the noise of original code observations (not smoothed by program RNXSMT) may differ significantly for different receivers the sigma factors may be used to weight the code observations in the parameter estimation or to rescale the outlier rejection thresholds in program CODSP. Station sigma factors are not necessary when processing phase observations.

A file containing normalized residuals which were generated in GPSEST using a station observation sigma file already applied, *cannot* be used to generate a new station sigma file.

6.6.3. Detect Misbehaving Stations and Satellites (RESCHK)

For a robust automated processing it is essential to have a tool at hand to detect and exclude misbehaving stations, e.g., stations with strange data that cannot be handled properly in the preprocessing programs of Version 5.2 of the *Bernese GNSS Software* — at least not with the default settings used in an automated processing. Also satellites whose orbits are not modeled sufficiently well (e.g., due to a repositioning event) should be detected and excluded from the processing.

The *Bernese GNSS Software* Version 5.2 provides such a tool with the program RESCHK ("Menu>Service>Automated processing>Detect misbehaving stations/satellites"). It analyzes the summary file of the program RESRMS and detects events in the solution. The program handles only one problem type per run according to this priority:

1. MANEUVER DETECTED FOR SATELLITE(s),
2. BAD STATION(S) DETECTED,
3. BAD SATELLITE(s) detected,
4. SATELLITE(s) W/O OBSERVATIONS detected, or
5. NO SPECIAL EVENTS FOUND IN THIS SOLUTION.

The result is reported by the above strings in the program output.

The conclusion “bad station” or “bad satellite” is influenced by an RMS-ratio if the RMS threshold is exceeded for stations and satellites at the same time (criteria described below). The RMS-ratio is computed as the relation of the RMS of the individual station or satellite with respect to the total RMS considering all stations and satellites. The biggest ratio decides whether a station or a satellite is assumed to be bad.

Keep in mind that the identification of “misbehaving” stations or satellites may also indicate that your settings of the preprocessing input options are not optimal!

Bad Station Detection

A station or baseline is assumed to be “bad” if the total RMS in the last column of the RESRMS residual summary file exceeds a user specified threshold (“Maximum allowed overall RMS” in panel “RESCHK 2.1: Detection of Bad Stations”). In the case of baseline residuals the “bad” stations are extracted in the following way from the list of “bad” baselines²:

²This algorithm is not robust in the context of multi-GNSS: if a station has a particular problem with a satellite the threshold may be exceeded for a certain baseline. If the station with the problem is also contributing to another baseline where this particular satellite is not included (e.g., not tracked by the other station), the station is identified as “good” because the RMS threshold is not exceeded for the second baseline.

- If a station from a “bad” baseline is found in any “good” baseline, too, the station is assumed to be “good”. If both stations of a “bad” baseline are set back to “good” this may indicate a problem in the preprocessing of the baseline (e.g., options for program MAUPRP).
- If a station is found in only one baseline, the other station of the baseline is checked. If this other station is found in “bad” baselines only, the first station is marked as “good”. If the second station is “good”, the first station is marked as “bad” (it is assumed that a “bad” baseline contains only one “bad” station).

The option “Maximum number of stations to delete” provides a limit for the number of stations to be deleted per program run. If more “bad” stations are found then the stations with the biggest total RMS errors are selected. If you analyze baseline residuals the total RMS of a station is computed as the mean RMS over all baselines containing the station. If the total RMS of at least one station in the zero-difference case exceeds the limit specified in option “RMS threshold level for a bad solution”, only the station with the biggest total RMS error will be marked as “bad”. The residual screening has to be repeated after removing the station.

The bad stations may be listed in a file allowing to delete the corresponding observation files. If you have detected and removed bad stations you should recompute the residual files (program GPSEST) and generate a new edit information file (program RESRMS) before marking the observations with the program SATMRK. If you are processing a network of baselines you have to rebuild the entire network (program SNGDIF) after deleting the observation files of the bad station. Of course, the new baselines have to be preprocessed again (program MAUPRP) before the residuals may be recomputed.

Bad Satellite Detection

You can download the file indicating satellite problems from the anonymous ftp account of AIUB (http://www.aiub.unibe.ch/download/BSWUSER52/GEN/SAT_yyyy.CRX, where yyyy is the four digit year). This file is updated every time when a new satellite problem appears (satellite maneuvers, bad data, ...) in the routine processing for the IGS at CODE. Observations of misbehaving satellites are rejected by the program RXOBV3 in your processing if you use this file. It is, therefore, not necessary for you to repeat the detection procedure for misbehaving satellites.

Nevertheless, the description of the algorithm is given here:

1. The CODSPP extraction (program CODXTR, see Section 6.3.4) and the arc split summary (program DEFXTR, see Section 5.4.3) may contain hints for a repositioning of a satellite. If at least one of these files shows an indication of a repositioning, a maneuver is postulated for the corresponding satellites.
2. Satellites for which a maneuver is postulated but which show no abnormal behavior with respect to the mean RMS in the bottom line of the RESRMS-residual summary (option “Maximum ratio of satellite RMS to overall RMS” in the section “Maximum ratio of satellite RMS to overall RMS”) are dropped from the maneuver list.
3. Satellites without any observations in the RESRMS summary table are added to the list of bad satellites. This can happen, e.g., when all observations of the satellite in all contributing observation files are marked.
4. The number of observations from all stations or baselines to each satellite are compared in the first and in the second table of the RESRMS residual summary (before

- and after the screening of post-fit residuals). A satellite for which a big amount of data is removed is assumed to be “bad” (option “Maximal percentage of deleted data”). This part is skipped if a maneuver hypothesis holds for at least one satellite because a maneuvered satellite may affect the residuals of other satellites. Note that for GLONASS a four times higher value is applied than for GPS because of the lower total number of observations (see subroutine `$_{LG}/RCSATCHK.f90`).
5. The ratio of the overall RMS for one satellite w.r.t. the mean total RMS for all satellites is computed. If this ratio exceeds the specified maximum ratio (option “Maximum ratio of satellite RMS to overall RMS”), the satellite is assumed to be “bad”. Two different threshold ratios are used depending on whether satellites with a maneuver hypothesis were identified or not.
 6. If the total RMS of a satellite in the RESRMS residual summary table exceeds a specified RMS threshold value (option “RMS threshold level for a bad solution”) it is considered that it is the only one (really) “bad” satellite affecting the entire solution. If more than one satellite exceed this limit only the one with the largest RMS is considered. If a maneuver hypothesis holds for this satellite it is assumed that a repositioning occurred. Otherwise the satellite is marked as “bad”.

If a repositioning or a misbehaving satellite was detected, an existing satellite problem file may be updated. If the updated file is used in GPSEST (and all other processing programs in the further steps) the observations of this satellite will be excluded (see Section 6.7.2).

6.7. Marking of Observations

Individual observations may be flagged with a so-called marking flag (the other flag used is the so-called cycle slip flag) in the Bernese binary observation files (code or phase observations, zero- or single-differences). The marking flags are used to mark outliers, observations at low elevation, small pieces of observations, etc. If this marking flag is set, no program will use the corresponding observation for the data analysis. It is also possible to reset the marking flags again. There are several preprocessing programs in the software which may mark observations:

RNXSMT marks the code and phase measurements of both frequencies in RINEX files using the signal to noise ratio as flag (see Section 6.2.6).

CODSPP marks both phase and code observations for which no receiver clock corrections could be estimated. Outliers may be marked on request in the Bernese code and/or phase observation files.

MAUPRP marks the observations with low elevations, small pieces of observations, and the observations suspected to be corrupted by a cycle slip (see Section 6.5).

Note that the program SNGDIF does not use marked zero-difference observations at all.

6.7.1. Manipulation of Observation Files (SATMRK)

The program SATMRK (“Menu>Service>Bernese observation files>Mark/delete observations”) may be used to manipulate flags in Bernese observation files, i.e., to set and reset marking flags or to remove observations. Possible actions are:

EDIT FILE: The entries of an edit information file (description in Section 24.11.12) will be applied to the Bernese observation files. This edit file is usually an output of program RESRMS.

MARK MANUAL: Mark (set marking flags), reset (remove marking flags — requires to repeat the full preprocessing procedure), or eliminate (delete) observations of a satellite for a user specified time window.

SYNCHRONIZATION: The observations in the corresponding code and phase observation files are synchronized. If an observation is available in only one of the files it will be removed. If an observation is marked in one file it will be marked in the other file, too. The result are pairs of code and phase files which contain for a station the same epochs and the same satellites. This may be important for processing steps involving both observation types (e.g., to make sure that all clocks in GPSEST are estimated with phase and code measurements).

INITIALIZE: Ambiguities which are already resolved (see Chapter 8) in the baseline phase observations header file are re-initialized (set to status “unresolved”).

6.7.2. Use of Satellite Problem File

The satellite problem file (the so-called “satcrux”-file, see Section 24.3.5) is located in the general file directory ($\${X}/GEN$). The user may exclude measurements of specific satellites for a period of time by adding a corresponding entry in this file. The other important usage of the satellite problem file is the setting of a new arc for a satellite and the handling (adding or removal) of stochastic orbit parameters. These topics are discussed in Chapter 16.

The satellite problem file is updated daily in the routine processing for the IGS at CODE. It is provided to the users of the *Bernese GNSS Software* via the anonymous ftp account of AIUB (http://www.aiub.unibe.ch/download/BSWUSER52/GEN/SAT_yyyy.CRX, where yyyy is the four digit year).

If a satellite is specified to be bad for an observation epoch, the processing programs of the *Bernese GNSS Software* (e.g., CODSP, MAUPRP, and GPSEST) will not use the corresponding measurements. The program RXOBV3 does not write the observations of a satellite into the Bernese observation files if they are indicated as bad. The program MAUPRP will mark the corresponding measurements in the preprocessed observation files. All other programs do not consider the observations of bad satellites, but they do not modify the observation files.

PRN numbers of satellites that are currently not active are listed at the top of the file. These entries prevent that “dummy” satellites enter the processing, if they occasionally appear in some RINEX observation files.

7. Parameter Estimation

7.1. Introduction

Parameter estimation in the *Bernese GNSS Software* is based on least-squares adjustment. The two main programs in the software package that allow for the adjustment of model parameters based on GNSS observations are: GPSEST ("Menu>Processing>Parameter estimation") and ADDNEQ2 ("Menu>Processing>Combine normal equation systems"). The first program processes the observations starting from the observation files. Whereas GPSEST sets up the observation equations and solves the normal equation (NEQ), ADDNEQ2 manipulates and combines solutions at the NEQ level. ADDNEQ2 is discussed in more detail in Chapter 9. This chapter provides general information for the program GPSEST. Details on the estimation of various parameters available in the *Bernese GNSS Software* are given in the following chapters.

GPSEST offers many processing options. Additional options such as a flexible datum definition by means of a free network condition, saving SINEX files, or estimating station velocities and other parameters from a long time series analysis, are available within ADDNEQ2. On the other hand, a number of short-epoch parameters are only supported by GPSEST, in particular epoch parameters (kinematic coordinates and stochastic ionosphere parameters) and phase ambiguities. The *Bernese GNSS Software* Version 5.2, as opposed to the previous versions, supports the handling of receiver/satellite clock corrections in both programs GPSEST and ADDNEQ2. An overview of the availability of the parameters supported by the *Bernese GNSS Software* Version 5.2 is given in Table 1.1, page 4.

As all programs in the *Bernese GNSS Software*, GPSEST is running in batch mode, i.e., it assumes that all observations are available in files. No real-time or data-streaming mode is supported. The program, furthermore, assumes that good a priori values for all parameters are available. The program does not iterate but computes the improvements of the parameters from the linearized observation equations. If iteration is necessary the program has to be run again using the improved parameters as a priori values or using screened observations.

7.2. Basic Theory of Least-Squares Estimation

The (linearized) observation equations in the *Gauss-Markoff Model* of full rank are given, e.g., by Koch (1988) as

$$\mathbf{E}(\mathbf{y}) = \mathbf{A}\mathbf{p} \quad ; \quad \mathbf{D}(\mathbf{y}) = \sigma^2 \mathbf{P}^{-1} \quad (7.1)$$

with

- n, u number of observations, number of unknowns,
 \mathbf{A} $n \times u$ matrix of given coefficients with full rank ($\text{rank } \mathbf{A} = u$);
 \mathbf{A} is also called *design matrix*,
 \mathbf{p} $u \times 1$ vector of unknown parameter improvements,
 \mathbf{y} $n \times 1$ vector containing the difference between the actual observations and computed observations, i.e. “observed *minus* computed” (O–C) ,
 \mathbf{P} $n \times n$ positive–definite weight matrix,
 $\mathbf{E}(\cdot)$ operator of expectation,
 $\mathbf{D}(\cdot)$ operator of dispersion,
 σ^2 variance of unit weight (variance factor).

The observation equations of Section 2.3 may be written in this form. For $n > u$, the equation system $\mathbf{A}\mathbf{p} = \mathbf{y}$ is not consistent. Adding the residual vector \mathbf{v} to the observation vector \mathbf{y} a consistent but ambiguous system of equations is obtained, which is also called system of *observation equations*:

$$\mathbf{y} + \mathbf{v} = \mathbf{A}\mathbf{p} \quad \text{with} \quad \mathbf{E}(\mathbf{v}) = \mathbf{0} \quad \text{and} \quad \mathbf{D}(\mathbf{v}) = \mathbf{D}(\mathbf{y}) = \sigma^2 \mathbf{P}^{-1}. \quad (7.2)$$

Eqns. (7.1) and (7.2) are formally identical. $\mathbf{E}(\mathbf{v}) = \mathbf{0}$ because $\mathbf{E}(\mathbf{y}) = \mathbf{A}\mathbf{p}$, and $\mathbf{D}(\mathbf{v}) = \mathbf{D}(\mathbf{y})$ follows from the law of error propagation.

The method of least–squares estimation asks for restrictions for the observation equations (7.1) or (7.2). The parameter estimates \mathbf{p} should minimize the quadratic form

$$\Omega(\mathbf{p}) = \frac{1}{\sigma^2} (\mathbf{y} - \mathbf{A}\mathbf{p})^T \mathbf{P} (\mathbf{y} - \mathbf{A}\mathbf{p}), \quad (7.3)$$

where $(\mathbf{y} - \mathbf{A}\mathbf{p})^T$ is the transposed matrix of $(\mathbf{y} - \mathbf{A}\mathbf{p})$. The introduction of the condition that $\Omega(\mathbf{p})$ assumes a minimum in order to come from the ambiguous observation equations (7.1) or (7.2) to an unambiguous NEQ system for the determination of \mathbf{p} . The establishment of minimum values for $\Omega(\mathbf{p})$ results in a system of u equations $d\Omega(\mathbf{p})/d\mathbf{p} = \mathbf{0}$, also called *normal equations (NEQs)*. The following formulae summarize the *least–squares adjustment* in the Gauss–Markoff model:

Normal equations:

$$(\mathbf{A}^T \mathbf{P} \mathbf{A}) \hat{\mathbf{p}} = \mathbf{A}^T \mathbf{P} \mathbf{y} \quad \text{or} \quad \mathbf{N} \hat{\mathbf{p}} = \mathbf{b} \quad (7.4)$$

Estimates:

of the vector of parameters:	$\hat{\mathbf{p}} = (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{P} \mathbf{y}$
of the (variance-)covariance matrix:	$\mathbf{D}(\hat{\mathbf{p}}) = \hat{\sigma}^2 (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1}$
of the observations:	$\hat{\mathbf{y}} = \mathbf{A} \hat{\mathbf{p}}$
of the residuals:	$\hat{\mathbf{v}} = \hat{\mathbf{y}} - \mathbf{y} \quad (7.5)$
of the quadratic form:	$\Omega = \hat{\mathbf{v}}^T \mathbf{P} \hat{\mathbf{v}}$ $= \mathbf{y}^T \mathbf{P} \mathbf{y} - \mathbf{y}^T \mathbf{P} \mathbf{A} \hat{\mathbf{p}}$
of the variance of unit weight (variance factor):	$\hat{\sigma}^2 = \Omega / (n - u)$

Degree of freedom, redundancy:

$$f = n - u$$

Normal equation matrices:

$$\mathbf{A}^T \mathbf{P} \mathbf{A}, \quad \mathbf{A}^T \mathbf{P} \mathbf{y}, \quad \mathbf{y}^T \mathbf{P} \mathbf{y} \quad (7.6)$$

This algorithm is used in the parameter estimation program GPSEST.

7.3. The Observations

The three measurement types supported by the current version of program GPSEST are:

- GNSS phase observations,
- GNSS code (pseudo-range) observations, and
- SLR range observations.

Code and phase observations may be processed together, e.g., for a precise time transfer solution (see Chapter 15 for more details). It is even possible to process linear combinations (linear combinations (LCs), see Section 2.3) between code and phase observations in order to have access to the Melbourne–Wübbena linear combination. The term GNSS indicates that the processing of GPS and GLONASS observations is equally well possible, even in a rigorously combined mode. Observations may stem from GPS-only or from GPS/GLONASS-combined receivers.

The processing of data from the upcoming European Galileo system is possible with Version 5.2 of *Bernese GNSS Software* as a combined GPS–Galileo or even as a triple-system solution. The processing of Galileo data, however, is still in an experimental stage. There are many open questions that need to be addressed in the frame of the Multi-GNSS EXperiment (MGEX) from the IGS, for instance.

GNSS data may stem from static ground-based receivers or kinematic roving receivers, see Chapter 10. In addition, data from spaceborne receivers may also be processed (details are discussed in Chapter 17).

For details on processing SLR data we refer to Chapter 19.

Observation selection

With the first option “Space geodetic technique” in panel “GPSEST 1.1: Input Files 1” you have to decide whether you are going to process SLR or GNSS data. In the latter case, you may choose between the two basic processing modes of program GPSEST for GNSS data processing (option “Differencing level” in the same panel), namely

- zero-differences of observations, or
- double-differences of observations.

Whereas in the first case the program reads zero-difference observation files, single-difference (baseline, station-difference) observation files are read in the second case. The double-differences (satellite-differences) are then created at run-time. In both cases it is possible to select phase and/or code observation files for processing.

Additional options to select observations for processing are available in panel “GPSEST 3.1: General Options 1” (displayed in Figure 7.1), such as the satellite system, the frequency or linear combination thereof, a minimum cutoff angle, a sampling interval, and a time window. For special applications observations acquired in daytime or during eclipses may be excluded with option “Special data selection”.

With the program GPSEST the following frequencies and linear combinations thereof may be processed (option “Frequency/linear combination”):

- L1 First frequency L_1 . This frequency is the first choice when processing “small” high-precision control networks (with an extent of a few kilometers only) taking into account local or global/regional ionosphere models.

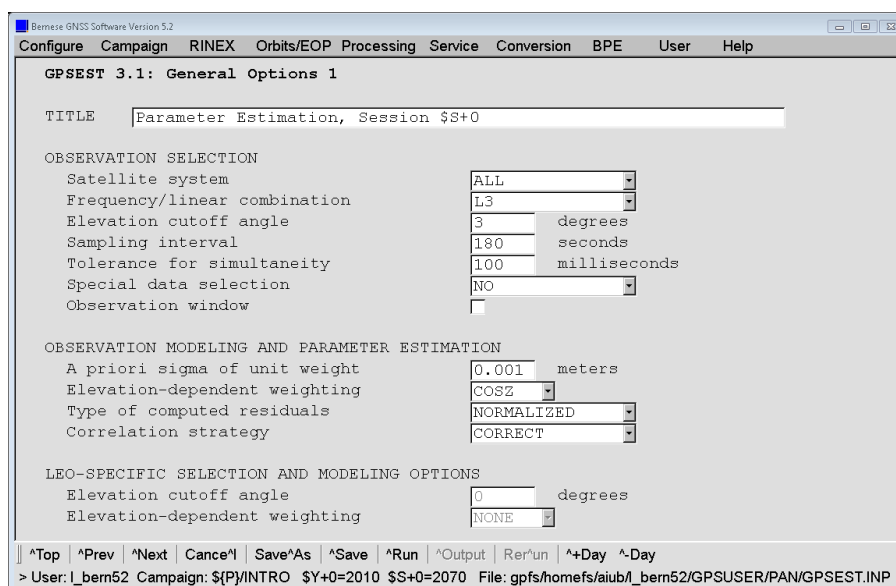


Figure 7.1.: General options for GPSEST.

- L2 Second frequency L_2 .
- L3 Ionosphere-free LC of dual-band measurements. This LC eliminates the first order ionospheric refraction effects and is thus recommended for most applications.
- L4 Geometry-free LC of dual-band measurements corresponding to the difference $L_1 - L_2$ (in meters). This LC is useful when monitoring the deterministic component of the ionosphere and is recommended when producing ionosphere models.
- L5 Wide-lane LC of dual-band measurements. In principle this LC is only used to resolve the wide-lane ambiguities without code measurements on “medium” baselines (with lengths of a few hundred kilometers only). One wide-lane cycle corresponds to a wavelength of about 86 cm which is quite large compared to the expected ionospheric (and tropospheric) biases.
- L1&L2 Both original frequencies. The simultaneous processing of both frequencies is required by several ambiguity resolution strategies (see Chapter 8).
- L3&L4 Ionosphere-free and geometry-free LCs. This option is not recommended.
- MELWUEBB The Melbourne-Wübbena LC of dual-band phase and code measurements is recommended for resolving wide-lane ambiguities if high-quality code measurements are available. This LC is free of hypotheses concerning the ionosphere and the “geometry”, where “geometry” includes the troposphere, the satellite orbits (and clocks) as well as the station coordinates (and clocks). Best performance is obtained when processing smoothed code (program RNXSMT, see Section 6.2) together with original phase (not pre-processed by RNXSMT).
- DTEC The squared temporal differences of the geometry-free LC can be used to map the stochastic component of the ionosphere.

The modeling of the observables includes (as far as relevant)

- different displacement effects on terrestrial stations (see Section 10.1),
- tropospheric and ionospheric refraction (see Chapters 12 and 13),

- phase center variations for receiving and transmitting antennas (see Chapter 18) or satellite laser array offset (for SLR, see Chapter 19),
- the geometric part of the polarization effect (phase windup) (Wu et al. 1993).
One part of the polarization effect considers the effect of varying relative geometry of receiver and satellite. Another part is the contribution originating from the satellite’s attitude. The latter can be fully absorbed by the satellite clock corrections, and
- the relevant biases (see Chapter 14 and Chapter 15) and SLR range biases (see Chapter 19).

7.4. Weighting and Correlations

7.4.1. A Priori Sigma of Unit Weight

The RMS of unit weight usually refers either to the phase weight of the zero-difference L_1 phase observable at zenith if elevation-dependent weighting is enabled (see Section 7.4.3) or it is an average over all zenith angles if elevation-dependent weighting is not enabled. The a priori weights w_p and w_c for the L_1 phase and the code observable are defined in the file `#{X}/GEN/CONST`. as the ratio $w_c/w_p = 10^{-4}$, i.e.,

$$\frac{\sigma_c}{\sigma_p} = 100$$

where σ_c and σ_p represent the measurement noise for pseudo-range observations and phase observations, respectively.

The a priori sigma specified in panel “GPSEST 3.1: General Options 1” should approximately agree with the actual measurement noise of the one-way L_1 phase observations (the a posteriori sigma of unit weight given in the GPSEST output file). The value of this sigma is used to scale any a priori constraints applied to specific parameters. The σ in Eqn. (7.1) corresponds to σ_p as defined in `#{X}/GEN/CONST`. and not to the user-specified a priori sigma. Therefore, when changing the a priori sigma, you also change the strength of the defined a priori constraints. The default value is 0.001 m if elevation-dependent weighting is enabled.

7.4.2. Station-Specific Weighting of Observations

Station-specific weighting of observations is primarily intended for pseudo-range measurements if data from different receivers are processed together in order to consider the potentially different noise level depending on the receiver.

The weighting is performed by so-called sigma factors that scale the a priori sigma used for weighting the observations. The same factors are used for rescaling the edit level for code observations in the zero-difference processing mode (see option “Maximum tolerated O-C term” in panel “GPSEST 3.3: General Options 3”). In this case, however, values below unity are set to unity.

The observation sigma factors are included in a file (see Section 24.7.14) that can be specified in option “Observation sigma factors” in panel “GPSEST 1.2: Input Files 2”. For each station the file contains a factor equal to or larger than unity. Sigma factors may be specified independently for each measurement type and they are annotated with a time window. For missing stations values are automatically set to unity.

A station sigma file may be generated by the program RESRMS based on the station-specific histogram of observation residuals (see Section 6.6.2). For most of the stations the factors should be close to unity. It is recommended to use the same station sigma file for all processing steps (CODSPP and GPSEST).

In general, station observation sigma factors are only important for processing pseudo-range observations. For phase measurements or smoothed code measurements (generated by RNXSMT) station sigma factors are typically not required.

7.4.3. Elevation-Dependent Weighting of Observations

Observations at low elevations are generally more susceptible to tropospheric refraction and multipath effects than those at high elevations. The unmodeled systematic errors affect the quality of results. Using low-elevation observations, however, may also improve the estimation of tropospheric zenith delays and, consequently, the vertical component of station positions (Rothacher et al. 1998; Meindl et al. 2004). In case of SLR observations, these measurements may improve even the horizontal station coordinate components and decorrelate the vertical station component from the estimated range biases (Sošnica 2015). In order to optimize the use of low-elevation observations, the program GPSEST supports elevation-dependent weighting of observations. The weighting function $w(z)$, where z is the zenith angle of the satellite, can be defined as:

- Model 0 with: all observations equally weighted,
- Model 1 with:

$$w(z) = \cos^2(z),$$

- Model 2 with:

$$w(z) = \cos^4(z),$$

- Model 3 with:

$$w(z) = \begin{cases} \cos^2(z) & \text{for phase measurements} \\ \cos^4(z) & \text{for code observations.} \end{cases}$$

Thus, an observation at zenith always has unit weight. The user has the possibility to enable or disable elevation-dependent weighting of observations in panel “GPSEST 3.1: General Options 1” (see Figure 7.1). Users may also implement other weighting models within the subroutine `LG/WGTELV.f`. Whatever model is used, $w(0) = 1$ should hold. Elevation-dependent weighting (e.g., from Model 1) is recommended especially when processing data having elevations smaller than 10° .

With elevation-dependent weighting enabled it is strongly recommended to reduce the a priori sigma in option “A priori sigma” of panel “GPSEST 3.1: General Options 1” from 0.002 m (default value for a weighting scheme independent of elevation) to 0.001 m. Note that for elevation-dependent weighting the a priori sigma of unit weight corresponds to the weight of the zero-difference L_1 phase observable at zenith. If elevation-dependent weighting is not used, however, the a priori sigma of unit weight corresponds to the weight of the observable averaged over all zenith angles. Adopting the unit weight is necessary in order not to bias the weights of the a priori constraints.

7.4.4. Real and Normalized Residuals

According to their definition in Eqn. (7.5), residuals correspond to the difference between adjusted and actual observations: $\hat{\mathbf{v}} = \hat{\mathbf{y}} - \mathbf{y}$. Vice versa, the sum of the actual observation

vector plus the residual vector gives the adjusted observation vector. In the *Bernese GNSS Software* the residuals $\hat{\mathbf{v}}$ are called *real residuals*.

Normalized residuals (option “Type of computed residuals” in panel “GPSEST 3.1: General Options 1”) are residuals divided by the square root of the diagonal element of the cofactor matrix of the residuals

$$v_{\text{norm}}(i) = \frac{v(i)}{\sqrt{\mathbf{D}_{ii}(\mathbf{v})}}.$$

The cofactor matrix of the residuals is the difference between the inverse of the weight matrix of the actual observations and the cofactor matrix of the adjusted observations

$$\mathbf{D}(\mathbf{v}) = \mathbf{P}^{-1} - \mathbf{D}(\mathbf{y})$$

with

$$\mathbf{D}(\mathbf{y}) = \mathbf{A}(\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \mathbf{A}^T. \quad (7.7)$$

In contrast to real residuals, normalized (phase as well as code) residuals are always converted to one-way L_1 carrier phase residuals. I.e., if you divide these residuals by the a posteriori sigma of unit weight, you should get random variables with a standard deviation of 1. It is recommended to save the normalized residuals for a reliable outlier detection using the program *RESRMS* when analyzing low-elevation data, for applying an elevation-dependent observation weighting model, or for introducing station-specific weights. Be aware that, e.g., a real double-difference L_3 carrier phase residual of 36 mm corresponds to a normalized one-way L_1 residual of 6 mm (assuming that no elevation- or station-specific weighting is applied).

A special option, namely *NORM APRIORI*, is available for the conversion of real residuals to normalized residuals by using the a priori variance of observations

$$\mathbf{D}(\mathbf{v}) \simeq \mathbf{P}^{-1} \quad .$$

This option is useful when epoch parameters are epoch-wise pre-eliminated and back-substituted (see Sections 7.7.1 and 7.7.2). If the option “Var-covar wrt epoch parameters” in panel “GPSEST 6.7: General Options for Epoch Parameters” is set to *SIMPLIFIED* to speed up the back-substitution, the matrix $\mathbf{A}^T \mathbf{P} \mathbf{A}$ in Eqn. (7.7) contains only the epoch parameters. As a consequence, the observation residuals that do not contribute to epoch parameters are normalized in a different way than the residuals of those observations that do contribute if option *NORMALIZED* is used. In this case the residuals are not comparable.

If residuals are requested (a residual output file in panel “GPSEST 2.2: Output Files 2” must be specified) the observation equations, i.e., the design matrix \mathbf{A} and the observation vector \mathbf{y} are saved to a binary scratch file while processing each observation and accumulating the normal equation matrix $\mathbf{A}^T \mathbf{P} \mathbf{A}$. After solving the normal equation the scratch file is read and the adjusted residuals are computed according to Eqn. (7.2). As a matter of fact, residuals can only be computed if all parameters (including ambiguity parameters) are solved for. It is not possible to pre-eliminate any parameter before the residuals are computed. Note that epoch parameters such as ionosphere stochastic parameters, satellite and receiver clock corrections, or kinematic coordinates are handled in a special way (see Section 7.6.2). Parameters may, however, be pre-eliminated using the option *PRIOR_TO_NEQ_SAVING* (see Section 7.7.1) if they should not appear in the normal equation file saved for later use in *ADDNEQ2* (see Chapter 9). This is particularly

important for ambiguity parameters that are not supported by ADDNEQ2. Saving a residual file and a normal equation file in the same run is only possible if ambiguity parameters are pre-eliminated using the option `PRIOR_TO_NEQ_SAVING`.

The binary scratch file may become large if many observations are processed (many stations or high sampling rate). Some operating systems have a limit of 2 Gb for the size of a binary file. For that reason the file is automatically split into several files if it becomes too big. By default the scratch files are saved in the user-specific directory `#{U}/WORK`. Make sure that enough disk space is available. This is also true for the `#{T}`-environment of the BPE if GPSEST is executed in parallel (see Chapter 22).

Residuals may be browsed using the program REDISP or they may be used to screen the observation files for outliers using the programs RESRMS and SATMRK. For details see Section 6.6.2.

7.4.5. Correlations between Observations

If double-differenced observations are processed, mathematical correlations between the differenced observations have to be considered because the same original observations might have been used for several observation differences. This is the case for one baseline but also for different baselines as soon as they are connected.

Let \mathbf{y} represent the vector of undifferenced observations and \mathbf{y}'' the vector containing the double-differenced observations. With the difference operator \mathbf{C} defined in the following way

$$\mathbf{y}'' = \mathbf{C}\mathbf{y} ,$$

the covariance matrix corresponding to the two observation types is converted according to

$$\mathbf{D}(\mathbf{y}'') = \mathbf{C}\mathbf{D}(\mathbf{y})\mathbf{C}^T .$$

In the above equations the vector \mathbf{y} contains all simultaneous observations of the network to be processed. This “simultaneity” can be defined with the option “Tolerance to identify observations of one epoch” in panel “SNGDIF 3: Options” when forming baselines with the program SNGDIF and with the option “Tolerance for simultaneity” in panel “GPSEST 3.1: General Options 1” for the program GPSEST (displayed in Figure 7.1 on page 172).

The option “Correlation strategy” in the same GPSEST panel allows to modify the correlation strategy. Naturally, we should model the correlations in a mathematically and statistically correct way (selection CORRECT). With this option all correlations within baselines, between baselines, and between different frequencies and linear combinations are handled correctly. The program resources (memory, CPU time, etc.) might, however, become critical if more than about 30 to 40 sites are processed with correct correlations. For such cases the *Bernese GNSS Software* allows to reduce the degree of correctness of the mathematical correlations. For the creation of final solutions it is recommended to model the correlations in a correct way.

A first compromise consists of processing clusters of sites with full correlations taken into account only within each cluster in program GPSEST. The cluster results may then be combined at the NEQ level using the program ADDNEQ2 (see Chapter 9). In this second step the observations used to process the individual clusters are considered to be uncorrelated. Optimized clusters may be generated using a cluster definition file (description see Section 24.7.18), with the program SNGDIF, or with the program MKCLUS.

The correlation strategy `FREQUENCY` allows us to neglect correlations between different frequencies or linear combinations of frequencies (e.g., if processing `L1&L2` together).

The correlation strategy `BASELINE` may be applied in order to speed up processing in case of non-final double-difference solutions such as intermediate solutions for residual screening. This strategy should always be used for ambiguity resolution. With this strategy, baselines are processed sequentially (and not in parallel as in the case of correct correlations) and only correlations within each baseline are considered. Especially when pre-eliminating ambiguities, this “baseline mode” is very efficient because memory for ambiguity parameters of only one baseline is required. As soon as one baseline is processed the ambiguities are pre-eliminated from the normal equation system and the ambiguity parameters of the next baseline are loaded.

No mathematical correlations between observations exist when zero-difference GNSS observations or SLR measurements are processed. Nevertheless, the correlation strategy `CORRECT` has to be used as soon as epoch-wise pre-elimination of parameters is enabled. Otherwise, these epoch parameters become independent for each observation file which makes no sense for satellite clock parameters or receiver clock corrections, if code and phase observations are processed simultaneously. An exception might be the Stochastic Ionosphere Parameters (SIPs) since they are independent from observation file to observation file. This is one of the reasons why independent SIPs for code and phase observations are assumed.

Temporal correlations, i.e., correlations between consecutive epochs, which may also exist between observations, are *not* considered within the *Bernese GNSS Software*.

7.5. Constraining of Parameters

In general, the observations of a given type may not be sensitive to all parameters in a theoretical model, or the estimated parameters may be collinear. In these cases the NEQs are singular or very close to singularity: the NEQ has a rank deficiency. Additional (external) information must be introduced to the least-squares solution (so-called *constraints*), to make the NEQ non-singular. Constraints may be useful also for parameters which would be estimated with a very high RMS error.

Let us introduce “external” information concerning the parameters in the following way

$$\mathbf{H}\mathbf{p} = \mathbf{h} + \mathbf{v}_h \quad \text{with} \quad \mathbf{D}(\mathbf{h}) = \sigma^2 \mathbf{P}_h^{-1} \quad (7.8)$$

where

- \mathbf{H} $r \times u$ matrix with given coefficients with $\text{rank } \mathbf{H} = r$,
- r number of constraining equations with $r < u$,
- \mathbf{p} vector of unknown parameters with dimension $u \times 1$,
- \mathbf{h} $r \times 1$ vector of known constants,
- \mathbf{v}_h $r \times 1$ residual vector, and
- \mathbf{P}_h^{-1} dispersion matrix of the introduced constraining equations with dimension $r \times r$.

If the constraints are nonlinear, a linearization has to be performed using a first-order Taylor series expansion. We may interpret the constraints (Eqn. 7.8) as additional pseudo-observations or as *fictitious observations*. This leads to the following observation equations:

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{h} \end{bmatrix} + \begin{bmatrix} \mathbf{v}_y \\ \mathbf{v}_h \end{bmatrix} = \begin{bmatrix} \mathbf{A} \\ \mathbf{H} \end{bmatrix} \hat{\mathbf{p}} \quad \text{with} \quad D\left(\begin{bmatrix} \mathbf{y} \\ \mathbf{h} \end{bmatrix}\right) = \sigma^2 \begin{bmatrix} \mathbf{P}^{-1} & \emptyset \\ \emptyset & \mathbf{P}_h^{-1} \end{bmatrix}$$

or to the associated NEQ system

$$(\mathbf{A}^T \mathbf{P} \mathbf{A} + \mathbf{H}^T \mathbf{P}_h \mathbf{H}) \hat{\mathbf{p}} = \mathbf{A}^T \mathbf{P} \mathbf{y} + \mathbf{H}^T \mathbf{P}_h \mathbf{h} .$$

The equation above shows that by adding the terms $\mathbf{H}^T \mathbf{P}_h \mathbf{H}$ and $\mathbf{H}^T \mathbf{P}_h \mathbf{h}$ to the original NEQ system, a priori information is introduced.

Constraints may be introduced in GPSEST and ADDNEQ2 for the following parameter types:

- coordinates: absolute constraints (station constraining), station fixing, free network constraints (in ADDNEQ2 only), relative constraints (between stations, in ADDNEQ2 only),
- velocities: absolute and relative (concerning sites) constraints (in ADDNEQ2 only), relative constraints (between stations, in ADDNEQ2 only),
- kinematic coordinates: absolute constraints with respect to the a priori trajectory,
- troposphere: absolute and relative (in time) constraints for zenith path delays and gradient parameters,
- global ionosphere models: absolute and relative constraints between model coefficients and single-layer height parameters,
- stochastic ionosphere parameters: absolute and relative (in time) constraints,
- orbit: absolute constraints for Keplerian elements and for dynamical and stochastic parameters,
- geocenter coordinates: absolute constraints,
- Earth orientation parameters: absolute constraints (UT1 and first value of a nutation parameter sequence have to be constrained to VLBI-based values in GPSEST or to at least one VLBI-based value in ADDNEQ2 when using piecewise linear parametrization) and continuity constraints (in GPSEST only), see also Chapter 16,
- reference clock if receiver and satellite clock corrections are estimated as well as related biases (DCB, ISB, and IFB for GLONASS) by zero-mean condition and/or absolute constraints,
- receiver and satellite antenna offsets and patterns or laser array offsets: absolute constraints,
- scaling factors for non-tidal loading displacement models and higher-order ionosphere corrections: absolute constraints to one (taking into account the full model or corrections) or absolute constraints to zero (neglecting the model or corrections), only in ADDNEQ2,
- SLR range biases: absolute constraints for station and/or satellite parameters,
- various constraining options for GNSS-specific translation parameters.

Constraints are always applied *after* saving normal equation files in the Bernese NEQ file or SINEX format. Therefore, whatever constraints were defined in GPSEST or in a previous run of ADDNEQ2, new constraints for the current solution have to be defined in the program ADDNEQ2 if needed.

Next the implementation of parameter constraining in the *Bernese GNSS Software* shall be discussed.

7.5.1. Absolute Constraining

Any parameter may be constrained to its a priori value by constraining the parameter improvement to zero (*absolute constraint*) using the fictitious observation in the form

$$p_i = 0 .$$

Such a fictitious observation has the weight

$$P_i = \frac{\sigma_0^2}{\sigma_i^2} ,$$

where both σ_0^2 (a priori variance of unit weight, option “A priori sigma” in panel “GPSEST 3.1: General Options 1”) and σ_i^2 are input parameters of the program. This type of constraining is used for many purposes, e.g., for UT1–UTC estimates at the starting epoch where it is “almost mandatory”.

The situation is slightly more complicated when *ellipsoidal coordinates* shall be constrained. The reason for constraining ellipsoidal coordinates rather than rectangular coordinates might be, e.g., the different accuracy of the a priori horizontal and vertical coordinates. The ellipsoidal coordinates might be fixed using the fictitious observation

$$\mathbf{H}\mathbf{p} = \mathbf{0} ,$$

where \mathbf{H} is the Jacobi matrix of the transformation between a rectangular and ellipsoidal coordinate system:

$$\mathbf{H} = \begin{pmatrix} \frac{\partial\varphi}{\partial x} & \frac{\partial\varphi}{\partial y} & \frac{\partial\varphi}{\partial z} \\ \frac{\partial\lambda}{\partial x} & \frac{\partial\lambda}{\partial y} & \frac{\partial\lambda}{\partial z} \\ \frac{\partial h}{\partial x} & \frac{\partial h}{\partial y} & \frac{\partial h}{\partial z} \end{pmatrix} .$$

For the computation of the matrix \mathbf{H} the spherical approximation is sufficient.

7.5.2. Relative Constraining

It is also possible to constrain (the improvements of) two parameters i and j with respect to each other (*relative constraints*) using the fictitious observation

$$p_i - p_j = 0$$

with a specific weight P_{ij} . Ellipsoidal coordinates of two stations can be constrained as well:

$$\mathbf{H}_i \mathbf{p}_i - \mathbf{H}_j \mathbf{p}_j = \mathbf{0} .$$

Using GPSEST relative constraining is possible for troposphere zenith path delay and gradient parameters as well as for stochastic ionosphere parameters. The program ADDNEQ2 additionally supports relative constraining of station coordinates and station velocities (see Section 9.3.7).

7.5.3. Zero–Mean Condition

Another type of constraints available in the *Bernese GNSS Software* is the zero–mean condition of the estimated improvements for a group ($m \dots n$) of parameters:

$$\sum_{i=m}^n p_i = 0 .$$

Zero–mean conditions may be selected by the user in GPSEST for realizing an ensemble of reference clocks, for instance (see Section 15.2.3). In some cases a zero–mean condition is applied automatically (e.g., for inter–system bias and inter–frequency bias parameters in GPSEST and ADDNEQ2, see Chapter 15).

7.5.4. Fixing of Parameters

Parameters may also be fixed. In GPSEST this is possible for station coordinates (e.g., reference stations). Parameters to be fixed are not set up in the NEQ resulting from the GPSEST run. In ADDNEQ2 these parameters are fixed to their a priori value and then deleted. Fixed parameters are removed from the normal equation system in ADDNEQ2. There is no way to “unfix” parameters nor to recover the parameters at a later stage. Fixing parameters should, therefore, be avoided if the NEQ is stored for further use. This is particularly true for fixing station coordinates in GPSEST. If coordinates are fixed, the datum definition can no longer be modified at the normal equation level. For any further applications and manipulations in ADDNEQ2 it is thus strongly recommended to tightly constrain parameters in GPSEST (when they have to be) rather than fixing them. On the other hand, it can be advantageous to remove parameters in ADDNEQ2 instead of tightly constraining them. First, no correction can be obtained for a parameter if its constraint is not tight enough. Second, the normal equation that must be inverted to compute the solution becomes smaller reducing the CPU time.

7.6. Types of Parametrization

The list of adjustable parameters implemented in GPSEST is given in Table 1.1. Within the following chapters the estimation of the different parameters will be discussed. The parametrization as a function of time may have one of the following three forms:

1. A parameter may be *constant* for the entire session.
This is, e.g., the case for station coordinates in GPSEST (not necessarily in ADDNEQ2), geocenter coordinates, scaling factors, antenna calibration parameters, dynamical orbital parameters, and bias parameters.
2. A parameter may be represented as a *piecewise linear* function.
This parametrization corresponds to a continuous polygon in time which is particularly beneficial to establish continuity in parameter series without applying any constraint. Troposphere parameters and ionosphere parameters are parametrized in this way. EOPs are represented in GPSEST by offsets and drifts. A continuity condition may, however, be applied between adjacent parameter sets. EOPs may be transformed to a piecewise linear representation in ADDNEQ2.

3. a) Parameters may be valid for a *single observation epoch* only. Clock corrections or kinematic coordinates are examples for this type of parametrization.
- b) Parameters (pulses) may be valid only for *an infinitesimal epoch*. This kind of parameters is used to apply pseudo-stochastic pulses (instantaneous velocity changes at particular epochs in three directions) to satellite orbits.

In this respect phase ambiguities are special as they are represented as constant parameters but they are only valid until the next ambiguity parameter for the respective combination of station and satellite becomes valid. Some constant parameters, such as satellite antenna offsets, may be set up several times within a long-term solution series and are thus modeled as piecewise constant (non-continuous).

7.6.1. Piecewise Linear Parameters

A piecewise linear parameter x is modeled in each particular time interval $[t_1, t_2]$ by a linear function according to one of the two representations shown in Figure 7.2. Both types of parametrization

$$\tilde{\mathbf{x}} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad \text{and} \quad \mathbf{x} = \begin{pmatrix} x_1 \\ \frac{dx}{dt} \end{pmatrix}$$

are equivalent. For the transition between these two parameter sets we may use the following transformation equation

$$\mathbf{x} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix} \cdot \tilde{\mathbf{x}} = \mathbf{C} \tilde{\mathbf{x}} .$$

In the *Bernese GNSS Software* we use the first parametrization and piecewise linear parameters are defined by their values at equidistant nodal points (except for ERPs in GPSEST). The nodal points t_i are defined by a time offset from the beginning of the session and by a time interval. The time offset, which is common for all piecewise linear parameters, is specified in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” using the option “Time offset for Parameter intervals”. The value is specified in hours, minutes, and seconds and refers to the beginning of the session. The parameter spacing can be defined individually for all piecewise linear parameters.

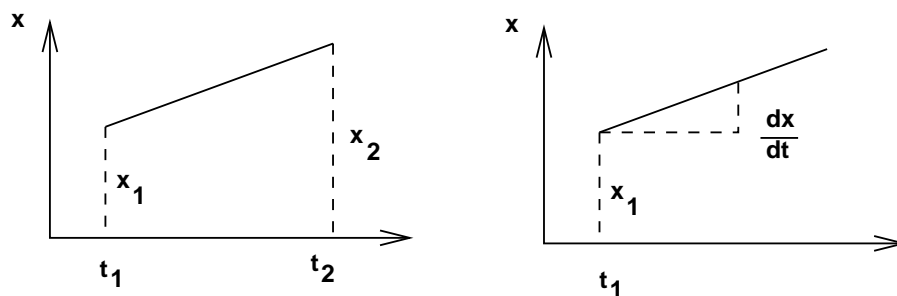


Figure 7.2.: Modeling of time-dependent parameters by x_1, x_2 resp. x_1, \dot{x}_1 .

Note that nodal points of the parametrization have to coincide as soon as you want to combine such parameters in program ADDNEQ2. It is, thus, necessary to carefully plan the setup of a parameter. (see Chapter 9 for more details on stacking of piecewise linear parameters).

7.6.2. Epoch-Parameters

Epoch-parameters are valid only for one individual epoch. Examples are satellite and receiver clock corrections, kinematic station coordinates, and stochastic ionosphere parameters. Due to their large number it is not beneficial to keep these parameters in one NEQ to be inverted together with all other parameters of interest (even if it is possible with GPSEST). It is more efficient to set up only those parameters that are relevant for the epoch that is currently processed and to pre-eliminate the epoch-parameters immediately when all measurements of the particular epoch are analyzed (see Section 7.7.1). This is possible because epoch-parameters are, by definition, not directly correlated (physical correlations are neglected). The correlations exist only between non-epoch parameters.

In the *Bernese GNSS Software* Version 5.2 all epoch-parameters, namely stochastic ionosphere parameters, clock parameters, and kinematic coordinates may be recovered in a back-substitution step after solving the main NEQ system in order to write the output file(s), see Section 7.7.2 for more information. The back-substitution of stochastic ionosphere parameters, however, is limited in that sense that they have to be pre-eliminated for every epoch. Thus, they are only implicitly included in the solution but not written into the output file.

The option “Sampling rate for preelimination” in panel “GPSEST 6.7: General Options for Epoch Parameters” allows to keep a few epoch parameters in the main NEQ. They are not part of the epoch-wise pre-elimination and back-substitution procedure even if the parameter type is indicated with EVERY_EPOCH. This allows to transfer these parameters into a NEQ file, e.g., for clock parameters. This feature is useful if clock parameters together with ISB and/or IFB parameters shall be estimated in clusters because of a large number of stations. To establish consistency between these clusters, not only the bias parameters but also the satellite clock parameters need to be combined in the program ADDNEQ2. For this purpose a limited number of epochs (e.g., hourly epochs) is sufficient.

All observations, which are selected with the features explained in Section 7.3, are processed and contribute to the epoch-wise pre-eliminated parameters. In some cases it might be interesting to use a reduced sampling for the back-substitution. This can be realized with the option “Sampling rate for resubstitution”. The back-substitution step can also be limited to the phase measurements by enabling the option “Epoch parameters only from phase”. Both options can be found in “GPSEST 6.7: General Options for Epoch Parameters”.

7.7. Parameter Operations

7.7.1. Pre-Elimination of Parameters

The pre-elimination of parameters is a basic procedure to reduce the dimension of the NEQ system without losing any information (apart from the estimates of the pre-eliminated parameters). Assume that the parameters are ordered in such a way that

the parameters \mathbf{p}_2 , which shall be pre-eliminated, are located at the end of the parameter array:

$$\begin{bmatrix} \mathbf{N}_{11} & \mathbf{N}_{21}^T \\ \mathbf{N}_{21} & \mathbf{N}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{bmatrix}. \quad (7.9)$$

We may invert the second set of equations for \mathbf{p}_2

$$\mathbf{p}_2 = \mathbf{N}_{22}^{-1}(\mathbf{b}_2 - \mathbf{N}_{21}\mathbf{p}_1)$$

and substitute \mathbf{p}_2 in the first set of equations in Eqn. (7.9). This leads to the new NEQ system for the parameter vector \mathbf{p}_1

$$(\mathbf{N}_{11} - \mathbf{N}_{21}^T \mathbf{N}_{22}^{-1} \mathbf{N}_{21}) \cdot \mathbf{p}_1 = (\mathbf{b}_1 - \mathbf{N}_{21}^T \mathbf{N}_{22}^{-1} \mathbf{b}_2).$$

The pre-elimination formulae thus basically compute the effect of the pre-eliminated parameters on the other (remaining) parameters of the NEQ system. As a result, the normal equation matrices (7.6) are modified. The results for the remaining parameters are the same as without pre-elimination. Hence, pre-elimination is *not* equivalent to canceling the corresponding lines and columns from the NEQs, i.e., fixing parameters as described in Section 7.5.4.

Pre-elimination of parameters is possible with both programs GPSEST and ADDNEQ2. Which parameters should be pre-eliminated is a question of processing time and disk space.

Before pre-elimination parameters may be constrained. Keep in mind that parameters that are pre-eliminated remain implicitly in the equation system. The constraints imposed on them are “frozen” and can no longer be changed. Therefore, constraints on parameters that are pre-eliminated have to be selected carefully.

The program GPSEST offers the following pre-elimination options (see panels “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” and “GPSEST 5.3: Parameter Setup of Experimental Parameters”):

EVERY_SESSION: The parameters are pre-eliminated after each session (or after each file if baseline-wise correlation is enabled). They neither appear in the result files nor in the output normal equation.

PRIOR_TO_NEQ_SAVING: The parameters are pre-eliminated before saving the normal equation. The parameters remain, however, in the solution provided by GPSEST, i.e., output files containing the parameters may be written.

EVERY_EPOCH: This option is only available for epoch parameters, i.e., for clock corrections, kinematic coordinates, and stochastic ionosphere parameters.

AS_SOON_AS_POSSIBLE: This option allows for pre-elimination of ambiguity parameters as soon as they are no longer used.

We refer also to the flow diagram of GPSEST in Figure 7.3 where the different pre-elimination options are included. ADDNEQ2 offers different options of pre-elimination originating from the NEQ stacking and manipulation options (see Section 9.4.3).

7.7.2. Back-Substitution of Epoch-Parameters

Epoch-parameters are generally set up and pre-eliminated epoch-wise due to their potentially large number. In order to obtain a solution for these parameters a back-substitution

step is necessary. This procedure is implemented in GPSEST of the *Bernese GNSS Software* Version 5.2 for clock parameters, ionosphere stochastic parameters, and kinematic station coordinates. After having solved the main NEQ, the resulting non-epoch parameters are inserted back into the observation equations which are successively solved for each epoch. For this purpose, parts of the observation equation are stored in a scratch file when the epoch is processed including the corresponding clock parameters or kinematic coordinates.

The program GPSEST offers two options for recovering the variance-covariance information concerning epoch parameters, see option “Var-covar wrt epoch parameters” in panel “GPSEST 6.7: General Options for Epoch Parameters” (see Figure 8.5). By using the option CORRECT the variance-covariance information is correctly recovered by including the corresponding information for the non-epoch parameters.

The NEQ for the parameter vectors \mathbf{p}_i with $i = 1, \dots, n$ may be written in the following way if \mathbf{p}_1 denotes the non-epoch parameters and \mathbf{p}_i denotes the parameters valid for epochs $i = 2, \dots, n$:

$$\mathbf{N} = \begin{pmatrix} \mathbf{N}_{11} & \mathbf{N}_{12} & \mathbf{N}_{13} & \dots & \mathbf{N}_{1n} \\ \mathbf{N}_{21} & \mathbf{N}_{22} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{N}_{31} & \mathbf{0} & \mathbf{N}_{33} & \dots & \mathbf{0} \\ \dots & \dots & \dots & \dots & \dots \\ \mathbf{N}_{n1} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{N}_{nn} \end{pmatrix} .$$

Taking advantage of the fact that all off-diagonal matrix blocks referring to two epoch parameters are zero, the block \mathbf{Q}_{ii} , which refers to epoch parameters \mathbf{p}_i in the inverted normal equation, can be written as

$$\mathbf{Q}_{ii} = \mathbf{N}_{ii}^{-1} + \mathbf{N}_{ii}^{-1} \mathbf{N}_{i1} \mathbf{Q}_{11} \mathbf{N}_{1i} \mathbf{N}_{ii}^{-1} \quad \text{for } i = 2, \dots, n \quad (7.10)$$

where \mathbf{Q}_{11} is the inverted normal equation matrix block of the non-epoch parameters. The multiplication with the variance factor gives the variance-covariance information for the epoch parameter i .

With the option SIMPLIFIED only the variance information of the epoch parameters are considered:

$$\mathbf{Q}_{ii} \simeq \mathbf{N}_{ii}^{-1} .$$

This implies that the statistical errors of the non-epoch parameters are ignored for the computation of the variance-covariance information of the epoch-parameters. Their error information will, therefore, be too optimistic. When selecting this option it has to be considered, however, that the computation of the errors according to Eqn. (7.10) may be very CPU time- and memory-intensive. It has to be stated clearly that the option for computing the variance-covariance information has no impact on the estimated *values* of the epoch parameters. Only the reported formal errors are affected. Due to the resulting unrealistic formal errors it is strongly suggested to apply a priori scaling of normalized residuals (option NORM_APRIORI in “Type of computed residuals” in panel “GPSEST 3.1: General Options 1”, see Section 7.4.4) whenever the epoch parameters are pre-eliminated epoch-wise.

To perform the back-substitution step in an efficient way, all observations contributing to the parameters of one epoch have to be available in one batch in the scratch file. This is only guaranteed if the option “Correlation strategy” in panel “GPSEST 3.1: General Options 1”

is set to `CORRECT`. In Section 7.4.5 you can find a more detailed discussion of this option. Depending on the number of stations and on the sampling rate, the binary scratch file may become large. It is stored by default in the user-specific directory `#{U}/WORK` for which sufficient disk space should be available.

7.8. Flow Diagram of Program GPSEST

Figure 7.3 shows the flow diagram of the actions performed by the program GPSEST. The core of the program is (1) the loop over all epochs in which the observations are read, the partials are computed and the normal equation is accumulated and (2) the inversion of the normal equation and the computation of the solution. The diagram indicates where the parameter pre-elimination of different types take place.

By choosing the option “Stop program after NEQ saving” in panel “GPSEST 3.2: General Options 2”, only the NEQ file is set up and stored without inverting the NEQ. When this feature is enabled the section between “solve normal equation” and “save result files” in Figure 7.3 is skipped. Because no results for the parameters are estimated, the solution has to be generated later on in the program `ADDNEQ2`. This option is in particular useful to save CPU time for the inversion of the NEQ if only the solution generated by `ADDNEQ2` is relevant. It also allows also to generate weakly defined NEQs or even NEQs having a negative degree of freedom (i.e., the number of estimated parameters is larger than the number of observations). This kind of NEQs become only reliably solvable after manipulating the NEQs in `ADDNEQ2`.

Memory Allocation

GPSEST reads the input options and some information from the input files and adjusts the size of the main arrays to the expected needs of the current tasks. In this way the memory occupied by the program during run-time can be limited to a minimum.

At the same time, the module `#{I}/P_GPSEST.f90` contains the so-called default settings for the expected size of the arrays. As long as the adjusted size is smaller than the default size, the adjusted size is used to allocate the memory for the program run. If the adjusted size exceeds the default size a warning message is issued pointing out that the current setup is considered as an “extreme task” that might need more CPU-time. If this repeats on a regular basis you might consider a reorganization of your work flow (e.g., by pre-elimination of parameters). Nevertheless, the task is executed using the adjusted size of the arrays. Only when the adjusted size becomes twice as large as the default size the program stops with an error. This is done to avoid unintentional program runs (a large number of epoch parameters is not pre-eliminated epoch-wise, for instance). With the extended printing option “Printing: Statistics on parameter dimensions” (see Section 7.9.1), a comparison between adjusted values and default values can be included in the program output.

The following parameters are considered for the procedure because they are crucial for the largest arrays used by GPSEST:

MAXLOC: Maximum number of parameters to be processed

Number of all parameters to be set up. In the case of epoch-wise pre-elimination only the epoch parameters from one epoch are counted.

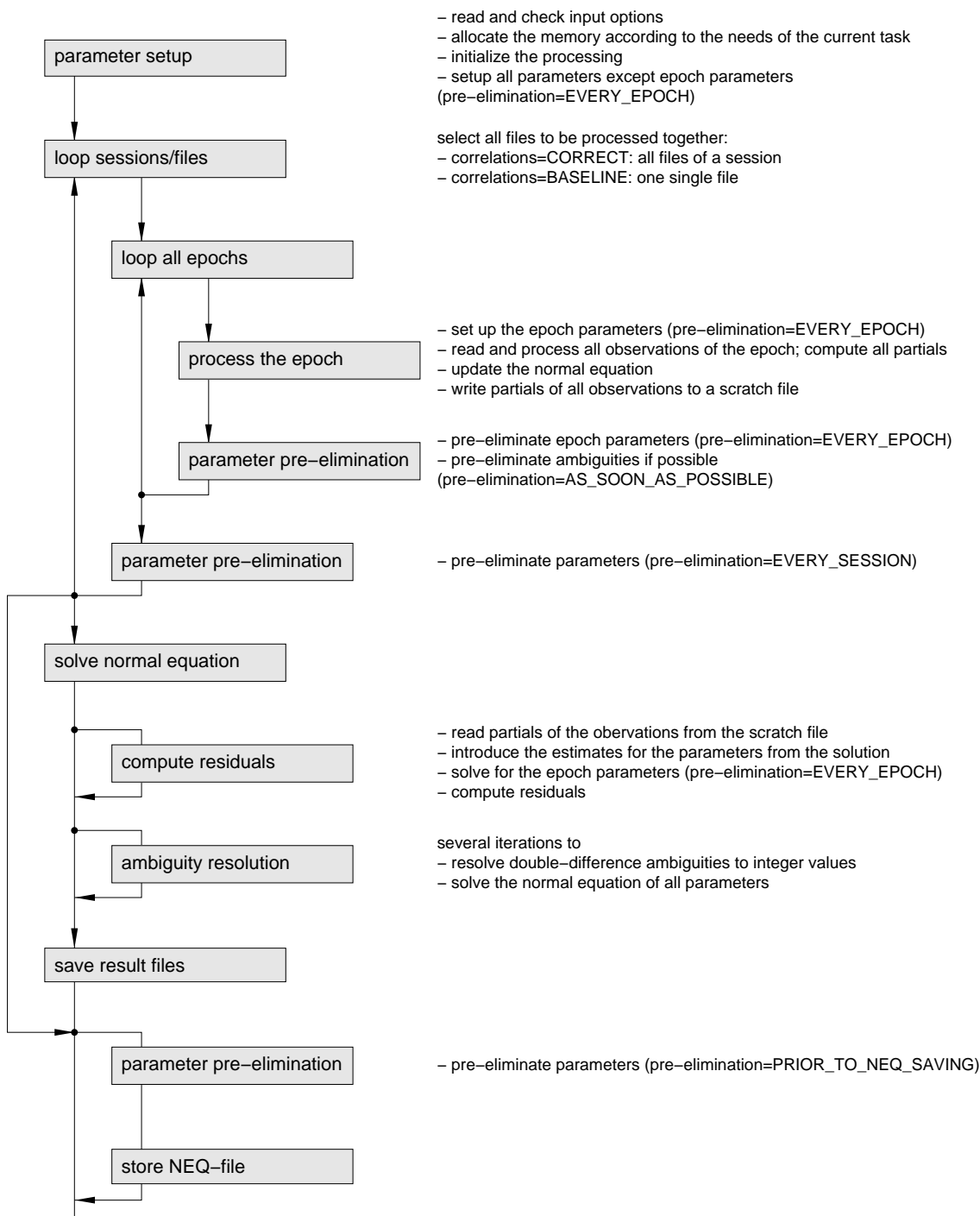


Figure 7.3.: Flow diagram of actions performed by the program GPSEST.

- MAXFIL:** Maximum number of files to be processed
Number of code and phase files selected either for zero or double difference processing.
- MAXSTA:** Maximum number of stations involved
Total number of stations considering all selected observation files.
- MAXSAT:** Maximum number of satellites involved
Total number of satellites considering all selected observation files irrespective of the selection for the option “Satellite system” in panel “GPSEST 3.1: General Options 1” .
- MAXAMB:** Maximum number of ambiguities in an observation file
- MAXPAR:** Maximum number of parameters simultaneously processed
Number of parameters that have to be hold in the design matrix at the same time. Parameters that are pre-eliminated `EVERY_SESSION` or `EVERY_EPOCH` give their position in the design matrix free when the next session or epoch is processed.
- MAXFLS:** Maximum number of files simultaneously processed
If the option “Correlation strategy” is set to `BASELINE` each observation file is processed individually. Otherwise all observation files that have the same session ID in the header are processed together.
- MAXSAS:** Maximum number of satellites simultaneously processed
The dimension has to account for the total number of satellites in the observation files that are processed together (according to the option “Correlation strategy”). The selection for the option “Satellite system” is considered.
- MAXAMP:** Maximum number of ambiguities simultaneously processed
Number of ambiguity parameters that have to be held in bookkeeping for the processing at the same time. Ambiguity parameters that are pre-eliminated `EVERY_SESSION` or `AS_SOON_AS_POSSIBLE` give their position in the design matrix free when the next session or epoch is processed.
- MAXSNG:** Maximum number of non-zero elements in one line of the first design matrix.

7.9. Program Output and Extraction Program

7.9.1. The Program Output

The program output of GPSEST includes all necessary information to document the run of the program such as the names of all input and output files, an echo of the most important user options, statistical information about observations and parameters as well as detailed results in an easy-to-read format.

The output is divided into 14 sections. The first 12 sections refer to the input data and to the a priori information. This first part includes (not a complete list)

- a list of all input and output file names including path specification,
- a list of observation files, station names, receiver names as well as the number of observations and a list of observed satellites for each input file,
- the selected cutoff angle, sampling rate, a priori RMS of unit weight, observation weighting scheme, ambiguity resolution strategy, etc,
- the a priori station coordinates, geodetic datum, selected specifications for datum definition,

- the satellite orbital elements and satellite problems in the processed session according to the satellite problem file,
- the selected a priori troposphere model, mapping functions, troposphere parameters set up for each station including imposed constraints,
- information about the selected ionosphere model, and
- pole information.

The results section is divided into two parts (PART 1 and PART 2) if ambiguities are resolved to integers. The first part gives the results before ambiguity resolution and the second part after ambiguity resolution. If no ambiguities are resolved only the first part is printed. The results section contains statistical information about the solution as well as detailed information about the estimated parameters. In particular, the improvement and formal errors are given also for those parameters that are not written to any output file. In a standard GPSEST network processing run you find the following information:

- A detailed statistics is provided for each type of estimated parameters, the number of parameters that are set up, pre-eliminated, or that turned out to be singular.
- The number of used observations is listed for each observation file.
- The a posteriori sigma of unit weight, converted to the one-way L_1 phase observable (at zenith in case of elevation-dependent weighting), together with the solution's degrees of freedom f and χ^2/f are printed.
- A priori coordinates and estimated coordinates for each station in geocentric and elliptical coordinates, coordinate improvements, RMS errors, and error ellipsoids are given (see Section 10.3.1 for more details).
- If ambiguities are resolved detailed information is provided for each ambiguity before and after the resolution to an integer as well as for each iteration.
- Information about troposphere zenith delay parameters and gradient parameters is provided (corrections and formal errors). For gradients zenith tilting angles and error ellipsoids are given.

In a successful GPSEST the a posteriori sigma of unit weight is expected to be in the order of 1.0 – 1.5 mm with elevation-dependent weighting and in the order of 2.0 – 2.5 mm without elevation dependent weighting for phase processing. Whereas for code observations a similar sigma is expected (because converted to L_1 phase), the sigma for smoothed code should be in the range of 0.2 – 0.3 mm.

Additional output information may be activated in panels “GPSEST 3.2.1.1: Extended Program Output Options” and “GPSEST 3.2.1.2: Extended Program Output Options”. These panels are active if the option “Enable extended program output” in panel “GPSEST 3.2: General Options 2” is activated. The special output refers to additional output concerning a priori information or to output that further details the estimated parameters. Among other data the additional output comprises

- a list of observations in the observation files and a list of observations used for processing,
- a table of satellite elevations as a function of time for the first station,
- a histogram of observations by elevation angle bin and by nadir angle bin,
- phase-connected time intervals, i.e., intervals really connected by overlapping ambiguity parameters may be displayed.

Independent whether these intervals are displayed in the program output or not they are used to constrain the reference ambiguity in case of a phase-only zero-difference solution,

- a detailed list of parameters set up along with their characterization,
- unresolved ambiguities after each iteration step,
- a list of resolved ambiguities from observation files,
- general constants, antenna phase center offsets, coefficients of the selected ionosphere model,
- station eccentricities, receiver and antenna names and numbers,
- receiver synchronization errors,
- Helmert transformation parameters of the estimated station coordinates with respect to the a priori coordinates (note: this is not a minimum constraint solution as available in ADDNEQ2),
- the RMS of ellipsoidal coordinates and differences,
- slope distances and their RMS, and
- statistics of the parameter dimensions related to the automated array allocation described in Section 7.8.

It is also possible to suppress the output of long lists of parameters that are either typically not of interest (e.g., ambiguity parameters) or that extend the output file simply due to their large number, e.g., epoch parameters such as kinematic coordinates or clock corrections. If no corresponding output files and no residual file are written, the option suppresses, in addition, the back-substitution of epoch parameters to save computing time.

7.9.2. The Output Extraction Program GPSXTR

The program GPSXTR may be used to extract information from the GPSEST (or also ADDNEQ2) output files and to generate different types of summary files (see the online help for more information as well as for output examples):

- The “Output summary” extracts the a posteriori RMS, the number of input files, observations, and parameters as well as the maximum correction in the semimajor axis if satellite orbit parameters are estimated.
- The “Coordinate summary” provides a processing quality check for baselines processed independently with GPSEST. For each baseline the number of observations and ambiguities, the a posteriori RMS, the length of the baseline as well as the correction of the baseline coordinates in height, north, east, and length.
- The “Kinematic summary” contains the kinematic coordinate estimates extracted from the GPSEST output file. It reports the difference between the estimated kinematic position and the a priori coordinates in north, east, and up components as a function of time. In addition, statistical information is provided.
- The “GIM summary” contains useful statistical information related to the estimated Global Ionosphere Model (GIM) such as latitude range coverage and mean, minimum, and maximum TEC values.
- “Clock summary: clock differences” extracts clock differences for pairs of receiver and/or satellite clocks from a GPSEST output containing clock correction estimates. The pairs of clocks are given as “Pairs of clocks for clock summary” in panel “GPSXTR 2: Output Files”. A baseline file is selected here to define the pairs of clocks to be reported in the summaries of “Clock summary: clock differences” and “Clock summary: Allan deviation”. More than one pair can be specified but both clocks must be provided in the same

GPSEST program output, because, in the general case, each individual GPSEST run may be based on an individual reference clock.

- “Clock summary: Allan deviation” extracts clock differences for pairs of receiver and/or satellite clocks from a GPSEST output containing clock correction estimates. Allan Deviations are computed and provided in the summary file. The pairs of clocks are given as “Pairs of clocks for clock summary” (see “Clock summary: clock differences”).
- To get an “Ambiguity res. summary”, select output files of GPSEST ambiguity resolution runs executed independently for each baseline. This summary contains information such as the number of ambiguities before resolution, the percentage of resolved ambiguities, and the solution RMS before and after ambiguity resolution or each baseline. This summary looks different for different ambiguity resolution strategies. Users can specify whether they want all GNSS systems summarized in one line (ALL), one line for each GNSS together with an overall summary (EACH), or a summary line printed for only one selected GNSS (i.e., GPS or GLONASS or GALILEO).
- In the separate “Ambiguity fractionals” summary file the fractional parts of the resolved ambiguities are listed for the QIF and SIGMA strategy.
- The one–line “Campaign summary” contains the solution RMS, the number of observations, parameters, stations, files as well as the maximum correction in the semimajor axis and pole parameters.
- The one–line “Weekly summary” contains the number of files, observations, parameters and the solution RMS.
- The “Pole output” contains estimated corrections for the EOPs estimated in GPSEST.

Concerning the program output of ADDNEQ2, the extraction program only provides the “Output summary”, the “GIM summary”, the “Campaign summary”, and the “Weekly summary”.

8. Initial Phase Ambiguities and Ambiguity Resolution

8.1. Motivation

According to the measurement principle, the initial phase ambiguity parameters in the original observation equations are integer numbers of cycles. Unfortunately, the equations contain several additional linear terms which cannot be separated unambiguously: receiver and satellite clock corrections, their hardware delays, and an initial phase shift between receiver and satellite. These numerous linear terms prevent direct access to the integer nature of the carrier phase ambiguities.

The equations (2.20c) and (2.20d) are simplified since the ambiguity term contains all these linear parameters. Consequently, the n_{Fk}^i are not integer anymore. As the implementation of the zero-difference processing follows exactly these equations, ambiguity resolution in the zero-difference case is not possible in the *Bernese GNSS Software*.

After differencing the observations between two stations and two satellites (double differenced observation), the clock corrections, hardware delays for receiver and satellite, as well as the initial phase shift term have canceled out or may be neglected. We then have again access to the integer nature of the initial phase ambiguities.

Technically, two steps are necessary: The initial phase ambiguity parameters have to be estimated as real-valued parameters in a first step. In a second step the ambiguities are resolved to their integer values. This means that (in our terminology) the correct integer numbers are assigned to the real-valued estimates. Let us introduce the following notation:

- \mathbf{p}_1 is the column array containing all non-ambiguity parameters,
- \mathbf{p}_1^0 are the corresponding a priori values,
- \mathbf{p}_2 is the column array containing all ambiguity parameters,
- \mathbf{p}_2^0 are the corresponding a priori values,
- $\bar{\mathbf{p}}_2^0$ are the corresponding known true (integer) numbers.

Moreover

- Ψ is the array containing the model function (terms “computed”),
- \mathbf{l} is the array containing all measurements (terms “observed”),
- \mathbf{y}, \mathbf{y}' are the arrays of reduced measurements (terms “observed — computed”),
- \mathbf{v}, \mathbf{v}' are the arrays containing the residuals.

Let us inspect the effect of introducing the known (integer valued) ambiguities into the normal equation system. In the case of the float solution we may write the observation equations in matrix form as

$$(\mathbf{A}_1, \mathbf{A}_2) \cdot \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \end{pmatrix} - \underbrace{(\mathbf{l} - \Psi(\mathbf{p}_1^0, \mathbf{p}_2^0))}_{\mathbf{y}} = \mathbf{v}$$

(\mathbf{A}_1 and \mathbf{A}_2 are the parts of the first design matrix corresponding to the non-ambiguity and ambiguity parameters, respectively). The corresponding system of normal equations is

$$\begin{pmatrix} \mathbf{N}_{11} & \mathbf{N}_{12} \\ \mathbf{N}_{21} & \mathbf{N}_{22} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{A}_1^T \mathbf{P} \mathbf{y} \\ \mathbf{A}_2^T \mathbf{P} \mathbf{y} \end{pmatrix} = \begin{pmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{pmatrix} \quad (8.1)$$

(\mathbf{P} is the weight matrix). Eliminating \mathbf{p}_2 from Eqn. (8.1) we obtain

$$(\mathbf{N}_{11} - \mathbf{N}_{12} \mathbf{N}_{22}^{-1} \mathbf{N}_{21}) \cdot \mathbf{p}_1 = \mathbf{b}_1 - \mathbf{N}_{12} \mathbf{N}_{22}^{-1} \mathbf{b}_2 .$$

Assuming that the ambiguity parameters are known we may write

$$\mathbf{A}_1 \mathbf{p}_1 - \underbrace{(\mathbf{l} - \Psi(\mathbf{p}_1^0, \bar{\mathbf{p}}_2))}_{\mathbf{y}'},$$

which gives

$$\mathbf{N}_{11} \mathbf{p}_1 = \mathbf{A}_1^T \mathbf{P} \mathbf{y}' = \mathbf{b}'_1 .$$

We may write

$$\mathbf{y} - \mathbf{y}' = \Psi(\mathbf{p}_1^0, \bar{\mathbf{p}}_2) - \Psi(\mathbf{p}_1^0, \mathbf{p}_2^0) = \mathbf{A}_2 \cdot (\bar{\mathbf{p}}_2 - \mathbf{p}_2^0) = \mathbf{A}_2 \cdot d\mathbf{p}_2$$

and therefore

$$\mathbf{N}_{11} \mathbf{p}_1 = \mathbf{A}_1^T \mathbf{P} \mathbf{y} - \mathbf{A}_1^T \mathbf{P} \mathbf{A}_2 \cdot d\mathbf{p}_2 . \quad (8.2)$$

This last equation shows how the normal equation system changes if the ambiguities have been resolved (fixed on their integer values). Fixing ambiguities considerably reduces the number of parameters and the solution will get much more stable. It should be pointed out, that usually the majority of unknown parameters actually are the ambiguities. How do the solutions improve if the ambiguities have been resolved? The answer depends strongly on the ratio between the number of unknown non-ambiguity parameters and the number of measurements which are used for the estimation of these parameters (the length of the observing sessions for static applications). Figure 8.1 shows the effect of ambiguity resolution if only the receiver coordinates and few troposphere parameters are estimated in a regional (European) network (for details see Mervart 1995). In this case the main effect may be seen for session length up to 4 hours.

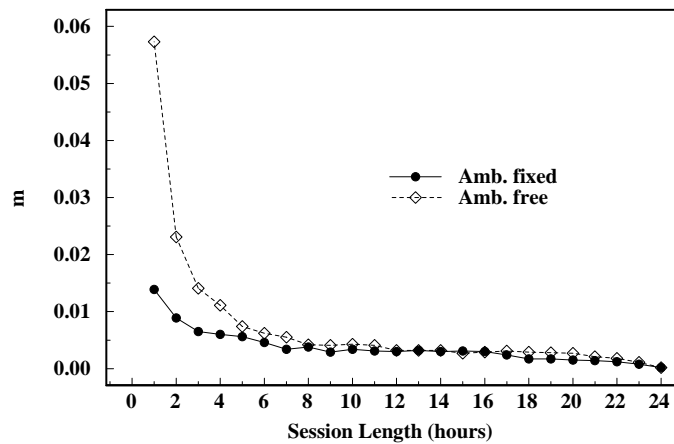


Figure 8.1.: RMS of a 7-parameter Helmert Transformation with respect to the “true” coordinate set.

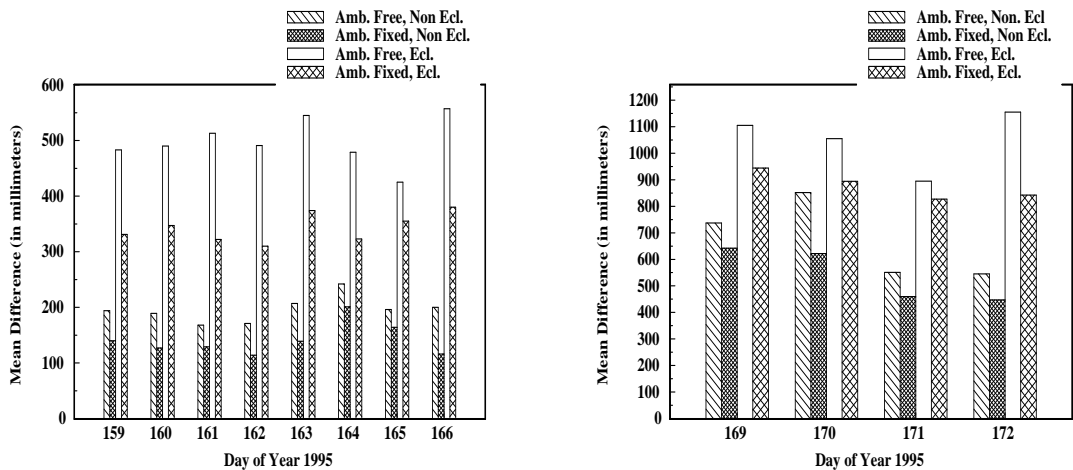


Figure 8.2.: Orbit quality estimated from discontinuities at day boundaries (eclipsing and non-eclipsing satellites).

However, the second important advantage of the ambiguity fixed solutions is the significantly reduced number of parameters which have to be solved for. A reduction of the normal equation to be inverted is important because usually a duplication of its size leads to a four time longer computing time for the inversion. If many parameters are estimated (orbits, Earth orientation parameters etc.) ambiguity resolution improves also the results of much longer sessions (3–days sessions used in CODE for IGS processing). Figure 8.2 shows the improvement in the estimated orbits (for details see Mervart et al. 1995): The ambiguity fixed solution is the official IGS CODE solution since June, 1995. For a long time, only the ambiguity for the measurements to GPS satellites have been resolved. Due to the FDMA technology the ambiguity resolution for GLONASS is not as easy. Nevertheless, since February 2011 also GLONASS ambiguities are resolved in the CODE solution for the IGS. Section 8.6 is dedicated to this feature of the *Bernese GNSS Software* Version 5.2 .

8.2. Theory

There are many methods how to resolve the ambiguities. Some of them are very sophisticated, some quite simple, but most of them consist of two steps:

- Step 1:** The ambiguities are estimated as real numbers together with other parameters.
Step 2: The integer values of the ambiguities are resolved using the results of Step 1 (the real-valued ambiguities and the variance–covariance matrix). Usually statistical tests are performed to resolve the ambiguities in a reliable way.

In the *Bernese GNSS Software* ambiguities may be resolved only if double–difference observations are processed. Single–difference (between receivers) ambiguities are then stored in the single–difference header files. For each session and each baseline we have to select one single–difference bias n_{Fkl}^j as reference and actually our estimated ambiguity parameters are the differences

$$n_{Fkl}^{ij} = n_{Fkl}^i - n_{Fkl}^j .$$

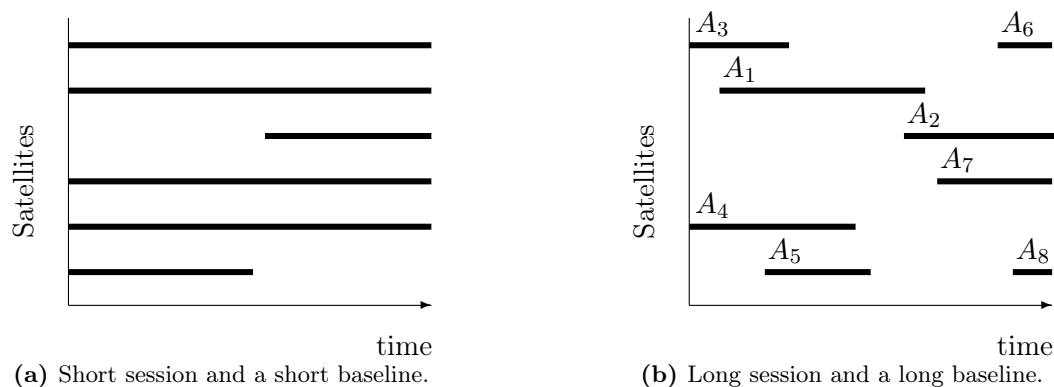


Figure 8.3.: Satellite visibility plot.

Usually, the ambiguity with the maximum number of observations is selected as reference. If there are N single-difference ambiguities for one session and one baseline, there are at most $N - 1$ linearly independent unknown ambiguity parameters. If there is an epoch when all the single-difference phase measurements were initialized again, the session breaks up into two parts and for each part one reference ambiguity *must* be selected. In that case only $N - 2$ ambiguity parameters may be estimated. The set of measurements corresponding to exactly one reference ambiguity, is called an *observation cluster* (different from an ambiguity cluster, see below). In the following we will assume to have only one observation cluster.

Figure 8.3a shows the satellite visibility plot for a short (several minutes) session. For short sessions there is usually one (or more) satellite(s) which was(were) observed all the time. One of these satellites may be selected as reference satellite (and the corresponding ambiguity as reference ambiguity). For longer sessions the situation is different:

- No satellite is observed during the entire session,
- there are periods during which only few satellites were observed, for very long baselines there may be even periods during which only one or two satellites were observed.

Typically, for long baselines and sessions we obtain a satellite visibility plot as in Figure 8.3b. In that case the program selects (single difference) ambiguity A_1 (maximum number of observations) as a reference. After the first ambiguity resolution step (real-valued ambiguities are estimated) a detailed inspection usually shows that the (double-difference) ambiguities $A_2 - A_1, A_6 - A_1, A_7 - A_1, A_8 - A_1$ have large a posteriori RMS errors. On the other hand, the parameters $A_3 - A_1, A_4 - A_1, A_5 - A_1$ have small RMS errors. This result is a consequence of the selection of the reference ambiguity. If A_2 would have been selected as reference the parameters $A_6 - A_2, A_7 - A_2, A_8 - A_2$ would have small a posteriori RMS errors and the parameters $A_1 - A_2, A_3 - A_2, A_4 - A_2, A_5 - A_2$ big ones. The following conclusions may be drawn:

- Depending on the selected reference, certain differences between single-difference ambiguities and the selected reference ambiguity are well defined, other differences have large a posteriori RMS errors.
- It is difficult to resolve *all* ambiguities if long sessions are processed because for each particular selection of a reference ambiguity some ambiguity parameters will have large a posteriori RMS errors.

These considerations seem to be of no importance nowadays with a full GPS constellation for forming the double-differences and about 10 satellites simultaneously in view. Never-

AMB	SAT	EPOCH	WLF	L1-AMBIG.	CLUS	L2-AMBIG.	CLUS	L5-AMBIG.	CLUS
1	1	1	1/1	681360.	69	530932.	69	0.	1
2	1	2843	1/1	0.	2	0.	2	0.	2
3	1	2879	1/1	0.	3	0.	3	0.	3
4	31	1	1/1	633381.	69	493546.	69	0.	4
5	31	1108	1/1	-145987.	69	-113753.	69	0.	5
6	31	2758	1/1	0.	6	0.	6	0.	6
..									
..									
..									
63	27	1	1/1	1551327.	69	1208828.	69	0.	81
67	16	1799	1/1	0.	67	0.	67	0.	86
68	16	2182	1/1	279589.	69	227907.	69	0.	87
69	2	1	1/1	1307750.	69	1019028.	69	0.	90
70	7	1	1/1	709357.	69	552748.	69	0.	93
71	5	1800	1/1	1334718.	69	1040042.	69	0.	97
72	6	1	1/1	1518492.	69	1183242.	69	0.	100

Figure 8.4.: Ambiguities stored in single-difference phase header file.

theless, the optimization is still relevant for reprocessing historical data or if ambiguities of new GNSS are resolved. The inter-system bias (ISB) for the phase measurements is by chance not an integer value. In consequence, no integer ambiguities between systems can be resolved. This means finally, that the ambiguity resolution has to be applied for each GNSS separately.

Assuming that n_{Fkl}^j denotes our reference ambiguity, we are therefore resolving either the double-difference ambiguity parameter

$$n_{Fkl}^{ij} = n_{Fkl}^i - n_{Fkl}^j \quad (8.3)$$

directly or the difference between two of these terms

$$n_{Fkl}^{ih} = n_{Fkl}^{ij} - n_{Fkl}^{hj} , \quad (8.4)$$

which, as a matter of fact, is a double-difference ambiguity again (now between the satellites i and h instead of the satellite pairs i/j and h/j).

Every possible double-difference ambiguity is covered by one of the two equations (8.3) or (8.4) and therefore any double-difference ambiguity may be to a candidate for resolution. The resolved ambiguities are saved in the observation header files. We resolve the double-difference ambiguities but for book-keeping reasons store single-difference ambiguities in the files. It does not make sense to state that a single-difference ambiguity is resolved without specifying the reference ambiguity. Therefore we introduce the term *ambiguity cluster*, which is the set of (single-difference) ambiguities which are resolved relative to each other.

In the single-difference observation files the L_1 , L_2 and L_5 ambiguities are stored. This actually is redundant because the L_5 ambiguity is nothing else but the plain difference between the L_1 and L_2 ambiguities. L_5 ambiguities are stored as well, because they may sometimes be resolved a priori, see the ambiguity resolution strategies below. Figure 8.4 shows the relevant part of a header file. Each ambiguity consists of an integer value (initialized to zero) accompanied by a cluster number. If two ambiguities refer to the same cluster number, this implies that they have been resolved relative to each other (see e.g., ambiguities 1, 4, and 5 in Figure 8.4). Any double-difference ambiguity derived from two single-difference ambiguities referring to the same cluster is then known.

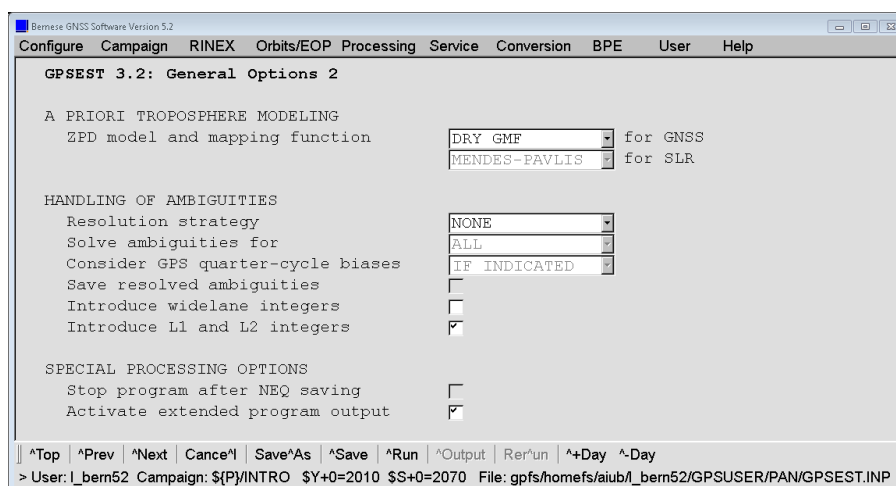


Figure 8.5.: Ambiguity resolution strategy selection for GPSEST.

8.3. Ambiguity Resolution Algorithms

There are four¹ ambiguity resolution strategies implemented in program GPSEST of the *Bernese GNSS Software Version 5.2*: ROUND, SIGMA, SEARCH, and QIF which may be selected in panel “GPSEST 3.2: General Options 2” (Figure 8.5). Different algorithms use different combinations of the L_1 and L_2 observations. Let us mention that for the QIF strategy, both L_1 and L_2 observations are required, that the SEARCH strategy leads to the best results also depending on observations on both frequencies, and that the remaining strategies ROUND and SIGMA work actually with one carrier (or one linear combination) only. It is possible to use two linear combinations in one run, but the ambiguity resolution is performed independently on both carriers. Which of these strategies is recommended for which solution will be discussed in Section 8.5.

Selecting the “Resolution strategy” NONE deactivates the ambiguity resolution. Note that the group of options related to the ambiguity resolution are only activated if phase baseline observation files are selected in the first panel of GPSEST.

If you have activated the option “Save resolved ambiguities” the resolved ambiguities are stored in the header of the observation files. If you mark option “Introduce L1 and L2 integers” or “Introduce widelane integers” in panel “GPSEST 3.2: General Options 2”, the ambiguities resolved in previous runs will be introduced as known values. All other ambiguities will be handled as unknown parameters and estimated — as are all ambiguities, if you do not mark the “Introduce widelane integers” or “Introduce L1 and L2 integers” options. All ambiguities to be estimated may or may not be pre-eliminated according to options in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”.

8.3.1. ROUND Algorithm

This is the simplest ambiguity resolution strategy which only rounds the real-valued estimates to the nearest integers, without using any variance-covariance information. Actually there is usually no need to use this strategy. The SIGMA strategy also works with

¹The fifth strategy LAMBDA is not yet supported even if it already appears on same places of the input panel (Schaer et al. 2010).

single frequencies only and leads to more reliable results. We do not recommend to use the strategy ROUND on baselines longer than a few kilometers. It is not a safe strategy.

8.3.2. SEARCH Algorithm

The SEARCH strategy is related to the so-called Fast Ambiguity Resolution Approach (FARA) algorithm (see Frei and Beutler 1990; Frei 1991). The following information from the initial least-squares adjustment is used:

- $\mathbf{p} = (p_1, \dots, p_u)^T$ the part of the solution vector consisting of all real-valued (double-difference) ambiguities, where u is the number of double-difference ambiguities,
- \mathbf{Q} the corresponding cofactor matrix, and
- σ_0^2 the a posteriori variance factor.

From the a posteriori variance factor and the corresponding cofactor matrix the standard deviation m_i for the ambiguity parameter p_i or the standard deviation m_{ij} for the difference p_{ij} between two ambiguity parameters p_i, p_j may be computed:

$$m_i = \sigma_0 \sqrt{Q_{ii}}, \quad m_{ij} = \sigma_0 \sqrt{Q_{ii} - 2 \cdot Q_{ij} + Q_{jj}}.$$

Choosing a confidence level α and assuming Student's t-distribution we compute the upper and lower range-width ξ for the integer valued alternative parameter p_{Ai} or for the difference p_{Aij} between two such parameters. Thus

$$p_i - \xi \cdot m_i \leq p_{Ai} \leq p_i + \xi \cdot m_i, \quad i = 1, 2, \dots, u \quad (8.5)$$

$$p_{ij} - \xi \cdot m_{ij} \leq p_{Aij} \leq p_{ij} + \xi \cdot m_{ij}, \quad i, j = 1, 2, \dots, u, \quad i \neq j. \quad (8.6)$$

All possible combinations of integer values which meet the conditions (8.5) and (8.6) are used to form alternative ambiguity vectors

$$\mathbf{p}_{Ah}, \quad h = 1, \dots, N$$

to the initial ambiguity estimate \mathbf{p} . These alternatives are generated in forming all possible combinations of vector components using the integer values within the corresponding confidence ranges. Each of these alternative vectors is introduced into a subsequent adjustment. The integer ambiguities are treated in these adjustments as known quantities. The resulting standard deviations

$$\sigma_h, \quad h = 1, \dots, N$$

are indicators for the success of the process: the integer vector \mathbf{p}_h yielding the smallest standard deviation is selected as the final solution, unless

1. its standard deviation is not compatible with the standard deviation σ_0 of the ambiguity-free solution (the fraction σ_h/σ_0 is too high), or
2. there is another vector \mathbf{p}_q yielding an almost identical standard deviation (fraction $\sigma_q/\sigma_h \approx 1$).

The maximum allowed fraction $(\sigma_h/\sigma_0)_{max}$ ("Maximum allowed RMS ratio re fixed to float") and the minimum discrimination fraction $(\sigma_q/\sigma_h)_{min}$ ("Minimum allowed RMS ratio re 2nd best to best") are input options in panel "GPSEST 3.2.2: General Search Ambiguity Resolution

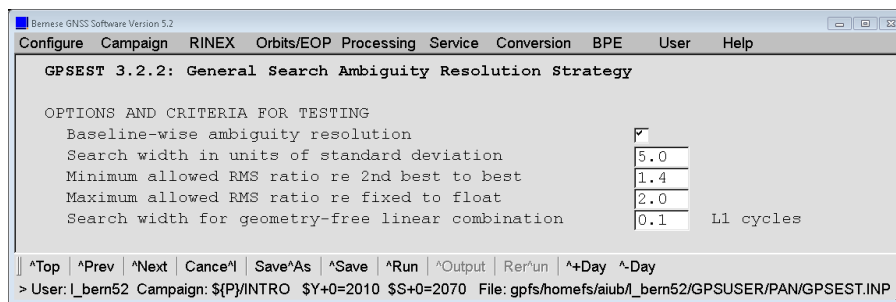


Figure 8.6.: Options for ambiguity resolution strategy SEARCH.

Strategy” (see Figure 8.6). In order to reduce the computation time and decrease the number of alternative vectors, one more condition is introduced if both frequencies (L_1 and L_2) are processed. Using the geometry-free linear combination (see Section 2.3), we may write

$$L_{4kl}^{ij} + I_{kl}^{ij} \left(1 - \frac{f_1^2}{f_2^2} \right) = \lambda_1 p_{1kl}^{ij} - \lambda_2 p_{2kl}^{ij}, \quad (8.7)$$

if the real-valued ambiguities p_{1kl}^{ij} , p_{2kl}^{ij} are taken into account. Instead of these real-valued ambiguities we may use the alternative (integer) values p_{A1kl}^{ij} , p_{A2kl}^{ij} to compute the right-hand side of Eqn. (8.7):

$$\lambda_1 p_{A1kl}^{ij} - \lambda_2 p_{A2kl}^{ij}.$$

The difference

$$| (\lambda_1 p_{1kl}^{ij} - \lambda_2 p_{2kl}^{ij}) - (\lambda_1 p_{A1kl}^{ij} - \lambda_2 p_{A2kl}^{ij}) |$$

is actually the difference between the ionosphere bias which was estimated during the initial ambiguity-free solution and the ionosphere bias which would be the result of the alternative ambiguity-fixed solution. The difference has to be very small (see option “Search width for geometry-free linear combination (L1 cycles)” in panel “GPSEST 3.2.2: General Search Ambiguity Resolution Strategy”).

It is almost mandatory to use the SEARCH strategy in rapid static mode. If both frequencies are available (L_1 and L_2 measurements are processed), usually several minutes of data are sufficient to resolve the ambiguities and achieve an accuracy of about one centimeter. If only one frequency is processed, the observation interval has to be longer (usually about 30 minutes of data are sufficient). In rapid static mode usually only short (up to several kilometers) baselines are processed.

The disadvantage of the SEARCH strategy has to be seen in the fact, that either all the ambiguities or none are resolved. This may cause problems if long sessions are processed and/or very long baselines are involved (see Figure 8.3b).

8.3.3. SIGMA-Dependent Algorithm

Let p_i , p_j be two (double-difference) ambiguity parameters (relative to the same reference ambiguity). For each parameter p_i we compute the a posteriori RMS error in the initial least-squares adjustment:

$$m_i = \sigma_0 \sqrt{Q_{ii}},$$

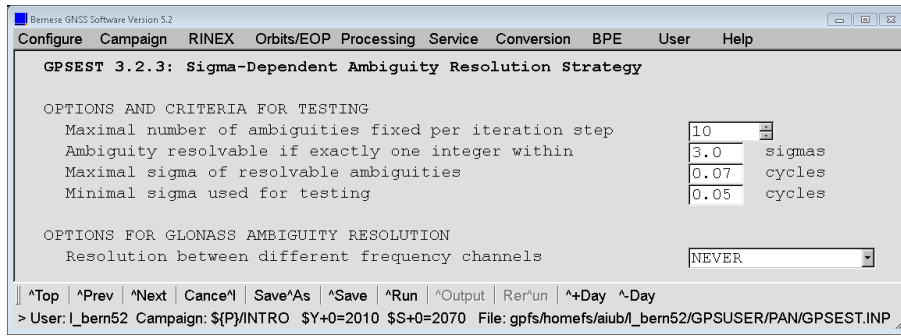


Figure 8.7.: Options for ambiguity resolution strategy SIGMA.

where Q_{ii} is the corresponding element of the cofactor matrix. For the difference $p_i - p_j$ the a posteriori RMS error is

$$m_{ij} = \sigma_0 \sqrt{Q_{ii} - 2 \cdot Q_{ij} + Q_{jj}}.$$

The RMS errors m_i and m_{ij} of every possible double-difference ambiguity (see Eqn. (8.3) and (8.4)) are first sorted in ascending order of their RMS errors. Within one iteration step the N_{max} best determined ambiguities (or differences between ambiguities) are then resolved (rounded to nearest integers), provided

- that the corresponding a posteriori RMS error m_i, m_{ij} is compatible with σ_0 ($m_i \leq \sigma_{max}$ or $m_{ij} \leq \sigma_{max}$), and
- that within the confidence interval $(p_i - \xi m_i, p_i + \xi m_i)$ or $(p_{ij} - \xi m_{ij}, p_{ij} + \xi m_{ij})$ there is exactly one integer number.

N_{max} (“Maximal number of ambiguities fixed per iteration step”), σ_{max} (“Maximal sigma of a resolvable ambiguity”) and ξ (“Ambiguity resolvable if exactly one integer within”) are input parameters of the program GPSEST (panel “GPSEST 3.2.3: Sigma-Dependent Ambiguity Resolution Strategy”, displayed in Figure 8.7). In the next iteration step the integer values are introduced for the resolved ambiguities and for the resolved differences between ambiguities (see Eqn. (8.2)). The iteration process is terminated, if:

1. all ambiguities have been resolved, or if
2. in the last step no additional ambiguity could be resolved based on the above criteria.

The iteration process described above may be applied to every linear combination. It may be used in the baseline mode, in the session mode, or even if several sessions are treated in the same program run. We recommend to use this strategy in two cases:

1. Only single-frequency measurements are processed, but the session is long (several hours). The baselines should not be too long (less than 20 km).
2. High quality code measurements are available on both frequencies. In this case it is possible to use the Melbourne–Wübbena linear combination and the corresponding strategy (see Section 8.5). The baselines may be very long (up to several thousand kilometers). The sessions have to be long, too (several hours).

8.3.4. QIF Algorithm

8.3.4.1. Theory of Quasi-Ionosphere-Free (QIF) Strategy

We start from the observation equations for double-difference phase measurements (2.21c) and (2.21d) but do not explicitly write the receiver and satellite indices k, ℓ, i, j

$$\begin{aligned} L_1 &= \varrho + T - I + \lambda_1 n_1 \\ L_2 &= \varrho + T - \frac{f_1^2}{f_2^2} \cdot I + \lambda_2 n_2 \end{aligned}$$

The corresponding equation for the ionosphere-free linear combination may thus be written as

$$L_3 = \varrho + T + B_3 = \varrho + T + \frac{c}{f_1^2 - f_2^2} (f_1 n_1 - f_2 n_2) .$$

The initial least-squares adjustment using both frequencies L_1 and L_2 gives real-valued ambiguity estimates b_1 and b_2 and we may compute the corresponding ionosphere-free bias \tilde{B}_3 as

$$\tilde{B}_3 = \frac{c}{f_1^2 - f_2^2} (f_1 b_1 - f_2 b_2) .$$

This bias may be expressed in narrow-lane cycles (one cycle corresponding to a wavelength of $\lambda_3 = c/(f_1 + f_2) \approx 11$ cm, see Section 2.3):

$$\begin{aligned} \tilde{b}_3 &= \frac{\tilde{B}_3}{\lambda_3} = \tilde{B}_3 \cdot \frac{f_1 + f_2}{c} = \frac{f_1}{f_1 - f_2} b_1 - \frac{f_2}{f_1 - f_2} b_2 \\ &= \beta_1 b_1 + \beta_2 b_2 . \end{aligned}$$

Denoting the correct (resolved) integer ambiguity values by n_{1p} and n_{2q} and introducing the associated L_3 -bias

$$b_{3pq} = \beta_1 n_{1p} + \beta_2 n_{2q}$$

we may use the difference between the real-valued and integer L_3 -bias

$$d_{3pq} = |\tilde{b}_3 - b_{3pq}| \quad (8.8)$$

as a criterion for the selection of the “best” pair of integers n_{1p}, n_{2q} . However, many pairs n_{1p}, n_{2q} give differences d_{3pq} of the same (small) order of magnitude. These pairs lie on a narrow band in the (n_1, n_2) space. The equation for the center line of this band is

$$\beta_1 n_{1p} + \beta_2 n_{2q} = \tilde{b}_3 . \quad (8.9)$$

The band-width is essentially given by the RMS of the bias \tilde{b}_3 . A unique solution only results if it is possible to limit the search range. The principle is shown in Figure 8.8. The solid line corresponding to Eqn. (8.9) passes through the real valued estimate (b_1, b_2) (shown as a small circle \circ in Figure 8.8) as well as through the point (n_{1p}, n_{2q}) which is accepted as “true” solution. This line represents an ionosphere-free combination (constant ionosphere-free bias). The second solid line in Figure 8.8 represents the constant wide-lane L_5 ambiguity (accepted as “true” value) and goes through the point (n_{1p}, n_{2jq}) , too. The dashed rectangle represents a search range in (n_1, n_2) space and the dashed trapezoid represents the corresponding search range in (n_1, n_5) space, see Eqn. (8.12).

8.3.4.2. The Role of the Ionosphere

For baselines longer than about 10 km separate processing of the two frequencies L_1 and L_2 does *not* result in sufficiently good initial real valued estimates b_1 and b_2 due to the influence of the ionospheric refraction. Two types of models to reduce the ionospheric biases are considered (see also Chapter 13):

1. **Satellite and Epoch Specific Ionosphere Estimation:** One ionospheric correction $I_k^i(t_j)$ for satellite i , receiver k and epoch t_j is estimated. Estimating these parameters without any a priori constraints would be equivalent to processing the ionosphere-free linear combination. If we want to resolve the integer ambiguities it is necessary to constrain these parameters to within a few decimeters. This constraining may be achieved by introducing an artificial observation

$$I_k^i(t_j) - I_{k,apr}^i(t_j) = 0 \quad (8.10)$$

for each epoch with a non-zero a priori weight. The actual values $I_{k,apr}^i(t_j)$ may stem from an ionosphere model, in many cases (baselines up to 500 km) even $I_{k,apr}^i(t_j) = 0$ may be sufficient. It is of course necessary to pre-eliminate all epoch-specific SIPs $I_{k,apr}^i(t_j)$, $i = 1, 2, \dots, n_s$ (n_s is the number of satellites per epoch) after having processed epoch t_j , because a huge number of parameters would have to be handled in the normal equation system after n_e epochs (see handling of epoch-parameters in GPSEST in Section 7.6.2).

2. **Deterministic Model:** Single-layer model developing the electron content within a layer of infinitesimal thickness at a height of about 450 km above the surface of the Earth into a series of harmonical coefficients in latitude and hour angle of the Sun. Such a model should be used if long baselines (500 km — 2000 km) are processed.

A combination of the two types of models may be used. Chapter 13 provides more information on both versions of ionosphere handling.

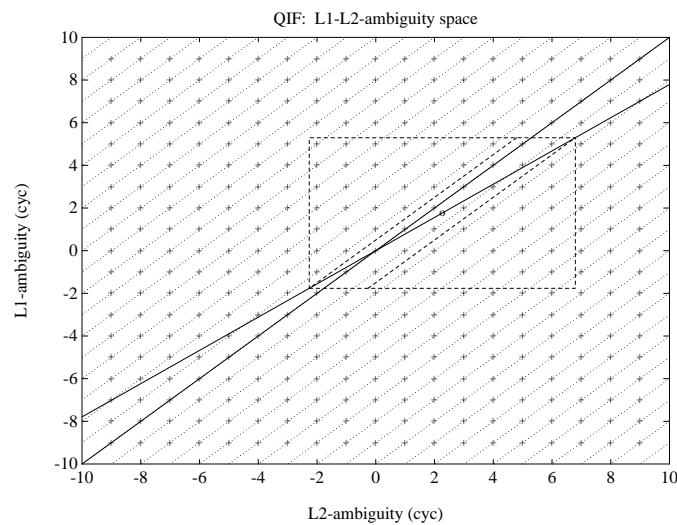


Figure 8.8.: Search ranges in (n_1, n_2) space.

8.3.4.3. Implementation of the QIF Strategy

Let us denote by b_{1p} , b_{1p_1} , b_{1p_2} the (real-valued) double difference L_1 ambiguities and by b_{2q} , b_{2q_1} and b_{2q_2} the corresponding L_2 ambiguities. Now, we check whether the pair

$$b_{1p}, \quad b_{2q}$$

or the pair

$$b_{1p_1} - b_{1p_2}, \quad b_{2q_1} - b_{2q_2},$$

which, as a matter of fact, is a pair of double-difference ambiguities again, meets the requirements to be close to integers and may be accepted as the correct pair of integer ambiguities. Let us explain the procedure in more detail. We compute the RMS error for each L_3 ambiguity bias \tilde{b}_3 associated with a pair b_{1p}, b_{2q} or with a pair of differences $b_{1p_1} - b_{1p_2}, b_{2q_1} - b_{2q_2}$:

$$\sigma = \sigma_0 \cdot \sqrt{\beta_1^2 Q_{11} + 2 \beta_1 \beta_2 Q_{12} + \beta_2^2 Q_{22}}, \quad (8.11)$$

where

$$Q_{11} = Q(b_{1p}, b_{1p}), \quad Q_{12} = Q(b_{1p}, b_{2q}), \quad Q_{22} = Q(b_{2q}, b_{2q})$$

in the case of a pair b_{1p}, b_{2q} ($Q(\dots)$ is an element of the cofactor matrix) or

$$\begin{aligned} Q_{11} &= Q(b_{1p_1}, b_{1p_2}) - 2 Q(b_{1p_1}, b_{1p_2}) + Q(b_{1p_1}, b_{1p_2}) \\ Q_{12} &= Q(b_{1p_1}, b_{2q_1}) - Q(b_{1p_1}, b_{2q_2}) - Q(b_{1p_2}, b_{2q_1}) + Q(b_{1p_2}, b_{2q_2}) \\ Q_{22} &= Q(b_{2q_1}, b_{2q_1}) - 2 Q(b_{2q_1}, b_{2q_2}) + Q(b_{2q_2}, b_{2q_2}) \end{aligned}$$

in the case of a pair of differences $b_{1p_1} - b_{1p_2}, b_{2q_1} - b_{2q_2}$. We sort the ambiguity pairs in ascending order of their σ -values. For the ambiguity pair (or pair of the differences) with the smallest σ (if this σ is lower than the specified σ_{\max} , option “Maximal sigma of resolvable NL ambiguities” in panel “GPSEST 3.2.4: Quasi-Ionosphere-Free Ambiguity Resolution Strategy”, Figure 8.9) we define the search ranges (option “Search width for pairs of L1 and L2 ambiguities”)

$$\begin{aligned} \tilde{n}_1 &= \text{NINT}(b_1) \pm i, \quad i = 0; 1; \dots; i_{\max} \\ \tilde{n}_5 &= \text{NINT}(b_1 - b_2) \pm k, \quad k = 0; 1; \dots; k_{\max} \\ \tilde{n}_2 &= \tilde{n}_1 - \tilde{n}_5 \end{aligned} \quad (8.12)$$

and for each pair \tilde{n}_1, \tilde{n}_2 of integers within the search range we compute the test value (8.8)

$$d_3 = |\beta_1 (b_1 - \tilde{n}_1) + \beta_2 (b_2 - \tilde{n}_2)|.$$

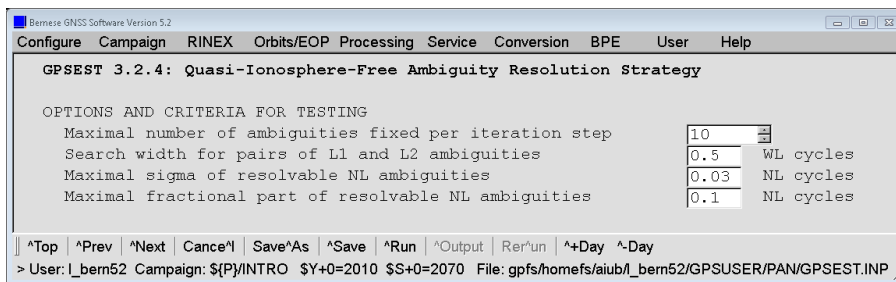


Figure 8.9.: Options for ambiguity resolution strategy QIF.

The pair associated with the smallest value d_3 is accepted as a potential solution, unless

$$d_3 \geq d_{\max} ,$$

where d_{\max} is a user-defined maximum value (option “Max. fractional part of resolvable NL ambiguity”). If no ambiguity set passed the test, we proceed to the next pair of ambiguities associated with the second smallest σ . After having accepted one pair the entire least-squares adjustment and the procedure described above are repeated. The ambiguities are thus resolved iteratively. All or only a subset of ambiguity pairs may be resolved in the iteration process.

8.4. GPS Quarter-Cycle Issue

In Eqn. (2.1) (Section 2.1.1.2) it is shown that the L_2 Civil code (L2C-code) is shifted by a quarter cycle with respect to the P-code. Consequently, if a receiver is using either the one or the other code to reconstruct the phase measurements, they will also be shifted by a quarter of a wavelength relative to each other.

The noise of phase measurements based on L2C-code may be expected to be lower than the noise of phase observations reconstructed based on P-code. For that reason, many receivers prefer the first choice. Unfortunately, this is only possible for GPS Block IIR-M and Block IIF satellites. Older GPS satellites (about half of the current constellation in September 2015) do not provide the L2C-code signal and thus the receivers have to track the phase based on P-code for those satellites.

When forming double differences according to Eqn. (2.21d) and mixing up the reference for the phase measurements from satellite i to satellite j , at one of the two stations k or ℓ the resulting double difference ambiguity $n_{2k\ell}^{ij}$ is not an integer anymore (but contaminated by nasty ± 0.25 cycles).

In order to prevent potential problems in the ambiguity resolution, some receiver manufacturers do correct the phase measurements by 0.25 cycles to recover consistency. Other manufacturers (currently Javad, Leica, Novatel) use to provide in the RINEX files the original uncorrected observations. In some cases, the correction is configurable by the user. Exclusively in the RINEX format description version 3.02², it is defined that the phase measurements need to be corrected to have a consistent set of observables that can be introduced for ambiguity resolution on double-difference level without limitations.

Because of this development, the *Bernese GNSS Software* offers in Version 5.2 a dedicated option “Consider GPS quarter-cycle biases” in panel “GPSEST 3.2: General Options 2” (also displayed in Figure 8.11). By selecting ALWAYS, no ambiguities between a Block IIR-M/Block IIF and older satellites get resolved. With this choice, you are on the safe side, but you are not solving for the optimal number of ambiguities. As an alternative, you may limit the accepted fractional part for resolved ambiguities to below 0.25 cycles and switch off this option by selecting NEVER. In this way, however, you may not resolve all potential ambiguities, either. A compromise for most applications may be achieved by selecting IF_INDICATED where a hardwired list of receiver types is considered to decide whether a problem from the quarter cycle handling may arise or not.

²Note that many RINEX files with the label of version 3.02 have already been generated before this convention was added to the format description. You may only be sure about the alignment of the phase measurements if the data come from a RINEX file of version 3.03 or later or if the header of the version 3.02 file is containing specific records on the alignment.

8.5. Resolution Strategies

Let us now give comments and recommendations concerning the selection of the appropriate ambiguity resolution strategy. All algorithms described in the previous section may be used either in the baseline mode or in the session mode. However, for the sake of efficiency, we recommend to resolve the ambiguities in the baseline mode (processing each baseline separately) and then introduce the resolved ambiguities as known quantities into the subsequent session processing. There are several aspects determining the optimal ambiguity resolution strategy. Before selecting the strategy the following questions should be answered:

1. Are phase measurements available on both carriers? If yes, are there high quality code measurements available on both carriers, too? (This is often not the case under the AS regime.)
2. How long is the baseline?
3. How long is the session?

If only single frequency data is processed, there are not many possibilities how to resolve the ambiguities. Either the SEARCH algorithm (for short sessions) or the SIGMA algorithm (for long sessions) must be used. Only short (several kilometers) baselines should be processed.

If both frequencies are available, we have the following options:

1. For very short baselines (up to several kilometers), the ambiguities may be resolved independently on L_1 and L_2 using the SIGMA algorithm (it is possible to do that in one program run, if both carriers are processed). This case is similar to processing single frequency data.
2. For longer baselines (up to approximately 2000 km), it is possible to process both carriers together and to try to resolve both (L_1 and L_2) ambiguities in the same run. The recommended strategies are QIF for long sessions and baselines of almost arbitrary length, and SEARCH for short sessions and short baselines.
3. Using the so-called wide-laning technique, each baseline is processed twice. First, the L_5 or Melbourne–Wübbena linear combination is processed and the wide-lane (L_5) ambiguities are resolved and stored in the observation header file. In the subsequent run the L_3 linear combination is processed, the wide-lane ambiguities are introduced as known, and the narrow-lane (L_1) ambiguities are resolved.

It was stated above that in the first step of the third strategy (wide-laning technique), either the L_5 or the Melbourne–Wübbena linear combination is processed. Using L_5 (phase observations only) gets satisfactory results up to baseline lengths of about 100 km (or longer if a good a priori ionosphere model is used). In this case the processing steps are:

- Ambiguity-free L_3 solution saving the coordinate results to get good a priori coordinates for the next step.
- Wide-lane (L_5) ambiguity resolution fixing *all* coordinates on the values obtained in the previous step.
- L_3 solution introducing the resolved L_5 ambiguities and solving for the *narrow-lane* ambiguities. In this third step, the estimation of station-specific troposphere parameters is highly recommended (see Chapter 12) because the geometrical term ρ (including the tropospheric refraction) has to be accurately known — considering short wavelengths. Note that the estimation of troposphere parameters is always recommended for long baselines when doing narrow-lane ambiguity resolution or when using the QIF strategy.

Table 8.1.: The most important GPS ambiguity resolution strategies supported by the *Bernese GNSS Software Version 5.2*.

Case	Baseline length	Occupation time	P-code available?	Ambiguity resolution (AR) strategy
1A	short (20–40 km)	>1 hr	no	<i>SIGMA</i> : L1&L2 or L1 or L2
1B	short (<5–10 km)	ca.1–5 min	no	<i>SEARCH</i> : L1&L2, no TRP estimation alternatively <i>SEARCH</i> : L1, in reoccupation mode ^a
2 ^{b c}	medium (<100–200 km)	>2–4 hr	no	(0) Ambiguity float (network) solution: <i>NONE</i> : L3, estimate/save CRD and TRP (1) Wide-lane ambiguity resolution: <i>SIGMA</i> : L5, introduce (fix) CRD, TRP, and ION; save wide-lane ambiguities (2) Narrow-lane ambiguity resolution: <i>SIGMA</i> : L3, introduce wide-lane ambiguities; estimate CRD and TRP ^d ; save narrow-lane ambiguities
3A ^{b e}	long (<6 000 km)	>8–24 hr	yes	(1) Wide-lane ambiguity resolution: <i>SIGMA</i> : MELWUEBB ^f , introduce P1–C1 DCBs ^g ; save wide-lane ambiguities (2) Narrow-lane ambiguity resolution: <i>SIGMA</i> : L3, introduce wide-lane ambiguities; estimate CRD and TRP ^d ; save narrow-lane ambiguities
3B ^{b c}	long (<1 000–2 000 km)	>8–24 hr	no	<i>QIF</i> : L1&L2, estimate SIPs ^h , CRD and TRP ^d , introduce (or estimate) ION save L1/L2 ambiguities

^aTwo (or more) baseline sessions (separated by more than 1 hr) must be processed together.

^bUse of precise orbits is required.

^cUse of deterministic ionosphere models is recommended.

^dIntroduction of TRP results from ambiguity–float network solution is possible, if not recommended.

^eNo assumption concerning ionosphere is necessary.

^fPhase must be processed together with code tracking data.

^gP1–C1 DCB information required in case of a mixture of receiver tracking technologies-

^h(Epoch–specific) SIPs must be pre–eliminated every epoch.

The approach given above (using phase observations only) does not seem to have advantages over the QIF strategy.

Resolving wide-lane ambiguities using the Melbourne–Wübbena linear combination is very reliable and almost baseline-length independent. However, the quality of the code measurement is crucial. The use of smoothed code generated by the program RNXSMT may help.

The recommended strategies are summarized in Table 8.1.

8.6. GLONASS Ambiguity Resolution

Because GLONASS is based on the FDMA technology, a single difference bias term remains when forming double differences:

$$b_{k\ell}^{ij} = \Delta\lambda^{ij} n_{k\ell}^j. \quad (8.13)$$

This relation was derived in Section 2.3.7.

For GLONASS ambiguity resolution, different frequencies and consequently different carrier wavelengths between pairs of satellites are crucial. The bias introduced in the difference of two single difference ambiguities is proportional to the initialization bias of the involved single difference ambiguities and, moreover, proportional to the frequency difference between the pairs of satellites considered. According to Habrich (1999), GLONASS single difference ambiguity parameters have to be initialized with an uncertainty of better than 285 cycles to keep the single difference bias term $b_{k\ell}^{ij} < 0.1$ cycles (more precisely for a frequency channel difference $i - j$ of 1). This basic requirement is illustrated by Figure 8.10.

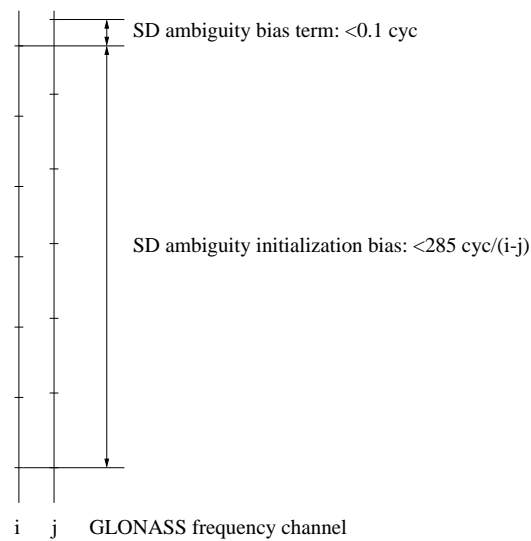


Figure 8.10.: Illustration of GLONASS single difference bias term.

Based on these assumptions, the SIGMA strategy can be applied also for GLONASS as described in Section 8.3.3. The only limitation is that the Differential Code-Phase Bias (DCPB), described for instance in Sleewaegen et al. (2012), is not automatically introduced into the processing. For this reason, we recommend to limit the usage to strategies that do not use code measurements (e.g., the Melbourne–Wübbena linear combination) — it means strategies 1A and 2, but not 3A in Table 8.1.

To enable the ambiguity resolution for GLONASS, you have to select either GLONASS or ALL (GPS and GLONASS) for option “Selection of GNSS for ambiguity resolution” in panel “GPSEST 3.2: General Options 2” (see Figure 8.11). You may either apply this strategy

- to L1&L2 (“Frequency/linear combination” in “GPSEST 3.1: General Options 1”) for a direct ambiguity resolution on L_1 and L_2 for short baselines (strategy 1A in Table 8.1), or

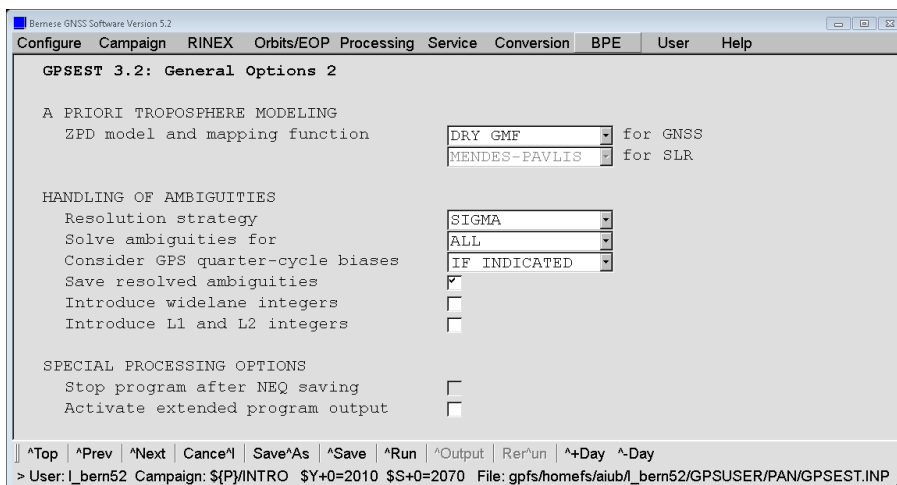


Figure 8.11.: GPSEST: Ambiguity resolution for GPS/GLONASS.

- to L5 in order to resolve the wide-lane ambiguities first and subsequently to L3 for resolving also the narrow-lane ambiguities when introducing the resolved wide-lane ambiguities (“Introduce widelane integers” in panel “GPSEST 3.2: General Options 2” enabled) — strategy 2 in Table 8.1.

Possible settings for the ambiguity resolution strategy SIGMA are displayed in the subsequent panel (shown in Figure 8.12). The meaning of the settings does not change with respect to the description in Section 8.3.3 when resolving ambiguities for GLONASS. In order to adjust the single difference bias term after each ambiguity resolution step only one ambiguity should be resolved in each iteration (or resolution) step. If the value in option “Maximal number of ambiguities fixed per iteration step” is greater than one, it becomes automatically readjusted to one.

When only phase measurements are selected (no Melbourne–Wübbena linear combination), all ambiguities can be resolved (select ALWAYS for option “GLONASS ambiguity resolution between different frequency channels”). There are several other choices that are relevant for an experimental handling of the DCPB and they are described in the online help. In the extreme case, NEVER could be selected, resulting in the resolution of ambiguities of the same frequency channel only (track-to-track ambiguity resolution). From Eqn. 8.13

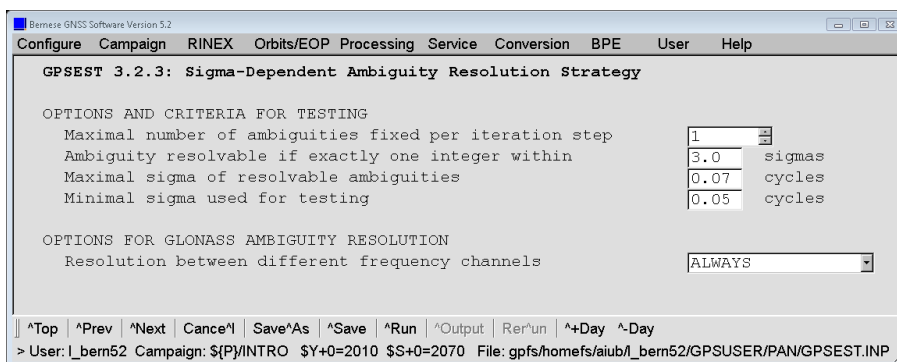


Figure 8.12.: GPSEST: Options for GLONASS ambiguity resolution when using the SIGMA strategy.

it is obvious that in such a case $\Delta\lambda^{ij} = 0$, leading to a zero-valued single-difference bias. This finally means that all described strategies may be applied to (GLONASS) ambiguity resolution within the same frequency channel.

9. Combination of Solutions

9.1. Motivation

The increasing number of permanent GNSS stations all over the world and the associated large number of observations to be processed ask for sequential processing methods. A conventional processing of all observations in one step using, e.g., GPSEST may be appropriate for small campaigns (a few days with 24 hour sessions of about 30–40 sites). The computing power, which is available nowadays, does not allow going far beyond this limit.

The program ADDNEQ2 ("Menu>Processing>Combine normal equation systems") was developed to compute multi-session solutions from the (statistically correct) combination of a set of single-session solutions. The theory of combining sequential solutions is well-known in geodesy since Helmert (1872). Sequential adjustment techniques, which operate at the NEQ level, are in general independent of the observation types of the individual solutions. This implies that even results from different techniques (terrestrial geodetic techniques or space techniques, such as GNSS, SLR, VLBI, DORIS) might be combined. Here, we focus solely on the combination of GNSS or SLR results.

The programs GPSEST and ADDNEQ2 allow storing normal equations (NEQs) in specific binary files for a sequence of solutions including a large number of parameter types (coordinates, troposphere, orbit parameters, clock corrections, bias parameters, etc.). The parameters supported by ADDNEQ2 are listed in Table 1.1. GPSEST is in general used to process individual sessions, whereas a combination of different sessions is done with ADDNEQ2.

The special features of normal equation stacking methods allow for an extremely rapid and flexible computation of many solution types because one does not have to deal with the original observations anymore. These features include a new definition of the geodetic datum, the setup of station velocities as unknowns, the modification of a priori sigmas for different parameter types, the change of physical models, such as the number of troposphere parameters, switching on/off models included by scaling factors, deleting parameters, stacking similar parameters (e.g., estimating one parameter value for all GPS and all GLONASS satellites instead of satellite-specific parameters), and different parameter pre-elimination options. Some unique options, such as a sophisticated definition of the geodetic datum, estimation of site velocities, or estimation of Helmert parameters between normal equations, are offered only by ADDNEQ2 and are not available in GPSEST.

This chapter presents the basics of sequential least-squares estimation (Section 9.2) and NEQ manipulation (Section 9.3). Section 9.4 describes further the use of ADDNEQ2 and Section 9.5 suggests a few typical applications.

9.2. Theory on Sequential Least–Squares Estimation

In this section we review the concept of sequential least–squares estimation techniques. The result of a least–squares adjustment — using all observations in one step — is the same as if the least–squares estimation would be split up in different parts and later be combined; these two parts have to be independent though. In order to prove the equivalence of both methods, we first solve for the parameters according to the common one–step adjustment procedure. Thereafter, we verify that the same result is obtained using a sequential adjustment.

Let us start with the observation equations (for the notation we refer to Section 7.2):

$$\begin{aligned} \mathbf{y}_1 + \mathbf{v}_1 &= \mathbf{A}_1 \mathbf{p}_c & \text{with} & & \mathbf{D}(\mathbf{y}_1) &= \sigma_1^2 \mathbf{P}_1^{-1} \\ \mathbf{y}_2 + \mathbf{v}_2 &= \mathbf{A}_2 \mathbf{p}_c & \text{with} & & \mathbf{D}(\mathbf{y}_2) &= \sigma_2^2 \mathbf{P}_2^{-1}. \end{aligned} \quad (9.1)$$

In this case we divide the observation array \mathbf{y}_c (containing all observations) into two independent observation series \mathbf{y}_1 and \mathbf{y}_2 . We would like to estimate the parameters \mathbf{p}_c common to both parts using both observation series \mathbf{y}_1 and \mathbf{y}_2 . Furthermore, we assume that there are no parameters relevant for only one of the individual observation series. This assumption is meaningful if we pre–eliminate “uninteresting” parameters according to Section 9.4.3. The proof of the equivalence of both methods is based on the assumption that both observation series are independent.

The division into two parts is sufficiently general. If both methods lead to the same result, we might derive formulae for additional sub–divisions by assuming one observation series to be already the result of an accumulation of different observation series.

9.2.1. Common Adjustment

In matrix notation we may write the observation equations (9.1) in the form:

$$\begin{aligned} \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \end{bmatrix} &= \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \end{bmatrix} \begin{bmatrix} \mathbf{p}_c \end{bmatrix} \\ \text{with } \mathbf{D} \left(\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} \right) &= \sigma_c^2 \begin{bmatrix} \mathbf{P}_1^{-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_2^{-1} \end{bmatrix} \end{aligned} \quad (9.2)$$

which is equivalent to

$$\mathbf{y}_c + \mathbf{v}_c = \mathbf{A}_c \mathbf{p}_c \quad \text{with} \quad \mathbf{D}(\mathbf{y}_c) = \sigma_c^2 \mathbf{P}_c^{-1}. \quad (9.3)$$

The matrices \mathbf{y}_c , \mathbf{v}_c , \mathbf{A}_c , \mathbf{p}_c , and \mathbf{P}_c^{-1} may be obtained from the comparison of Eqn. (9.3) with Eqn. (9.2). The independence of both observation series is given by the special form of the dispersion matrix (zero values for the off–diagonal matrices). Substitution of the appropriate values for \mathbf{y}_c , \mathbf{A}_c and \mathbf{p}_c into Eqn. (7.4) leads to the NEQ system of the least–squares estimation:

$$\left[\mathbf{A}_1^T \mathbf{P}_1 \mathbf{A}_1 + \mathbf{A}_2^T \mathbf{P}_2 \mathbf{A}_2 \right] \begin{bmatrix} \hat{\mathbf{p}}_c \end{bmatrix} = \left[\mathbf{A}_1^T \mathbf{P}_1 \mathbf{y}_1 + \mathbf{A}_2^T \mathbf{P}_2 \mathbf{y}_2 \right]. \quad (9.4)$$

9.2.2. Principle of Sequential Least-Squares Adjustment

In a first step, the sequential least-squares adjustment treats each observation series independently. An estimation is performed for the unknown parameters using only the observations of a particular observation series. In the second step, the contribution of each sequential parameter estimation to the common parameter estimation is computed.

Starting with the same observation equations as in the previous section, Eqns. (9.1) can be written as:

$$\begin{aligned} \mathbf{y}_1 + \mathbf{v}_1 &= \mathbf{A}_1 \mathbf{p}_1 & \text{with} & & \mathbf{D}(\mathbf{y}_1) &= \sigma_1^2 \mathbf{P}_1^{-1} \\ \mathbf{y}_2 + \mathbf{v}_2 &= \mathbf{A}_2 \mathbf{p}_2 & \text{with} & & \mathbf{D}(\mathbf{y}_2) &= \sigma_2^2 \mathbf{P}_2^{-1} \end{aligned}$$

or, in more general notation:

$$\mathbf{y}_i + \mathbf{v}_i = \mathbf{A}_i \mathbf{p}_i \quad \text{with} \quad \mathbf{D}(\mathbf{y}_i) = \sigma_i^2 \mathbf{P}_i^{-1} \quad \text{for } i = 1, 2, \quad (9.5)$$

where the vector \mathbf{p}_i denotes the values of the common parameter vector \mathbf{p}_c satisfying solely the observation series \mathbf{y}_i .

First, we solve each individual normal equation. The normal equations for the observation equation systems $i = 1, 2$ may be written according to Eqn. (7.4) as

$$\left[\mathbf{A}_i^T \mathbf{P}_i \mathbf{A}_i \right] \left[\hat{\mathbf{p}}_i \right] = \left[\mathbf{A}_i^T \mathbf{P}_i \mathbf{y}_i \right] \quad (9.6)$$

$$\begin{aligned} \mathbf{D}(\hat{\mathbf{p}}_i) &= \hat{\sigma}_i^2 (\mathbf{A}_i^T \mathbf{P}_i \mathbf{A}_i)^{-1} \\ &= \hat{\sigma}_i^2 \boldsymbol{\Sigma}_i \quad \text{with } i = 1, 2. \end{aligned} \quad (9.7)$$

In the second step, the a posteriori least-squares adjustment step, $\hat{\mathbf{p}}_c$ is estimated using the results of the individual solutions (9.6) and (9.7). The parameters \mathbf{p}_1 and \mathbf{p}_2 , which are used as pseudo-observations in this second step. They have the following form

$$\mathbf{y}_p + \mathbf{v}_p = \mathbf{A}_p \hat{\mathbf{p}}_c \quad \text{with} \quad \mathbf{D}(\mathbf{y}_p) = \sigma_c^2 \mathbf{P}_p^{-1}$$

or, more explicitly,

$$\begin{bmatrix} \hat{\mathbf{p}}_1 \\ \hat{\mathbf{p}}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{v}_{p1} \\ \mathbf{v}_{p2} \end{bmatrix} = \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \end{bmatrix} \hat{\mathbf{p}}_c \quad \text{with} \quad \mathbf{D} \left(\begin{bmatrix} \hat{\mathbf{p}}_1 \\ \hat{\mathbf{p}}_2 \end{bmatrix} \right) = \sigma_c^2 \begin{bmatrix} \boldsymbol{\Sigma}_1 & \boldsymbol{\emptyset} \\ \boldsymbol{\emptyset} & \boldsymbol{\Sigma}_2 \end{bmatrix}.$$

The results of the individual estimations $\hat{\mathbf{p}}_i$ and $\boldsymbol{\Sigma}_i$ are thus used to form the combined least-squares adjustment. The interpretation of this pseudo-observation equation system is as follows: each estimation is introduced as a new observation using the associated covariance matrix as the corresponding weight matrix. The corresponding NEQ system may be written as

$$\mathbf{A}_p^T \mathbf{P}_p \mathbf{A}_p \hat{\mathbf{p}}_c = \mathbf{A}_p^T \mathbf{P}_p \mathbf{y}_p \quad (9.8)$$

or, more explicitly,

$$\left[\mathbf{I}^T, \mathbf{I}^T \right] \begin{bmatrix} \boldsymbol{\Sigma}_1^{-1} & \boldsymbol{\emptyset} \\ \boldsymbol{\emptyset} & \boldsymbol{\Sigma}_2^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{I} \end{bmatrix} \hat{\mathbf{p}}_c = \left[\mathbf{I}^T, \mathbf{I}^T \right] \begin{bmatrix} \boldsymbol{\Sigma}_1^{-1} & \boldsymbol{\emptyset} \\ \boldsymbol{\emptyset} & \boldsymbol{\Sigma}_2^{-1} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{p}}_1 \\ \hat{\mathbf{p}}_2 \end{bmatrix}.$$

Substituting the results for $\boldsymbol{\Sigma}_i^{-1}$ we obtain

$$\left[\underbrace{\mathbf{A}_1^T \mathbf{P}_1 \mathbf{A}_1}_{\mathbf{N}_1} + \underbrace{\mathbf{A}_2^T \mathbf{P}_2 \mathbf{A}_2}_{\mathbf{N}_2} \right] \hat{\mathbf{p}}_c = \left[\underbrace{\mathbf{A}_1^T \mathbf{P}_1 \mathbf{y}_1}_{\mathbf{b}_1} + \underbrace{\mathbf{A}_2^T \mathbf{P}_2 \mathbf{y}_2}_{\mathbf{b}_2} \right] \quad (9.9)$$

which is identical to Eqn. (9.4). This simple superposition of normal equations, also called *stacking* of normal equations, is possible whenever the individual observation series are independent (indicated by a dispersion matrix in the form of Eqn. 9.2).

Let us emphasize that this condition is *not* fulfilled in the case of the superposition of double-difference solutions based on different clusters of baselines. If the clusters are connected by baselines (and only in this case stacking of the solutions yields an advantage due to common parameters), non-zero elements in the off-diagonal parts of the weight matrix \mathbf{P}_p , originating from mathematical correlations in the double-difference mode, are neglected. Clusters of baselines have, therefore, to be selected carefully in order to minimize the effect of this small incorrectness. In the same way clusters of stations in a zero-difference analysis are not independent if satellite clocks or other common parameters are not explicitly estimated.

9.2.3. Computation of the Combined RMS

In the previous section we only considered the combined parameter estimation. Sequential least-squares estimation leads to identical results for the a posteriori estimate of the variance of unit weight:

$$\Omega_c = \sum_{i=1}^m \mathbf{y}_i^T \mathbf{P}_i \mathbf{y}_i - \sum_{i=1}^m \mathbf{y}_i^T \mathbf{P}_i \mathbf{A}_i \hat{\mathbf{p}}_c$$

$$\hat{\sigma}_c^2 = \frac{1}{f_c} \left(\sum_{i=1}^m \mathbf{y}_i^T \mathbf{P}_i \mathbf{y}_i - \sum_{i=1}^m \mathbf{y}_i^T \mathbf{P}_i \mathbf{A}_i \hat{\mathbf{p}}_c \right),$$

where f_c is the degree of freedom of the combined solution. The importance of the “third normal equation part” $\mathbf{y}^T \mathbf{P} \mathbf{y}$ (see Eqn. (7.6)) is clearly seen in this formula. We refer to Brockmann (1997) for a complete discussion.

9.2.4. Generalization of the Principle

The limitation as defined in the introduction to this Section — that no parameter is permitted that is unique to one of the observation series (e.g., input normal equations according to Eqn. (9.9)) — can be avoided if for each normal equation the parameter list \mathbf{p} is sorted with respect to common parameters \mathbf{p}_c and unique parameters \mathbf{p}_i . For two such systems we obtain

$$\begin{bmatrix} \mathbf{N}_{1_{cc}} & \mathbf{N}_{1_{c1}} & 0 \\ \mathbf{N}_{1_{c1}} & \mathbf{N}_{1_{11}} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\mathbf{p}}_c \\ \hat{\mathbf{p}}_1 \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{b}_{1_c} \\ \mathbf{b}_{1_1} \\ 0 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \mathbf{N}_{2_{cc}} & 0 & \mathbf{N}_{2_{c2}} \\ 0 & 0 & 0 \\ \mathbf{N}_{2_{c2}} & 0 & \mathbf{N}_{2_{22}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{p}}_c \\ 0 \\ \hat{\mathbf{p}}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{b}_{2_c} \\ 0 \\ \mathbf{b}_{2_2} \end{bmatrix}$$

The stacking of both systems results in the combined NEQ system:

$$\begin{bmatrix} \mathbf{N}_{1_{cc}} + \mathbf{N}_{2_{cc}} & \mathbf{N}_{1_{c1}} & \mathbf{N}_{2_{c2}} \\ \mathbf{N}_{1_{c1}} & \mathbf{N}_{1_{11}} & 0 \\ \mathbf{N}_{2_{c2}} & 0 & \mathbf{N}_{2_{22}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{p}}_c \\ \hat{\mathbf{p}}_1 \\ \hat{\mathbf{p}}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{b}_{1_c} + \mathbf{b}_{2_c} \\ \mathbf{b}_{1_1} \\ \mathbf{b}_{2_2} \end{bmatrix} \quad (9.10)$$

The only remaining assumption is that the a priori values for the non-linear parameter adjustment are identical in all systems.

9.3. Manipulation of Normal Equations

Normal equations can be manipulated in a number of different ways, such as normal equation rescaling, expansion of normal equations, transformation of parameters, changing of a priori parameter information, stacking of parameters, reduction of the number of parameters, introduction of additional parameters, parameter constraining, and parameter pre-elimination. These manipulations are described in more detail in the following sections.

9.3.1. Changing Auxiliary Parameter Information

Parameters are always accompanied by auxiliary information, such as station name, as well as epoch, or time interval of validity. Changing the auxiliary parameter information is a very simple operation that does not have any influence on the system of normal equations. It comprises the renaming of stations and the change of receiver and antenna names. In ADDNEQ2 this manipulation is performed based on the information contained in the station information file (see Section 9.4.6). Users are notified about changes in the program output file and — on request — by the option “Notify changes due to station info file” (panel “ADDNEQ2 3.2: Options 2”) also as warning messages to the file given in the option “Error message”.

Within the station information file, a consistent change of station and equipment names is possible. Moreover, antenna eccentricities may be changed, which might be useful for reprocessing, for instance. A change in the antenna position is taken into account by transforming the a priori station position information (see Section 9.3.4.1). On the other hand, when changing the antenna name, only the antenna name is changed. It is not possible to consider an alternative antenna phase center variation model on this level of analysis. Some auxiliary parameter information can, however, not be changed at NEQ level. Examples are tropospheric mapping function, or satellite antenna group definition (see Section 9.3.9).

9.3.2. Rescaling the Normal Equation Matrices

Rescaling of normal equations is important, e.g., whenever two or more normal equation systems have to be combined, and each of them stems from a different processing software, or is based on a different strategy. A typical example is given by the use of different sampling rates for GNSS observations. Due to the temporal correlations of GNSS observations, the results remain (almost) the same. The variance-covariance matrices, however, change when different sampling rates are used.

The problem is solved by the following transformation: assuming the original NEQ system

$$\mathbf{N} \mathbf{p} = \mathbf{b} ,$$

the new system reads

$$\kappa \mathbf{N} \mathbf{p} = \kappa \mathbf{b} ,$$

where κ is the a priori scale factor. Its statistical meaning is the ratio of the variances

$$\kappa = \frac{\sigma_{\text{old}}^2}{\sigma_{\text{new}}^2} .$$

In program ADDNEQ2 rescaling is performed if the a priori information on the scale factor is provided in a WGT file (option “Variance rescaling factors”, cf. Section 24.11.11).

9.3.3. A Priori Transformation of Coordinates into a Different Reference Frame

For the transition between two reference frames, a parameter transformation must be used. Let us assume that we want to combine normal equations stemming from solutions based on the ITRF 2005 reference frame (denoted by index “05”) with another set of normal equations based on the ITRF 2008 reference frame (denoted further by index “08”). These reference frames are related by the 7-parameter (scaling factor μ , rotation angles α , β , γ , translations ΔX , ΔY , ΔZ) transformation (rates neglected)

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix}_{08} = (1 + \mu) \underbrace{\begin{pmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{pmatrix}}_{\mathbf{R}} \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix}_{05} + \underbrace{\begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}}_{\mathbf{\Delta}}.$$

Applying this transformation to the a priori coordinates in the ITRF 05-normal equations, we get the following expression in matrix notation:

$$\mathbf{X}_{08}^0 = \mathbf{R} \mathbf{X}_{05}^0 - \mathbf{\Delta}.$$

Only the a priori coordinates are changed. The matrices \mathbf{N} and \mathbf{b} remain untouched, which means the estimated coordinate corrections are unaffected by the transformation. This is allowed if rotation angles α , β , γ and scale parameter μ are small.

Since fixing reference station coordinates for datum definition is not recommended, the importance of the a priori coordinate transformation may be seen in the handling of small rotations between reference frames, caused by introducing orbits given in different reference frames.

9.3.4. Linear Parameter Transformations

At the NEQ level, only linear transformations are possible. Let us introduce the general transformation of the adjusted parameters from \mathbf{p} to $\tilde{\mathbf{p}}$:

$$\mathbf{p} = \mathbf{C} \tilde{\mathbf{p}} + \mathbf{c}. \quad (9.11)$$

Substituting this expression into the original normal equation system $\mathbf{N}\mathbf{p} = \mathbf{b}$, Eqn. (7.4) leads to a transformed normal equation system $\tilde{\mathbf{N}}\tilde{\mathbf{p}} = \tilde{\mathbf{b}}$ in the following way

$$\underbrace{\mathbf{C}^T \mathbf{N} \mathbf{C}}_{\tilde{\mathbf{N}}} \tilde{\mathbf{p}} = \underbrace{\mathbf{C}^T \mathbf{b} - \mathbf{C}^T \mathbf{N} \mathbf{c}}_{\tilde{\mathbf{b}}}$$

with

$$\tilde{\mathbf{N}} = \mathbf{C}^T \mathbf{N} \mathbf{C}, \quad \tilde{\mathbf{b}} = \mathbf{C}^T \mathbf{b} - \mathbf{C}^T \mathbf{N} \mathbf{c}. \quad (9.12)$$

9.3.4.1. Changing the A Priori Parameter Values

Changing the a priori values of parameters (\mathbf{x}^0) is based on the following relation between old and new parameters:

$$\mathbf{p} = \tilde{\mathbf{p}} + (\mathbf{x}_{\text{new}}^0 - \mathbf{x}_{\text{old}}^0)$$

which is a special case of the transformation equation (Eqn. 9.11) with $\mathbf{C} = \mathbb{E}$ and $\mathbf{c} = \mathbf{x}_{\text{new}}^0 - \mathbf{x}_{\text{old}}^0$. A priori values do not influence the normal equation matrix \mathbf{N} . They change, however, the vector \mathbf{b} on the right-hand side of the NEQ system, see Eqn. (9.12):

$$\tilde{\mathbf{b}} = \mathbf{b} - \mathbf{N} (\mathbf{x}_{\text{new}}^0 - \mathbf{x}_{\text{old}}^0) .$$

Remarks on the implementation in ADDNEQ2

The transformation of a priori values is performed immediately after reading each NEQ file. A priori values are adapted to the values given for the different parameter types in the related program input files (panels “ADDNEQ2 1.1: Input Files 1”, “ADDNEQ2 1.2: Input Files 2”, and “ADDNEQ2 1.3: General Files”). If the new value in the input file ($\mathbf{x}_{\text{new}}^0$) is the same as in the NEQ file ($\mathbf{x}_{\text{old}}^0$), the parameter transformation takes place with $\Delta x_i^0 = 0$. If no input files for a specific parameter type are provided, the related a priori values are not transformed.

- If a velocity input file in the input field “Station velocities” is specified, the station coordinate parameters are transformed to a priori values referring to the middle epoch of the parameter validity interval.
- Station coordinates, velocities, and EOPs require input files with a priori values if they are included in the NEQ file.
- If the NEQ system contains drift parameters such as EOPs from GPSEST, the a priori values of all drift parameters are automatically transformed to zero.
- If no input file is given for DCB parameters, the a priori values are set to zero (in order to allow a zero-mean condition for the biases, see Section 7.5.3).
- The a priori values for scaling factors may be defined to zero or one by specific input fields in the panels “ADDNEQ2 19: Options for Higher-order Ionosphere Scaling Factors” and “ADDNEQ2 20: Options for Parameter Scaling Factors” respectively.
- For troposphere parameters, the change of a priori values by introducing an input file (option “Troposphere estimates”) is connected to the deletion of the related parameters (see Section 9.3.8).
- The a priori values of orbit parameters cannot be changed by introducing an input file, since they are given in the standard orbit file (default extension STD).

9.3.4.2. Changing the Validity Interval

Changing the validity interval usually precedes parameter stacking (see below). In case of a (piecewise) linear function, this is performed by a parameter transformation $\mathbf{p} \rightarrow \tilde{\mathbf{p}}$ (see Figure 9.1).

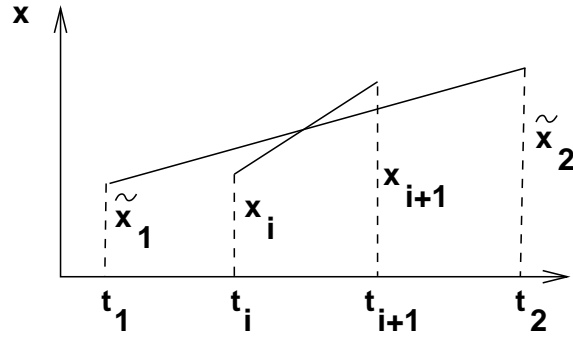


Figure 9.1.: Changing the validity interval for the linear function.

The time-dependent value $p(t)$ may be expressed in two ways:

$$p(t) = p_i \frac{t_{i+1} - t}{t_{i+1} - t_i} + p_{i+1} \frac{t - t_i}{t_{i+1} - t_i}$$

$$p(t) = \tilde{p}_1 \frac{t_2 - t}{t_2 - t_1} + \tilde{p}_2 \frac{t - t_1}{t_2 - t_1} .$$

Introducing $t = t_i$ and $t = t_{i+1}$ in the above two equations and equating the resulting expressions leads to:

$$\mathbf{p} = \begin{pmatrix} \frac{t_2 - t_i}{t_2 - t_1} & \frac{t_i - t_1}{t_2 - t_1} \\ \frac{t_2 - t_{i+1}}{t_2 - t_1} & \frac{t_{i+1} - t_1}{t_2 - t_1} \end{pmatrix} \tilde{\mathbf{p}} = \mathbf{C} \tilde{\mathbf{p}} . \quad (9.13)$$

This matrix may be extended for an arbitrary number of subintervals. Using Eqn. (9.13), the program ADDNEQ2 transforms the NEQ system according to Eqn. (9.12). Changing the validity interval has an influence on the normal equation matrix \mathbf{N} and on the vector \mathbf{b} .

Remarks on the implementation in ADDNEQ2

The validity interval of the following parameter types can be changed in panel “ADDNEQ2 8: Interval Length of Parameters”:

- “Troposphere zenith path delays”
- “Troposphere gradients”
- “Inter-system bias”
- “Earth rotation parameters”
- “Nutation parameters”

Note, the same algorithm is applied to transform station coordinate parameters into a piecewise linear representation (with two nodal points) for velocity estimation.

9.3.4.3. Parameter Stacking

A simple but basic operation of program ADDNEQ2 is the stacking of parameters. This operation is performed, for example, when station coordinates from different NEQ

files are combined to one set of parameters. In this case, the principle of combining normal equations with common parameters (e.g., station coordinates) and unique parameters (e.g., troposphere parameters) is applied as given in Eqn. (9.10), Section 9.2.4.

Sometimes it might be useful to stack the parameters p_i and p_{i+1} (belonging to one and the same normal equation) into one parameter p_i . For this purpose we can use the following parameter transformation:

$$\begin{pmatrix} \vdots \\ p_i \\ p_{i+1} \\ p_{i+2} \\ \vdots \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 1 & \cdots & 0 \\ 0 & \cdots & 1 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 1 \end{pmatrix}}_C \begin{pmatrix} \vdots \\ p_i \\ p_{i+2} \\ \vdots \end{pmatrix}.$$

The transformation of the NEQ system is performed using Eqn. (9.12).

Remarks on the implementation in ADDNEQ2

Parameter stacking is performed automatically for identical parameters from different NEQ files, such as coordinates of the same station, troposphere parameters referring to the same station and the same epoch, or dynamic orbit parameters for the same satellite and the same osculating epoch.

Stacking may be suppressed for station coordinates (e.g., in case of anomalous behavior) by marking the station as bad in the station information file (see Section 9.4.6). The coordinates of the indicated station will then not be stacked but pre-eliminated without any constraining before stacking the NEQ files.

Orbital elements may be stacked after the transformation to the same osculating epoch according to Beutler et al. (1996). For details, see Section 16.3.2.

Applications for stacking parameters within one NEQ file are discussed in Section 9.3.5.

9.3.5. Reduction of the Number of Parameters

Parameter stacking reduces the number of parameters in the normal equations that have to be estimated. An important application is the reduction of the number of parameters used to represent a piecewise linear function (cf. Figure 9.2 for an example). The operation is performed in two steps. First, the validity interval of each parameter is adjusted to the new interval according to Section 9.3.4.2. Second, the transformed parameters are stacked according to Section 9.3.4.3.

A typical example is the reduction of the number of troposphere parameters. If, for instance, we have estimated (and stored into NEQ files) 12 troposphere parameters per site and day, one has the possibility to reduce the number of parameters to 1, 2, 3, 4, or 6 values per day and site. Section 9.4.4 provides more details on how to use this option.

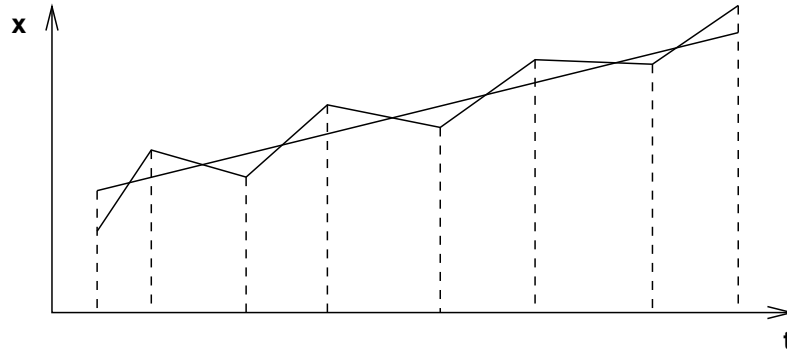


Figure 9.2.: Reducing the number of parameters.

Another opportunity to reduce the number of parameters in a new NEQ is the stacking of parameters as described in Section 9.3.4.3 for one of the following purposes:

- reduce the GLONASS inter-frequency bias parameters from a satellite-specific setup to a frequency-specific setup,
- transform the station-specific scaling factors for deformation models or HOI to groups, or even to one parameter per component,
- reduce the resolution of the components from 3D-resolution to 1D-resolution for the scaling factors of the deformation models,
- change the satellite antenna parametrization from satellite-specific to type-specific,
- group Helmert parameters estimated to absorb systematic effects between normal equations, or
- reduce the number of SLR range biases to be estimated per station.

9.3.6. Introducing Additional Parameters

The introduction of additional parameters is possible in some cases, even if these parameter types have not been set up in the individual normal equations. It is necessary though, that the influence of these parameters is negligible within each normal equations. For the site velocities, e.g., the influence of the site motion may actually be neglected for the time span of one day.

Adding new parameters to the system of normal equations leads to a so-called expansion of the NEQ system. The procedure may be described by the parameter transformation (cf. Eqn. (9.11)) where \mathbf{p} is the original vector of parameters and $\tilde{\mathbf{p}}$ is the expanded one. The transformation matrix \mathbf{C} is given by

$$\mathbf{C} = \begin{pmatrix} 1 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & & \vdots \\ 0 & \cdots & 1 & 0 & \cdots & 0 \end{pmatrix} = \begin{pmatrix} \mathbf{I} & \mathbf{0} \end{pmatrix}.$$

Obviously, after performing the transformation of the NEQ system according to Eqn. (9.12), the resulting normal equation matrix $\tilde{\mathbf{N}}$ becomes singular:

$$\begin{pmatrix} \mathbf{N} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{pmatrix} \tilde{\mathbf{p}} = \begin{pmatrix} \mathbf{b} \\ \mathbf{0} \end{pmatrix}. \quad (9.14)$$

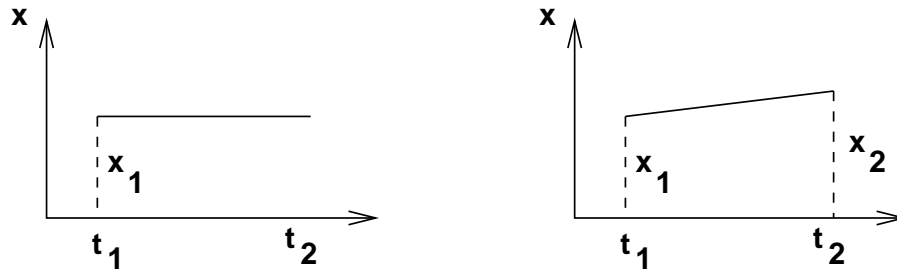


Figure 9.3.: Adding a new coordinate parameter.

The singularity is removed by accumulating additional normal equations to the system.

Remarks on the implementation in ADDNEQ2

Program ADDNEQ2 applies this operation in the following situations:

- the estimation of station velocities (see the following section and Chapter 10),
- the addition of stochastic pulses in long-arc combinations (see Chapter 16),
- the change of parameter representation for SINEX (see below), and
- the estimation of Helmert parameters between individual normal equations (see Section 9.4.5).

In addition, it is possible to add parameters for geocenter coordinates (see Section 16.4) to a NEQ system, if all station coordinate parameters are included in the NEQ. The singularity indicated in Eqn. (9.14) has to be solved by the datum definition (see Section 10.2).

9.3.6.1. Estimation of Station Velocities

In a terrestrial reference frame, coordinates of static stations are very stable over time. The program GPSEST usually processes data gathered within short time periods (typically a single day). Modeling each station coordinate by a single value is, thus, reasonable and sufficient. The analysis based on the combination of normal equations, however, may cover time intervals of several months, or even years. Station velocities have to be taken into account for such applications. The problem is solved in the following way: after reading the NEQ file, the system is expanded (i.e., station coordinate parameters are added) according to the scheme illustrated in Figure 9.3. The resulting system of normal equations is singular. However, it is now possible to change the validity interval according to Section 9.3.4.2. The length of the new interval covers the entire analyzed period (e.g., one year). The resulting NEQ system may then be stacked with the other systems (transformed as described in Section 9.3.4.3). Stacking many NEQ systems referring to different epochs removes the singularity.

9.3.6.2. Changing the Parameter Representation for SINEX

The *Bernese GNSS Software* consistently uses offset parameters for (piecewise) linear functions (see Section 7.6). To write a SINEX file (see Section 4.5), however, it may

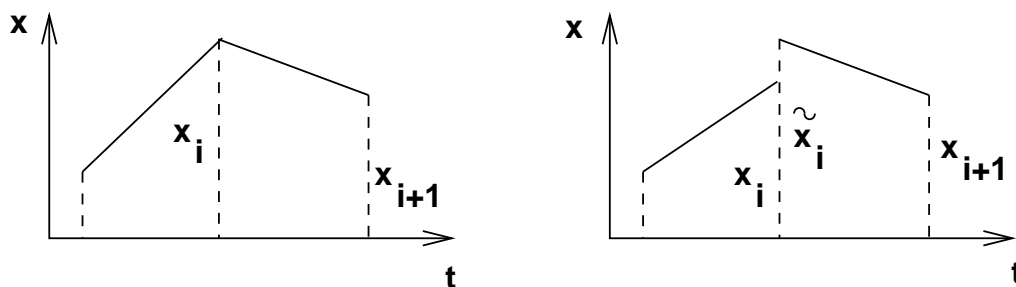


Figure 9.4.: Normal equation system expansion for SINEX.

be necessary to use offset and drift parameters for ERPs representation. The option “Transform ERP to offset/drift representation” in panel “ADDNEQ2 3.3: Options 3” allows this transformation.

In Section 7.6.1, the formulae for the transformation between these two approaches are given. If we want to change the parametrization from using offsets only to using offsets and drifts, the NEQ system has to be expanded according to Figure 9.4.

After the expansion, the pairs of offsets are transformed into offsets and drifts. The resulting NEQ system is, of course, singular. The singularity is removed, if continuity at the interval boundaries is imposed by applying constraints.

9.3.7. Constraining Parameters

In the *Bernese GNSS Software* parameters are constrained by adding fictitious observations. The principles in ADDNEQ2 are the same as in GPSEST (cf. Section 7.5). Nearly all parameters supported by ADDNEQ2 can be constrained to their *a priori* values. For this reason, parameters are constrained after parameter transformations took place — in particular the change of *a priori* values.

Parameters that appear explicitly in the resulting normal equation are stored into the file without any constraints. Only those parameters that are pre-eliminated are constrained before the pre-elimination procedure. Hence, NEQ files may contain constraints on implicit parameters.

SINEX files generated by ADDNEQ2 are also free of constraints regarding the explicit parameters, if they are stored in the normal equation representation (option “Content of SINEX” in panel “ADDNEQ2 2.1: Output Files 1” is set to NEQ). If the COV representation is selected, all potential constraints of explicit parameters are booked in the SOLUTION/MATRIX_APRIORI block of the SINEX file according to the selection in the option “Regularize a priori constraint matrix” in panel “ADDNEQ2 3.3: Options 3”.

Relative constraints between successive parameters in time may be applied for tropospheric zenith path delay and gradient parameters, as well as for global ionosphere parameters. A time interval must be defined, specifying the distance in time over which relative constraints shall be applied (usually the nominal parameter spacing).

Furthermore, relative constraints may be applied to pairs of station velocities according to the entries in Section TYPE 004: STATION COORDINATES AND VELOCITIES (ADDNEQ) of the station information file (see Section 10.3.5 for more details).

Station coordinates and velocities may be fixed (and deleted from the normal equation, which is not recommended if normal equations are saved, or velocities are estimated) or constrained to their a priori values that are provided by input coordinate and velocity files, respectively. A free solution without constraining station coordinates resp. station velocities may be generated (not recommended for a final solution), or minimum network constraints may be imposed (see the following section for more details).

Minimum Constraint Conditions

GNSS is in principle an interferometric technique. Therefore, it is in general not possible to estimate the absolute position of all stations. At least one of them has to be fixed to its a priori coordinates. Of course it is preferable if the compensation of the degree of freedom in the geodetic datum definition depends solely on one individual station. The compensation can be replaced by a so-called minimum constraint condition (sometimes also called free network condition), which compensates the degree of freedom in the datum definition based on an ensemble of stations. In most cases, this strategy is optimal to define the geodetic datum by a minimum number of constraints and without fixing or constraining particular site coordinates. This option is well suited to analyze inconsistencies in the reference site coordinates, see also Chapter 10.

Minimum constraint conditions are based on the assumption that there are two reference frames:

1. an a priori reference frame \mathbf{X} , and
2. a reference frame of the resulting coordinates $\widetilde{\mathbf{X}}$.

These two reference frames are related by the 7-parameter transformation

$$\begin{pmatrix} \widetilde{X}_i \\ \widetilde{Y}_i \\ \widetilde{Z}_i \end{pmatrix} = (1 + \mu) \begin{pmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{pmatrix} \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \quad (9.15)$$

The subscript i refers to all stations defining the reference frame.

The 7-parameter transformation may be written in this linearized form because only small rotations α , β , γ are considered. The idea of minimum constraint conditions is based on the requirement that some of these seven parameters (computed using the Helmert method) are set to zero. Setting the translations to zero results in a no-net-translation condition imposed on the estimated coordinates with respect to the a priori reference frame. Setting the rotations to zero results in a no-net-rotation constraint. Whereas the no-net-translation condition is typically used for the datum definition of regional networks or global networks with estimating geocenter coordinates, the no-net-rotation is used for global networks while estimating EOPs and orbits.

Eqn. (9.15) may be rewritten as

$$\begin{pmatrix} \widetilde{X}_i \\ \widetilde{Y}_i \\ \widetilde{Z}_i \end{pmatrix} = \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 & 0 & -Z_i & Y_i & X_i \\ 0 & 1 & 0 & Z_i & 0 & -X_i & Y_i \\ 0 & 0 & 1 & -Y_i & X_i & 0 & Z_i \end{pmatrix} \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \\ \alpha \\ \beta \\ \gamma \\ \mu \end{pmatrix}$$

or in vector notation as

$$\tilde{\mathbf{X}}_i = \mathbf{X}_i + \mathbf{B}_i \boldsymbol{\xi} .$$

Let us introduce the vectors $\tilde{\mathbf{X}}$, \mathbf{X} , and the matrix \mathbf{B} :

$$\tilde{\mathbf{X}} = \begin{pmatrix} \tilde{\mathbf{X}}_1 \\ \tilde{\mathbf{X}}_2 \\ \vdots \end{pmatrix} , \quad \mathbf{X} = \begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \end{pmatrix} , \quad \mathbf{B} = \begin{pmatrix} \mathbf{B}_1 \\ \mathbf{B}_2 \\ \vdots \end{pmatrix} .$$

If we want to compute the transformation parameters, we can use the following ‘‘observation equation’’:

$$\mathbf{v} = \mathbf{B} \boldsymbol{\xi} - (\tilde{\mathbf{X}} - \mathbf{X}) , \tag{9.16}$$

which results in the following system of normal equations:

$$\mathbf{B}^T \mathbf{B} \boldsymbol{\xi} = \mathbf{B}^T (\tilde{\mathbf{X}} - \mathbf{X}) .$$

In our case the expression $\tilde{\mathbf{X}} - \mathbf{X}$ is the difference between the estimated and the a priori value:

$$\tilde{\mathbf{X}} - \mathbf{X} = \mathbf{p} .$$

The parameters of the 7-parameter transformation are given by

$$\boldsymbol{\xi} = (\mathbf{B}^T \mathbf{B})^{-1} \mathbf{B}^T \mathbf{p} .$$

Thus, the minimum constraint condition may be imposed by adding the following fictitious observation

$$\mathbf{H} \mathbf{p} = \mathbf{0} ,$$

where

$$\mathbf{H} = (\mathbf{B}^T \mathbf{B})^{-1} \mathbf{B}^T .$$

Because of the regularity of the matrix $\mathbf{B}^T \mathbf{B}$ it is even possible to use

$$\mathbf{H} = \mathbf{B}^T .$$

Program ADDNEQ2 uses the first of the two possible equations. It is not always necessary to constrain all seven components of $\boldsymbol{\xi}$. The number of singularities which have to be removed using constraints, depends on the solution type. Minimum constraint conditions may be applied separately for coordinates and velocities. It is recommended, however, to apply the same constraints to both coordinates and velocities. We refer to Chapter 10 for more details.

9.3.8. Parameter Pre-Elimination and Deletion

The pre-elimination of parameters in ADDNEQ2 works in the same way as in GPSEST (cf. Section 7.7.1). The different pre-elimination options implemented in ADDNEQ2 are described in Section 9.4.3. Parameters may be pre-eliminated before or after the stacking of normal equations. Before pre-elimination, the parameters may be transformed and constrained.

In ADDNEQ2 parameter elimination (“delete”) is possible by removing the rows and columns corresponding to the respective parameters from the normal equation. As a result, these parameters are fixed to their a priori values. The effect is the same as if the parameters were pre-eliminated after having applied infinitely tight constraints or as if they were never set up.

9.3.9. Restrictions

All manipulations possible at the NEQ level are based on linear transformations. Therefore, only simple model changes are possible with program ADDNEQ2. In this section, examples such as setting up site velocities, geocenter coordinates, Helmert parameters between input NEQ files, stochastic orbit parameters at boundaries of the normal equations, and reduction of parameters for piecewise linear representations were given.

Model changes that require access to the observations are not possible. In particular, it is not possible to change

- the sampling rate,
- the analyzed linear combination of observations or frequency,
- the elevation cut-off angle and elevation-dependent weighting of observations,
- the troposphere model, the mapping function, or the gradients model,
- the type of correction model for site displacements (e.g., ocean tidal loading model),
- the models used for orbit determination such as Earth gravity field model, tidal gravity variations, mean pole, and subdaily pole definition,
- the receiver antenna offset or patterns (if the corresponding parameters are not available in the normal equation).

at the NEQ level. A reanalysis of the observations with program GPSEST (for orbit models also with ORBGEN) is required in order to get NEQ files referring to the new models. Exceptions in this context are models that are introduced with scaling factors. Examples are deformation models and HOI corrections. By defining the a priori value as zero or one and a proper constraining or even a deletion of these scaling parameters, these models can be disabled or enabled even at the NEQ level.

9.4. The Program ADDNEQ2

9.4.1. Flow Chart of the Program

Figure 9.5 depicts the flowchart with the most important blocks of program ADDNEQ2. For each input NEQ file, stations are renamed according to the station information file, parameters referring to stations with indicated problems (TYPE 003: HANDLING OF STATION PROBLEMS in the station information file) are pre-eliminated, and parameters without observations are removed (i.e. if the diagonal element of the normal equation matrix is zero,

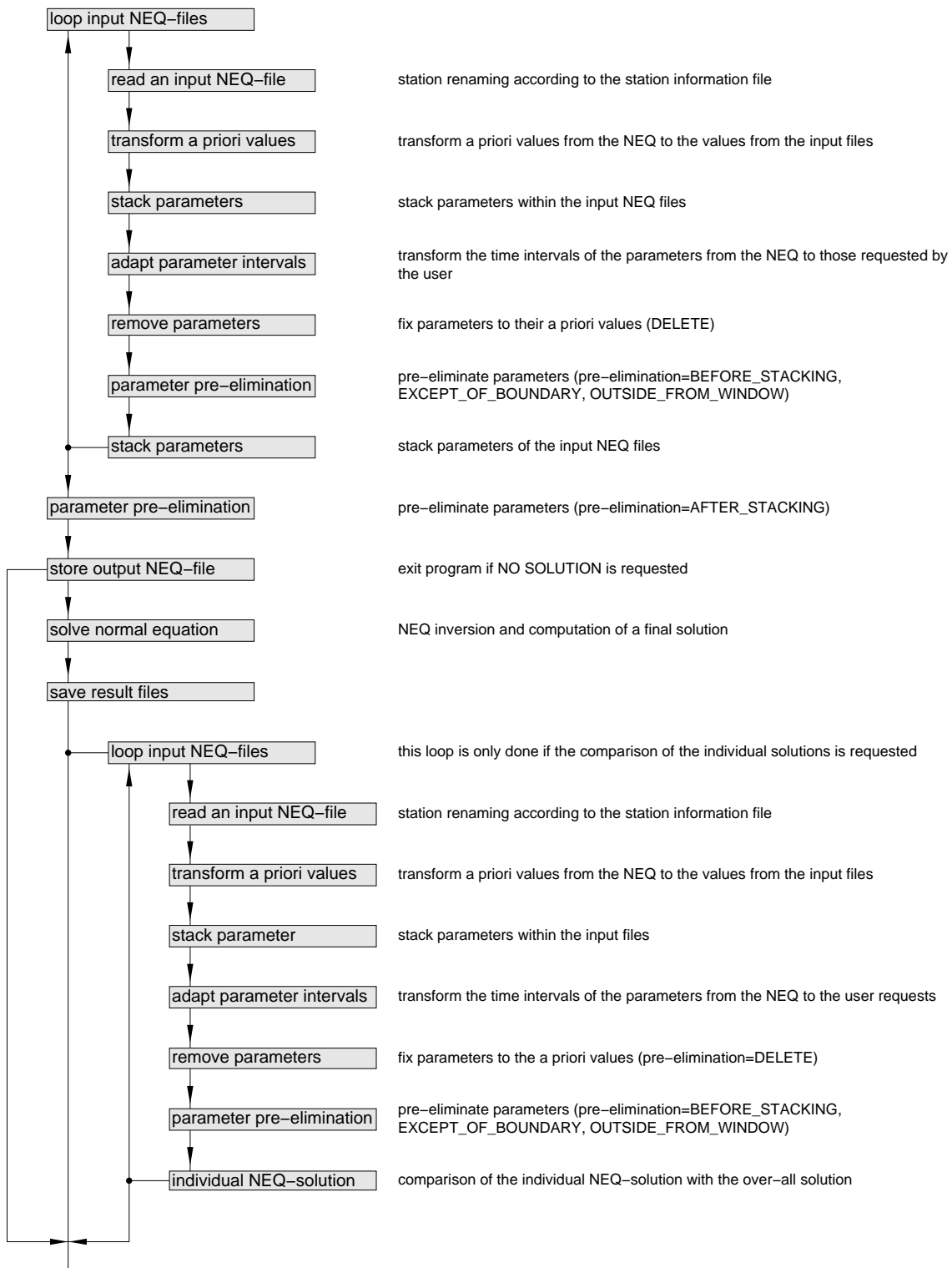


Figure 9.5.: Flowchart for the program ADDNEQ2.

the respective column and row is removed). Next, the input normal equation is rescaled according to the variance rescaling factors defined in the file specified in option “Variance rescaling factors” in panel “ADDNEQ2 1.1: Input Files 1” (see Section 9.3.2). In the same file, a priori Helmert transformation parameters may be specified that are applied to the indicated NEQ files as well (see Section 9.3.3).

The next step consists of the transformation of the a priori parameters to values specified in external files (cf. equations in Section 9.3.4.1).

The spacing of the piecewise linear description of time-dependent parameters is adapted as a next step according to the user input (see Section 9.4.4). If requested by the user, parameters are reduced by stacking according to the description in Section 9.3.5. Afterwards, parameters are deleted if requested by the user, constraints are added to parameters scheduled for pre-elimination, and pre-elimination (BEFORE_STACKING) is performed. For details about the available pre-elimination options in ADDNEQ2, see Section 9.4.3.

The stacking of parameters from the input NEQ with those from the previous NEQs concludes the loop over the input NEQs. Orbit parameters need a special transformation before they can be combined to a long arc over several normal equations (see Section 16.3.2).

In the next step, saving the resulting normal equation to a file is prepared. This involves the pre-elimination of parameters (AFTER_STACKING) after applying the user-specified constraints, sorting of parameters within the normal equation, and saving of the binary NEQ file. The processing may be terminated at this point, if the option “Compute no solution” in panel “ADDNEQ2 3.1: Options 1” is enabled. If this is not the case, the solution is computed after constraining the parameters that have not been pre-eliminated. Due to numerical reasons, the diagonal elements of the normal equation are normalized for the inversion process. The results are written to the program output and the parameter specific output files are prepared.

If the option “Compute and compare individual solutions” in panel “ADDNEQ2 3.1: Options 1” is not set to NO, each input NEQ is read a second time, an individual solution is computed with identical options as for the combined solution, and the individual solution is compared to the combined solution. The result from this step are station coordinate residuals for each station from each input NEQ. Depending on the number and on the size of the input normal equations, this step may be time-consuming. The option “Compute and compare individual solutions” can be set to

YES	each individual solution is directly compared to the combined solution, without any transformation parameters,
HELMERT	the same components as selected for the “Minimum constraint solution” in panel “ADDNEQ2 5: Datum Definition for Station Coordinates” are selected to compare each individual solution with respect to the combined solution. If another type of datum definition is selected, all seven parameters are used,
HLM_ALL	a seven-parameter Helmert transformation is applied to compare each individual solution with the combined solution,
HLM_ROT	three rotation parameters are applied to compare each individual solution with respect to the combined solution, or
HLM_TRA	three translation parameters are applied to compare each individual solution with the combined solution.

For details we refer to Section 10.3.3.

9.4.2. General Options

The primary input of ADDNEQ2 are either one or several NEQ files that can be specified in panel “ADDNEQ2 1.1: Input Files 1”. By default, the input files are ordered chronologically according to their first epoch of validity. An alphabetical order of the solutions can, however, be kept using the option “Keep input NEQs in alphabetical order” in panel “ADDNEQ2 3.2: Options 2”. In particular, when a SINEX output file is to be written, an alphabetical order of the solutions shall be kept.

ADDNEQ2 allocates the necessary memory dynamically. But since the number of parameters in the combined normal equation is only known after reading and processing all input NEQs, the expected number of parameters in the combined solution is an input parameter (option “Maximum number of parameters in combined NEQ”, see Figure 9.6). ADDNEQ2 uses this option to allocate memory for the combined NEQ system. Specifying a number greater than necessary does no harm if the computer has enough memory.

In panel “ADDNEQ2 3.1: Options 1” (see Figure 9.6), the a priori sigma of unit weight has to be specified. The unit weight usually corresponds to the weight of the zero-difference L_1 phase observable (at zenith) and should approximately agree with the actual measurement noise of the one-way L_1 phase observations (the post-fit sigma of unit weight given in the ADDNEQ2 output file). In the same way as for program GPSEST (see Section 7.4.1), the value of this sigma is only relevant for the correct scaling of any a priori constraints applied to specific parameters.

In the same panel, the omission of the solution (option “Compute no solution”) or the extension of the input NEQ system may be enabled in order to add site velocities and/or geocenter coordinate parameters according to Section 9.3.6.

9.4.3. Parameter Selection and Pre-Elimination Options

In the input panels for the pre-elimination options, all parameter types supported by ADDNEQ2 are listed. For this reason, these input fields are well suited to activate or deactivate parameter-specific options:

- Empty field:

The parameter type is *not* expected in the ADDNEQ2 solution and the related option

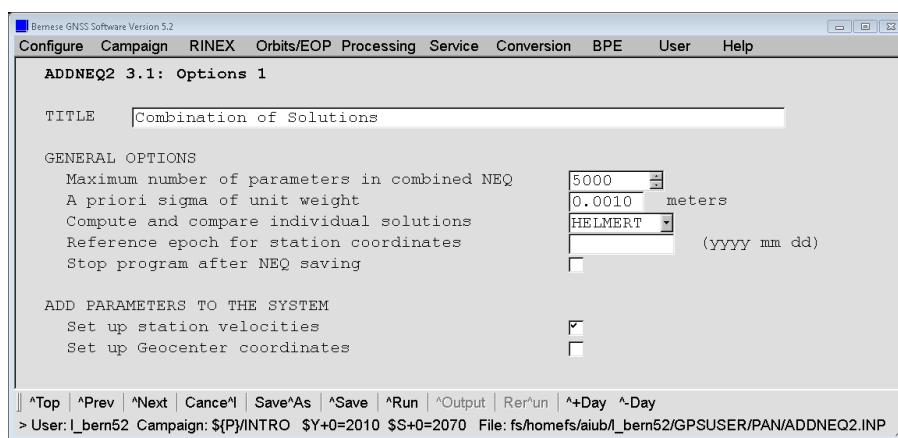


Figure 9.6.: General options for program ADDNEQ2.

panels will not be displayed. If the related parameter is detected in one of the normal equations, the program terminates with an error message.

- **NO** or any other value indicating the pre-elimination option:
The parameter type is expected in the solution and the panels containing the related input options are displayed. If nonetheless the parameter type does not appear in one of the normal equations, a warning message is generated.

The mathematical principle of pre-elimination of parameters was described in Section 7.7.1. Some comments on the implementation in ADDNEQ2 have been provided in Section 9.3.8.

Apart from leaving blank, you can select one of the following options separately for each parameter type supported by ADDNEQ2 to choose the pre-elimination strategy:

NO: The parameters are not pre-eliminated and remain explicitly in the system (i.e. they appear in the solution).

BEFORE_STACKING: Parameters are pre-eliminated immediately after reading each individual input NEQ file. The parameters are not stacked. The parameters may be transformed to new a priori values and constrained.

It is possible to formulate exceptions for the pre-elimination of parameters from specific NEQ input files. Either a comma-delimited list of file numbers, or F (first) or L (last) may be used. Using this option it is possible, e.g., to retain the troposphere parameters for the middle day of a three days solution by specifying the number 2 in the fields “Except for files: troposphere ZPDs” and “Except for files: Troposphere gradients” (second of three input NEQs); the troposphere parameters of the first and last day are pre-eliminated. In this case the troposphere results from the middle of the three-day solution are written to the output file.

AFTER_STACKING: Parameters are pre-eliminated after reading all input NEQ files and after the stacking of parameters, but before the solution is computed and the output normal equation is saved. The parameters appear neither in the solution nor in the output NEQ or SINEX file. This option may be used to reduce the size of the resulting NEQ file.

EXCEPT_FOR_BOUNDARIES: This option can be applied to parameters describing a piecewise linear function of time such as troposphere parameters, global ionosphere parameters, or EOPs. It allows us to pre-eliminate all parameters before stacking except for those located at the beginning and at the end of the validity time interval of a normal equation (see Figure 9.7). As a consequence, only parameters at the boundaries of the normal equations remain in the equation system. The parameters from successive normal equations can then be stacked. Thus, contrary to pre-elimination before stacking, the troposphere representation at the NEQ boundaries, for instance, remains continuous.

This operation is performed before stacking, i.e. it is performed individually for each input normal equation. It can be used to pre-eliminate a large number of parameters and — at the same time — to stack parameters from normal equations adjacent in time. After the operation, isolated parameters at former NEQ boundaries remain in the resulting normal equation. These may be removed by an additional ADDNEQ2 run.

The same options for excluding individual files from the pre-elimination are available in the same way as described above for the option BEFORE_STACKING.

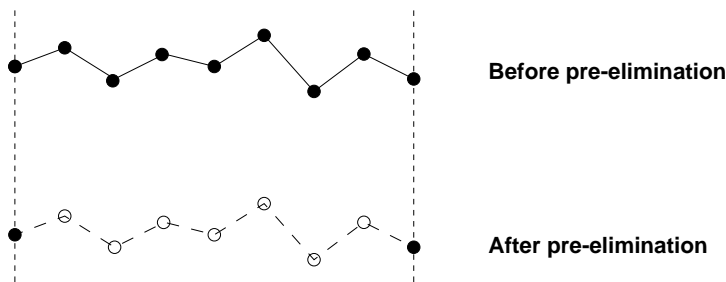


Figure 9.7.: Option EXCEPT_FOR_BOUNDARIES.

OUTSIDE_FROM_WINDOW: All parameters outside of a time window (to be specified in a subsequent panel) are pre-eliminated before stacking the individual input NEQ files.

DELETE: This option allows fixing parameters to their a priori value instead of pre-eliminating them from the system (see Section 9.3.8 for an explanation of the difference between this option and pre-elimination). This option is preferable over a strong constraining followed by pre-elimination because numerical problems caused by tight constraints are avoided. This operation is performed individually for each input NEQ after transforming the parameters to new a priori values.

Parameters from selected stations may be excluded from the pre-elimination strategy (e.g., troposphere parameters from a GNSS and VLBI solution on co-located sites) in panel “ADDNEQ2 4.5: Parameter Pre-Elimination” (shown in Figure 9.8). Options such as “Except for stations: troposphere ZPDs” (cf. panel “ADDNEQ2 4.1: Parameter Pre-Elimination”) are active when a specific parameter type is selected (e.g., station coordinates, biases, troposphere parameters, and loading displacement scaling factors).

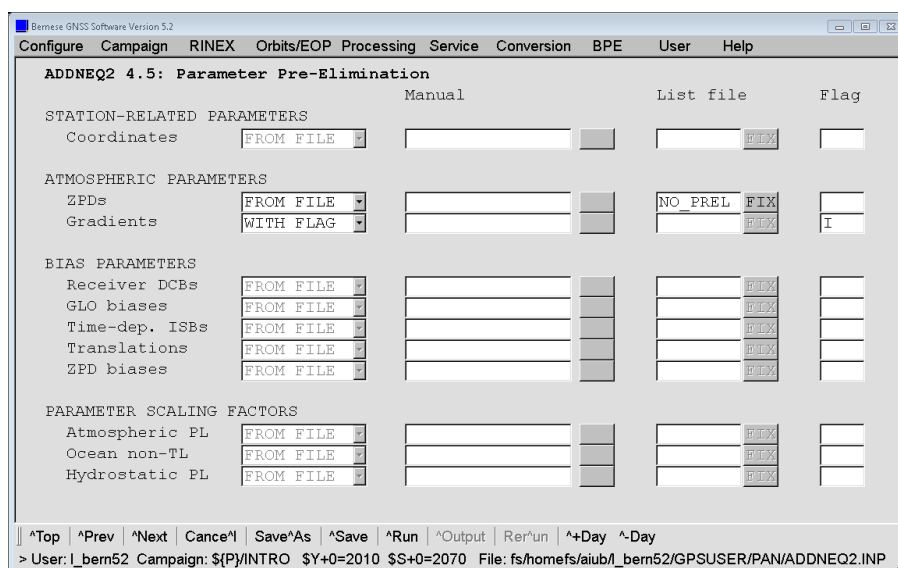


Figure 9.8.: Advanced pre-elimination options for station-related parameters in ADDNEQ2.

As already mentioned in Section 7.7.1, the constraints for pre-eliminated parameters have to be selected with care because they cannot be changed anymore.

Detailed information about the parameter pre-elimination is provided in the program output whenever the option “Print detailed list of all parameter manipulations” in panel “ADDNEQ2 3.2: Options 2” is enabled. See the online help for a description of the output.

9.4.4. Change of Parameter Interval Length

In ADDNEQ2, time-dependent parameters are modeled consistently as piecewise linear functions, i.e., as continuous functions. Parameters are estimated at regularly spaced time intervals (so-called nodal points). Between two nodal points, time-dependent parameters are modeled by linear functions. Using the options in panel “ADDNEQ2 8: Interval Length of Parameters”, it is possible to reduce the temporal resolution of the representation for troposphere parameters, time-dependent inter-system bias parameters, and EOPs by modifying the spacing of the parameters.

A reduction of the number of parameters is only possible by removing existing parameters. In this case the parametrization can be transformed to the new specification, resulting again in a piecewise linear parametrization using the linear parameter transformation as described in Section 9.3.5. Note that the new spacing must be an integer multiple of the original spacing. Hence, a 2-hourly troposphere representation can be changed to a 4-hourly representation but not to a 3-hourly representation.

In addition, the offset of the parameters with respect to the beginning of the session can be specified in the field “Reference epoch for parameter intervals: Time offset”. This option is implemented for special applications. In general, this field is left empty to retain the parameter offset from the input NEQs.

When a NEQ file is generated by GPSEST, the EOPs are represented by offset and drift for a specific time interval (e.g., 24 hours). In program ADDNEQ2 the representation is forced to be piecewise linear. The transformation (cf. Section 7.6.1) is enabled as soon as a value is specified in the input field to redefine the parameter spacing for EOPs. This value can even indicate the same resolution in time as in the input NEQ file (24 00 00 hours in our example). If the transformation to the piecewise linear representation is not performed, no continuity condition for consecutive parameter sets is applied. In addition to normal equations resulting from GPSEST, also NEQ files converted from SINEX files may contain the offset and drift representation for EOPs.

Detailed information about changes of parameter intervals is given in the program output under the title `Change number of intervals`.

9.4.5. Helmert Transformation Parameters between NEQs

ADDNEQ2 in the *Bernese GNSS Software* Version 5.2 allows to estimate Helmert transformation parameters for translation, rotation, and/or scale between the input NEQ files in order to compensate for systematic effects between the NEQ systems. These parameters should be used carefully because they can easily absorb relevant effects. Mind that these transformation parameters are not needed if all NEQ files are generated with the *Bernese GNSS Software*.

COVARIANCE COMPONENTS			26-MAR-09 16:35				
COVARIANCE COMPONENT ESTIMATION AND HELMERT PARAMETERS							
NUM	VALUE	FILENAME	GRP	HELMERT	PAR.	HELMERT	VALUES
***	*****	*****	***	*	*	*	*****
1	6.10126396545036E-01	\${P}/IGSFINAL/SOL/Q1N09052.NQO		2	2	0	0.0000
2	6.16395007991341E-01	\${P}/IGSFINAL/SOL/Q1N09053.NQO		2	2	0	0.0000
3	1.00000000000000E+00		BEK	2	2	0	0.0000
4	1.00000000000000E+00		CDE	2	2	0	0.0000

Figure 9.9.: Example of the variance rescaling factor with a setup of Helmert transformation parameters.

The parameters are set up in the columns HELMERT PAR. in the NEQ rescaling file (default extension WGT), which can be specified in the field “Variance rescaling factors” in panel “ADDNEQ2 1.1: Input Files 1” (see Figure 9.9 for an example). The following options are supported:

- indicator 1: applies given Helmert transformation parameters,
- indicator 2: sets up individual input NEQ files and the resulting combined normal equation as described in Section 9.3.6. The Helmert transformation parameters will be estimated together with the other parameters.

When Helmert transformation parameters between normal equations are available, some additional options for parameter handling are displayed in panel “ADDNEQ2 18: Options for Helmert Transformation Parameters”. They specify how the Helmert transformation parameters belonging to different groups should be treated:

- NO STACKING: keeps the parameters as they are in the input NEQs. This may result in time series of Helmert transformation parameters for each group.
- IDENT_GROUP: stacks only Helmert transformation parameters belonging to the same group. The group is defined by specific strings in the GRP column in the NEQ rescaling file (see Figure 9.9). This results in one set of Helmert transformation parameters per group that is valid over the entire time span covered by all input NEQs.
- STACK_ALL: stacks all Helmert transformation parameters independently of the group and epoch. This results in only one set of Helmert transformation parameters.

9.4.6. Station Information File

Station-related information such as station names, equipment, or antenna eccentricities can be changed using the station information file (see Section 24.7.6). If an antenna eccentricity is modified, the corresponding station coordinates are transformed accordingly and the estimated coordinates refer to the new antenna position. Note that in case of changing the antenna name, the corrections for the antenna phase center offset and variations cannot be adapted. The new equipment information is only considered when writing a SINEX file, whereas the renaming of station names affects all parameters related to the particular station (i.e. not only station coordinates but also troposphere or other parameters).

In the part TYPE 003: HANDLING OF STATION PROBLEMS of the station information file, station names with potential problems are listed together with the affected time interval.

As soon as the parameter interval is touching the time interval, the program is able to distinguish between the left, middle, or right nodal point of a series of piecewise linear parameters — in the station information file, all parameters related to this particular station (not only station coordinate but also, e.g. troposphere parameters or station-specific scale parameters) are pre-eliminated without constraints before stacking. In this way, a station with a problem does not degrade stacked parameters. The station parameters, however, remain implicitly within the normal equations. This implies that in case of severely affected stations, it might be reasonable to reprocess the particular day excluding the corresponding data already from the beginning.

If an equipment change (i.e. a receiver or an antenna change) takes place within an interval of a station coordinate parameter, the corresponding parameters can also be pre-eliminated with the same procedure. The options “Remove station in case of antenna change” and “Remove station in case of receiver change” from the panel “ADDNEQ2 3.2: Options 2” force the parameter pre-elimination of stations with (an) equipment change(s) in the station information file. In case of a jump in the coordinate time series due to antenna changes or earthquakes, for instance, the station may be renamed after the event. Coordinates before and after the event will then not be stacked. Station renamings for such jumps in the coordinate time series can be done automatically using the program FODITS, see Chapter 11.

Velocities of different stations, e.g., of co-located GNSS or GNSS-SLR stations, may be constrained to the same values by applying relative constraints to the respective parameter improvements. Note that in order to get the same velocity estimates for two stations, the corresponding a priori values have to be the same. In the same manner, it is possible to constrain station coordinate estimates of two stations. This might be helpful to consider local ties.

For more details on how to generate a multi-session solution we refer to Section 10.3.5.

9.4.7. Program Output

Like all Bernese processing programs, the output file of program ADDNEQ2 contains first the a priori information, documenting the input files and the important options. The validity interval, the number of observations, and the number of parameters are given for each input NEQ file. The number of explicit parameters is split up into the individual parameter types. Important information, such as a priori constraints or a change of parametrization (e.g., change of parameter spacing, see Section 9.4.4), is listed for each estimated parameter.

The section summarizing the results starts with a list of numbers of parameters and details — for each parameter type — the number of explicitly and implicitly adjusted parameters including information about the pre-elimination type. The number of deleted and singular parameters are listed separately. The a posteriori RMS of unit weight is given in units of the L_1 phase observable and should be in the order of 1 – 2 mm and 2 – 3 mm if the input NEQs were generated with and without elevation-dependent weighting, respectively.

The results for all estimated parameters are provided in tables in a generic format including a parameter description, the estimated correction, the estimated value, the RMS error, the a priori value, and the time interval of validity for constant parameters or the

parameter epoch for piecewise linear or epoch-related parameters. With the option “Provide extended output w.r.t. estimated parameters” in panel “ADDNEQ2 3.2: Options 2” enabled, additional columns are added containing the mean epoch in modified Julian date, the internal parameter number, and a string that characterizes the parameter allowing for the extraction of the information (by using, e.g., a simple `grep` command on UNIX platforms). Table 9.1 gives a complete list of these identification strings.

The tables in the output file contain information about the estimated parameters. Since, e.g., site velocities are parametrized by two coordinate sets at different epochs, the tables contain the information related to these two parameter sets if velocities are estimated. For coordinates, velocities, troposphere and global ionosphere parameters, additional sections provide an output similar to that of GPSEST. This output includes, e.g., station coordinate corrections in north, east, up, error ellipsoid information, as well as site velocity estimations (see Section 10.3.1) and information about the tilting angle information for tropospheric gradient parameters.

Provided that option “Compute and compare individual solutions” is enabled, the ADDNEQ2 output from *Bernese GNSS Software* Version 5.2 contains more statistics about the individual solutions than it was the case for the previous versions. The output file specified in option “All parameter residuals” (panel “ADDNEQ2 2.2: Output Files 2”) contains the full output for estimated parameters of each individual solution from one of the input NEQ files. Instead of the a priori value, the estimate from the overall solution is used, resulting in a repeatability series for all parameters.

The program GPSXTR may be used to extract information from ADDNEQ2 program output files and to write an “Output summary”, a “GIM summary”, a “Campaign summary”, and a “Weekly summary” (cf. Section 7.9.2 for more details).

Table 9.1.: Parameter-specific identification strings in the ADDNEQ2 output file.

Parameter ID	Description
#CRD	Station coordinates and velocities
#TRP	Site-specific troposphere parameters
#GIM	Global ionosphere map parameters
#DCB	Differential Code Bias parameters
#GCC	Geocenter coordinates
#ERP	Earth orientation parameters
#ORB	Orbit parameters (Keplerian and empirical)
#SORB	Stochastic orbit parameters
#SAO	Satellite antenna offset parameters
#SAP	Satellite antenna phase pattern parameters
#RAO	Receiver antenna offsets
#RAP	Receiver antenna pattern
#SCK	Epoch-wise satellite clock parameters
#RCO	Receiver clock offsets/biases
#RCK	Epoch-wise receiver clock parameters
#RGB	SLR range biases
#HOI	higher order ionosphere scaling factors
#GRD	Scaling factors for Vienna loading grid files
#GTRA	GNSS-specific parameters — translations
#GTRP	GNSS-specific parameters — troposphere biases
#HLM	Helmert parameters

9.4.8. Writing Normal Equations Using GPSEST and ADDNEQ2

Let us add a few remarks about writing NEQ files using GPSEST and ADDNEQ2:

- Do not fix coordinates in GPSEST or ADDNEQ2 when writing NEQ files, because coordinates for fixed sites are removed from the normal equation. Instead, constrain the station coordinates by using, e.g., an a priori sigma of 0.0001 m.
- Pre-eliminate ambiguity parameters `PRIOR_TO_NEQ_SAVING` in GPSEST when saving normal equations.
- Pre-eliminate epoch parameters such as kinematic coordinates and stochastic ionosphere parameters `PRIOR_TO_NEQ_SAVING` in GPSEST when saving normal equations. These parameters may be back-substituted in a subsequent step (see Section 9.5.3).

Clock parameters do not have to be pre-eliminated in the *Bernese GNSS Software* Version 5.2. Nevertheless, it is recommended to consider the potentially large number of clock parameters in a normal equation that must be inverted by ADDNEQ2. The option “Sampling rate for preelimination” in panel “GPSEST 6.7: General Options for Epoch Parameters” may be used to reduce the number of epochs to be included in the processing at NEQ level.

- In program GPSEST, EOPs are saved in the NEQs as offset and drift. In order to force a conversion to a piecewise linear representation, specify the parameter spacing in ADDNEQ2 (see Section 9.4.4).

9.4.9. SINEX Files

9.4.9.1. Writing SINEX Files

ADDNEQ2 supports the writing of SINEX Version 2.10. Station coordinates and velocities, troposphere parameters (zenith path delays (ZPDs) and gradients), EOPs, geocenter coordinates, satellite antenna offsets, and SLR range biases may be included as parameters. Other parameters have to be pre-eliminated (before or after stacking) when writing the solution to a SINEX file. According to the specification in option “Content of SINEX”, the SINEX file may contain the representation as normal equations (NEQ) or covariances (COV).

The information for the SINEX header blocks `FILE/REFERENCE`, `FILE/COMMENT`, and `INPUT/ACKNOWLEDGMENTS` is taken from the SINEX information file that is specified in option “SINEX general input file” in panel “ADDNEQ2 1.3: General Files” (see Section 24.3.18). A user should adapt the content of this file to his own needs before exchanging SINEX files with other institutions.

All other SINEX header information is extracted from the input NEQs and is originally written by GPSEST based on the station information file or the phase center file. This includes the station descriptions in the `SITE/ID` block, receiver and antenna names in the `SITE/RECEIVER` and `SITE/ANTENNA` blocks, antenna eccentricities in the `SITE/ECCENTRICITY` block, and antenna phase center offsets in the `SITE/GPS_PHAS_CENTER` block. The receiver serial numbers or firmware versions are not written. The antenna serial number is only reported if antenna corrections from an individual calibration was applied.

In this case, the last five characters from the long antenna number, as expected in the RINEX header, is extracted from the station information file.

The point code is incremented from A to B or C for station specific parameters related to stations with the same 4-character abbreviation but different DOMES code. If the 4-character abbreviation and the DOMES code are identical, the solution ID is incremented.

If the option “Truncate all NEQ station names after position 14” in panel “ADDNEQ2 3.2: Options 2” is enabled, all characters in the station names after position 14 are disregarded in order to eliminate characters such as B, C, etc., following the DOMES code and indicating different coordinate solutions. Instead of NO or YES, a number may be specified giving the position after which the station names shall be truncated. Truncated station names are not only for SINEX files but for all output files.

The a priori constraint matrix in the SINEX file (SOLUTION/MATRIX_APRIORI block) has to be regular. This is not the case if the datum is defined using a free network constraint or if not all stations are constrained. If YES is selected for the option “Regularize a priori constraint matrix”, an additional weight (i.e., in addition to the weight defined in the panel) of 10^{-7} is applied to the diagonal of the matrix (as well as to the solution matrix). Alternatively, you may specify another value as regularization constraint in the same field.

The option “Include ADDNEQ1-style statistics block” allows to include a comment block containing statistical information in the SINEX output file, as it was generated by the old ADDNEQ program; it is available solely for backwards compatibility.

9.4.9.2. Import of SINEX Files

Program SNX2NQ0 (“Menu>Conversion>SINEX to normal equations”) allows converting a list of SINEX files to binary NEQ files. The program supports SINEX Versions 0.05 to 2.10, see also Section 4.5. The program inverts the (constrained) correlation or covariance matrix (block SOLUTION/MATRIX_ESTIMATE) as well as the constraint matrix (block SOLUTION/MATRIX_APRIORI) before subtracting the second from the first matrix to obtain the unconstrained normal equation matrix.

Alternatively, the program may read normal equations directly from a SINEX file if the corresponding block SOLUTION/NORMAL_EQUATION_MATRIX is available. In option “SOLUTION block for generating normal equation system” in panel “SNX2NQ0 2: Options” the requested SINEX source block can be selected (COV or NEQ).

In case the SINEX files contain both a covariance block (COVA) and a normal equation block (NEQ, SINEX 2.x), the user must specify the block to be used to generate the NEQ files in the option “SOLUTION block for generating normal equation system”. If the necessary blocks are not available in the SINEX file, the program automatically goes for the other option. A corresponding message is written to the error message file.

If the option “Reconstruct original NEQ info from Bernese SINEX data” is enabled, the original NEQ information is reconstructed from SINEX files written by the *Bernese GNSS Software*. The SOLUTION/STATISTICS block is used for Bernese SINEX files written by ADDNEQ2 and the SINEX header information is used for Bernese SINEX files written by the old program version (ADDNEQ). Mind that the statistical information might be not extracted correctly if the SINEX files are not Bernese SINEX files.

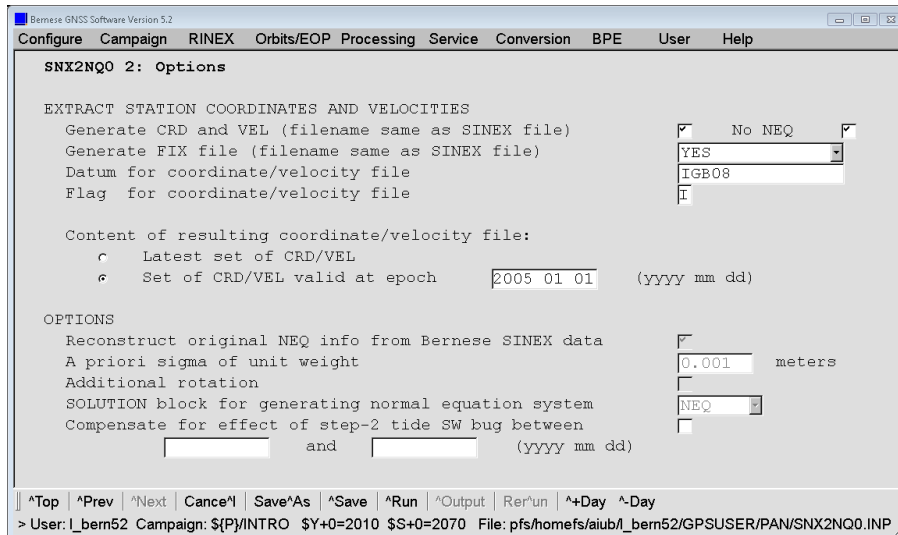


Figure 9.10.: SNX2NQ0 2: Preparing CRD and VEL files on the basis of NEQ files in SNX2NQ0.

The unit weight specified in option “A priori sigma of unit weight” usually corresponds to the weight of the zero-difference L_1 phase observable at zenith. If you reconstruct the original NEQ information from Bernese SINEX files, this a priori sigma is not used but it is extracted from the SINEX data.

With the option “Generate CRD and VEL (filename same as SINEX file)” in panel “SNX2NQ0 2: Options” (see Figure 9.10), station coordinates and — if available — velocities are extracted from the SINEX SOLUTION/ESTIMATE block and written to a file in Bernese format. It can be specified in the panel whether the station coordinates and velocities are to be valid for the latest set of coordinates and velocities or for a specific interval chosen by the user. The option “Do not save NEQ”, which allows for saving solely station coordinates and velocities without saving NQ0 files, significantly accelerates the procedure.

The new option “Generate FIX file (filename same as SINEX file)” allows it to generate a station selection file (default extension FIX) that is, in particular, useful for the datum definition. The online help provides further information.

Using the program SNX2STA (“Menu>Service>Station information files>Extract information from SINEX”) station information may be extracted from a SINEX file and written to a station information file. The information extracted includes station name and description (from SITE/ID block), receiver name and unit number (from SITE/RECEIVER block), antenna name and serial number (from SITE/ANTENNA block) as well as antenna eccentricity (from SITE/ECCENTRICITY block). All four blocks have to be present in the SINEX file and must be consistent.

You may specify a station selection file containing a list of station names. Only stations specified in this input file will be included in the output station information file. Note that only the first 14 characters of the station names are used to identify the stations.

In any case, it is important to check the content of the output file and, if necessary, to adapt or complement its content.

The program SNX2SLR (“Menu>Service>SLR utilities>Prepare SLR data handling file”) generates or merges SLR data handling files (e.g., with range biases) and station information files (STA with, e.g., data exclusions) from the ILRS SINEX format. For details about SLR data processing, see Chapter 19.

9.4.10. Conversion of Normal Equation Files

9.4.10.1. Conversion from and to ASCII

In order to allow the transfer of binary NEQ files between platforms that are binary incompatible (or for the case that a user would like to check the content of a NEQ file with an ASCII editor), the program NEQ2ASC ("Menu>Conversion>Normal equations (binary/ASCII)") is available. The program allows converting NEQ files in both directions. A list of files (binary or ASCII) may be selected for the conversion in a single run.

9.4.10.2. Old Normal Equation Files from ADDNEQ

Not all file types from Version 4.2 or older are supported by the *Bernese GNSS Software* Version 5.2. In particular, old NEQ files generated by the old program ADDNEQ (with extension NEQ) can be neither read nor converted to the new NQ0 format. Only a conversion using SINEX files from the old solutions is possible.

9.5. Typical Applications

ADDNEQ2 allows for a large variety of applications. Some examples are the combination of final results for larger campaigns, the combination and densification of networks, and the combination of results from short sessions (e.g., from hourly processing steps). In Chapter 10 more information about the application of ADDNEQ2 for the datum definition and for the estimation of station velocities is provided. Chapter 16 informs on how to use ADDNEQ2 to perform a long-arc orbit analysis.

ADDNEQ2 may be used, as well, to generate a multitude of different solutions for scientific investigations, which are all based on the same GPSEST run. You may, e.g., use GPSEST to compute a solution with hourly or sub-hourly resolution of troposphere parameters and to set up tropospheric gradient parameters. In a number of much shorter runs, you may then with ADDNEQ2 compute solutions with no gradient parameters (delete parameters) and/or with a reduced resolution of troposphere parameters. Based on the resulting series of different solutions you might, e.g., study the repeatability of station coordinates for the different solutions. Similarly, you may routinely set up, e.g., satellite or receiver antenna phase center offset parameters and delete them in a second ADDNEQ2 run for your official solution. Using the same normal equations you may then recover the phase center offsets and investigate their effect on the solution.

When scaling factors for HOI corrections and loading grid models are set up as additional parameters, switching on or off the total model is possible in ADDNEQ2 by deleting the parameters after setting them to one or zero, respectively. This operation does not require any further operations at the observation level in GPSEST. Operations with scaling factors are, thus, very flexible in ADDNEQ2 when testing, e.g., the impact of atmospheric pressure loading on estimated station coordinates or EOPs.

This section gives some additional examples for applications. Users are invited to invent more applications that fit their particular needs or interests.

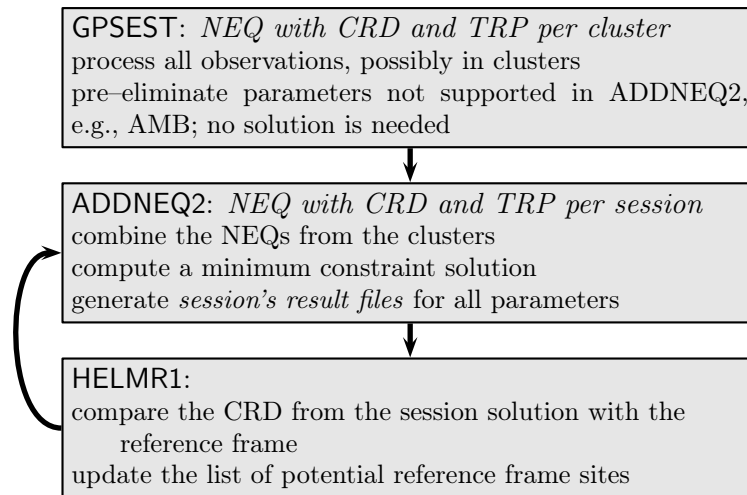


Figure 9.11.: Generate a session solution from clusters with datum definition.

9.5.1. Cluster Combination

In case of analyzing large networks, the number of stations may no longer allow processing all stations in a single GPSEST run applying correct correlations. If the number of stations is considerably larger than 100, the processing time and the memory consumption may become very large. Of course, this limit varies according to computer resources and potential computing time constraints, e.g., in case of near real-time processing. A solution might be to analyze groups of baselines (so-called clusters) independently in program GPSEST and to combine the cluster results afterwards using the program ADDNEQ2. The principle of this procedure is displayed in Figure 9.11.

Correct correlations can be enabled in the individual GPSEST runs. Since the solution is provided by the subsequent ADDNEQ2 run, there is no need to solve the resulting normal equations in GPSEST (enable option “Stop program after NEQ saving” in panel “GPSEST 3.2: General Options 2”). The only output apart from the program output file is a cluster NEQ file. These normal equations are combined using ADDNEQ2 to get the final solution. All result files such as the coordinate, troposphere and other output files are generated in this run.

The strategy described in the paragraph above allows us to partially consider the correlations between baselines, namely those within each cluster. Correlations between baselines in different clusters, however, are lost because they are not considered by ADDNEQ2 (this is a result of the diagonal structure of the weight matrix \mathbf{P}_p in Eqn. (9.8)). Clusters of baselines have, therefore, to be carefully selected for having minimum overlaps in order to minimize the effects of neglecting these correlations. Clusters of baselines may be defined either within the program SNGDIF using a cluster definition file (description in Section 24.7.18) or they may be automatically generated using the program MKCLUS (see Section 22.12.2.1).

Datum Definition

In most cases, the minimum constrained solution strategy (described in Section 9.3.7) should be used for the definition of the geodetic datum. The resulting coordinate solution

reflects the geometry of the network as given by the GNSS data. By comparing these coordinates with the reference frame coordinate set using the program HELMR1, the consistency can be checked. In case of significant deviations, certain stations can be excluded from the datum definition. The verified list of reference stations is used for the definition of the geodetic datum in the final solution (cf. loop displayed in Figure 9.11). More information about the datum definition in the *Bernese GNSS Software Version 5.2*, is provided in Section 10.2.

9.5.2. Generate Small Normal Equation Files

For reasonably large networks, the troposphere parameters constitute a large fraction of the overall number of estimated parameters and are, thus, responsible for large NEQ files. For experimental purposes it might make sense to set up a number of additional parameters in GPSEST since on the NEQ level the number of parameters can be reduced, but not increased. It may, however, be advantageous to archive smaller NEQ files for later use for coordinate time series analysis, for instance. Small NEQ files require less disc space and their inversion is significantly faster as the computational complexity. The computing time increases quadratically with respect to the number of explicitly estimated parameters (note that the number of explicitly estimated parameters corresponds to the dimension of the NEQ system). A reduction of the NEQ size may be performed with program ADDNEQ2.

Suppose that solutions with full-size NEQ files according to Figure 9.12 have been generated. Typically, they contain coordinate and troposphere parameters. In a separate ADDNEQ2 run with a single full-size NEQ file as input, the troposphere parameters may be pre-eliminated before stacking. Only parameters relevant for a long-time evaluation (typically coordinate parameters) remain in the reduced NEQ file resulting from this procedure.

In this step, it is not necessary to generate a solution because the result is identical with the inversion of the full size NEQ described in Section 9.5.1. Note that this step is also well suited to generate a SINEX output file containing coordinate parameters. If your reduced sized NEQ files shall contain additional parameters for a long-term evaluation (for instance scaling factors or satellite antenna parameters) you might need two runs of ADDNEQ2: the first to generate the reduced sized NEQ as described above and the second

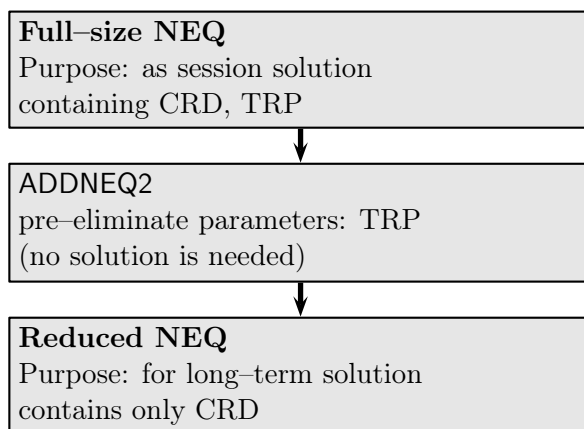


Figure 9.12.: Generation of small NEQ files for a long-term evaluation.

to reduce the parameters by pre-eliminating or deleting all parameters (see Section 9.3.5) that are not requested in the SINEX output file.

As an alternative to the pre-elimination of all troposphere parameters, the option `EXCEPT_FOR_BOUNDARIES` may be used (see Section 9.4.3). Troposphere parameters then remain accessible at the NEQ boundaries for stacking of a series of normal equations to establish continuity between the individual NEQ intervals. Note, however, that in this case, you may still end up with a large number of parameters when stacking a large number of normal equations.

9.5.3. Back-Substitution of Coordinates

Since troposphere parameters are highly correlated with the station height (and the station clock), troposphere estimates are improved if they are obtained, e.g., from a weekly solution instead of a daily solution. One may, therefore, be tempted to combine large daily NEQ files, which contain station coordinate and troposphere parameters, to a single weekly solution and extract both types of parameters from this `ADDNEQ2` run.

Depending on the size of the network, however, the number of parameters in the combined weekly solution may become very large and memory consumption as well as processing time may become extensive. A two-step pre-elimination and back-substitution procedure involving several `ADDNEQ2` runs may help to solve this situation (see Figure 9.13).

In the first step of the pre-elimination and back-substitution procedure, seven full-size NEQ files are combined using `ADDNEQ2` (cf. Figure 9.13). Troposphere parameters are pre-eliminated either `BEFORE_STACKING` (without continuity between the NEQs) or by using the option `EXCEPT_FOR_BOUNDARIES` (with continuity between the NEQs) when the resulting NEQ is stored. In a subsequent `ADDNEQ2` run, the remaining troposphere parameters are pre-eliminated and a weekly coordinate file is written. This step might be repeated with an adjusted set of reference stations after the verification using the `HELMR1` program. The obtained coordinates are identical to those which would have been computed if troposphere parameters were not pre-eliminated, because the troposphere parameters are implicitly contained in the solution, even if they are pre-eliminated.

If the repeatability of the daily coordinate sets shall be evaluated (option “Compute and compare individual solutions” in panel “`ADDNEQ2` 3.1: Options 1” is enabled), both `ADDNEQ2` steps have to be combined into one step. Note that the computing time is increased because the pre-elimination of the troposphere parameters has to be repeated after each update of the list of potential reference frame sites.

In the second step of the pre-elimination and back-substitution procedure, `ADDNEQ2` is executed independently for each large daily NEQ file (holding a complete set of explicit troposphere parameters). This time, troposphere parameters are not pre-eliminated, but estimated and written to a file. Coordinates are, however, fixed to the weekly coordinates estimated in step 1. Except for the missing stacking of troposphere parameters at the midnight epoch (in case troposphere parameters were not pre-eliminated at the borders in step 1), the troposphere delay estimates are equal to those that were obtained in a combination of the large normal equations without the pre-elimination step. The main difference resides in the estimated formal accuracies for the troposphere parameters because the described back-substitution step does not incorporate covariance information concerning the estimated weekly coordinates.

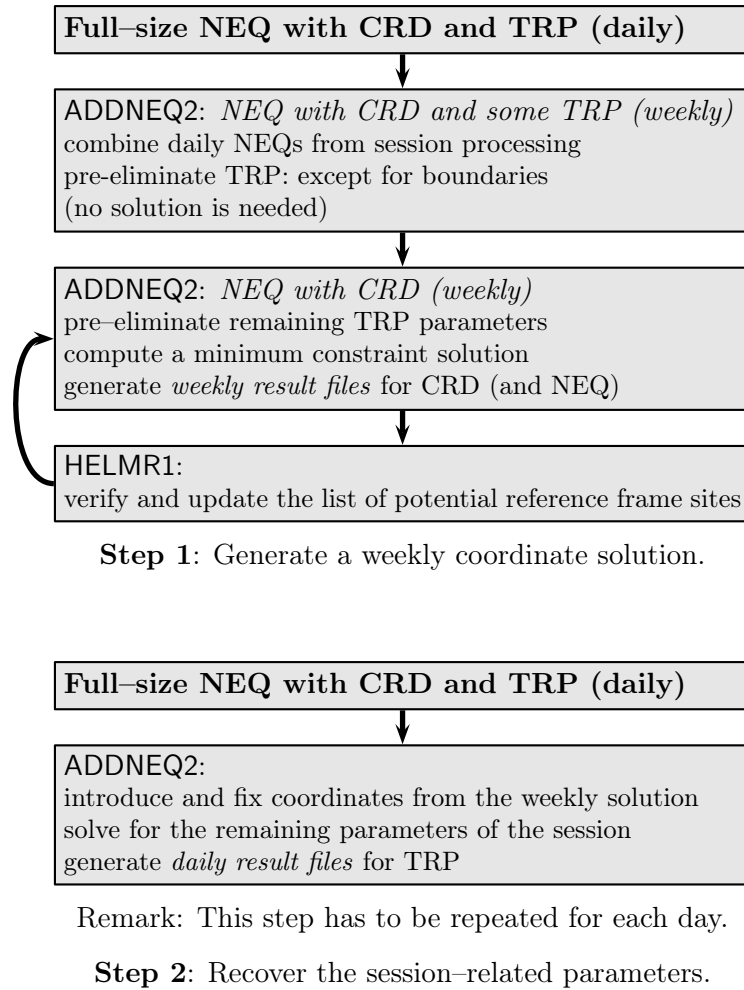


Figure 9.13.: Generation of weekly coordinates with back-substitution of daily parameters.

Note that a similar back-substitution scheme may also be applied for computing epoch parameters such as kinematic station coordinates or clock parameters. In this case, you may introduce coordinates of static stations and troposphere parameters computed with ADDNEQ2 as fixed into GPSEST and recompute the epoch parameters that were pre-eliminated in the first GPSEST run before saving the normal equations.

10. Station Coordinates and Velocities

Station coordinates and velocities are probably the most sought-after result of GNSS analyses. Moreover, good coordinates are a prerequisite for the accurate determination of most other parameters. Thus, the estimation of precise station coordinates will eventually become an issue in virtually all GNSS analyses.

GNSS is basically a differential technique, i.e., it only gives access to precise relative geometry information and not to absolute positions. This is rooted in the fact that the measurements are related to ranges only through unknown clock corrections and phase ambiguity parameters. As a matter of fact, the geodetic datum of GNSS-based site coordinates obtained in a network solution has to be defined by introducing external information. Reference frame issues and geodetic datum definition are intimately connected with coordinate estimation and are addressed in this chapter.

When estimating coordinates using GNSS observations two major processing modes can be distinguished, namely Precise Point Positioning (PPP) and a differential (relative) mode. PPP relies on precise orbit and clock information for deriving precise site coordinates and receiver clock corrections for each analyzed station independently and is based on undifferenced code and/or phase observations (Section 10.6). The differential mode promises highest precision for the relative geometry between the sites processed together in a network solution.

The *Bernese GNSS Software* allows estimating site coordinates in a network analysis based on undifferenced or double-differenced GNSS observations or undifferenced SLR ranges. Full profit from the integer nature of the phase ambiguities can only be taken in the double-difference mode (see Chapter 8), which is thus the first choice for obtaining highest quality results.

Apart from static coordinates, the *Bernese GNSS Software* Version 5.2 offers the possibility to estimate kinematic site coordinates (Section 10.5). Linear station velocities may be derived from a multi-session solution using program ADDNEQ2 which operates on normal equation level (Section 10.3.3). Several additional programs are available for comparing or manipulating coordinate files (Section 10.7). The automated analysis of time series of station coordinates using program FODITS is described in Chapter 11.

10.1. Site Displacement Modeling

To ensure a high accuracy of coordinates and other parameters estimated with the *Bernese GNSS Software*, a careful modeling of site displacements is mandatory. The most important effects and adopted models are described in the following.

10.1.1. Tectonic Plate Motion

Station coordinates are changing in time due to the steady movement of tectonic plates. Figure 10.11 shows the present day major tectonic plates. This movement must be taken

into account in GNSS analyses. Station coordinates (especially of reference sites) should, therefore, always be propagated from the reference epoch to the observation epoch based on corresponding station velocities. This ensures consistency with the IGS satellite orbits and prevents network deformations induced by moving plates.

If unavailable from other sources (e.g., the IERS), reasonable station velocities may be derived from a model, e.g., NNR-NUVEL-1A (DeMets et al. 1994), complying with the IERS Conventions (Petit and Luzum 2010).

The *Bernese GNSS Software* offers corresponding programs to compute model velocities and to propagate coordinates, namely NUVELO and COOVEL. Both are described in Section 10.7.

10.1.2. Solid Earth Tides, Solid and Ocean Pole Tides, and Permanent Tides

Effects of solid Earth tides have to be taken into account because they are two orders of magnitude larger than the accuracies currently achieved for GNSS- and SLR-derived coordinates. The *Bernese GNSS Software* Version 5.2 adheres to the IERS Conventions 2010 (Petit and Luzum 2010) to model the solid Earth tides. The “step 1” and “step 2” corrections are implemented. The effects of the solid Earth pole tide and the ocean pole tide are modeled according to the IERS Conventions 2010, as well.

In accordance with common geodetic practice, estimated coordinates are freed from all tidal corrections including the permanent tide. To obtain coordinate values that correspond to the mean over long periods, the permanent tide must be added to the estimated coordinates. Handling of the permanent tide can be changed in the subroutine `LG/TIDE2000.f`. A description of the “permanent problem of the permanent tide” is given, e.g., in Ekman (1995).

Note, that estimated positions for all stations are corrected for solid Earth tides and solid Earth pole tides. The only exception are stations that are flagged with `SPACEBORNE` in Section `TYPE 005: HANDLING STATION TYPES` in the station information file. Typically these are Low Earth orbiters equipped with GNSS receivers.

10.1.3. Ocean Tidal Loading

Another important site displacement effect is the crustal deformation caused by the changing mass distribution due to ocean tides (ocean tidal loading). A file containing station-specific coefficients for the magnitude of the ocean loading effect (amplitude and phase shift for the eleven most important constituents) may be selected to correct for the site displacement (programs `CODSPP`, `MAUPRP`, `GPSEST`, `GPSSIM`, and `CLKEST`). Although this file is not mandatory its use is strongly recommended, because otherwise vertical and horizontal corrections will not be applied. The eleven main constituents are internally interpolated to 342 constituents using an adapted version of the routine as provided in the IERS Conventions 2010 (Petit and Luzum 2010). Nodal modulations are not accounted for in Version 5.2. The related center of mass corrections are discussed in Section 5.4.1.

The format of the ocean tidal loading file and the procedure how to add more stations is described in Section 24.7.9. A file containing a subset of the IGS stations is available at the

anonymous FTP site <http://www.aiub.unibe.ch/download/BSWUSER52/STA/FES2004.BLQ> (see Section 4.13). The file <http://www.aiub.unibe.ch/download/BSWUSER52/TXT/BLQ.README> contains additional information and more details. Make sure to use a consistent set of coefficients (e.g., the same ocean tidal model for all stations). If a station is not found in the file a warning message is issued and no corrections are applied to this station.

10.1.4. Atmospheric Tidal Loading

The crustal deformations caused by the changing mass distribution in the atmosphere consist of the tidal and non-tidal part. The atmospheric tidal loading is typically expressed by S_1 and S_2 constituents, having maximal amplitudes of 1.5 mm in the equatorial area. Considering the uncertainty of related models, the IGS recommends to not apply the corresponding corrections to the observations.

On the other hand, the atmospheric tidal effect is usually not included in atmospheric non-tidal loading models. To correct for the full atmospheric pressure loading effect it is indispensable to apply both model components consistently, as it was intended when the loading models were constructed.

In analogy to site displacements caused by the ocean tidal loading, the loading effect of atmospheric tides is taken into account in data processing programs by introducing a specific file (default extension *ATL*), e.g., *GPSEST* and *CLKEST*. These atmospheric tidal corrections may be extracted from global grids for all stations in a coordinate file by using the program *GRDS1S2*. A detailed description of the program can be found in Section 10.7.10.

Even if the center of mass corrections are below the significance level, they can be treated analogously to the ocean tidal loading in the orbit programs (see Section 5.4.1).

10.1.5. Non-Tidal Loading

Any site displacement may be introduced for correcting the station coordinates during the processing of GNSS or SLR observations in Version 5.2 of *Bernese GNSS Software*. Three dimensional grids are expected using the same format as the grids for the VMF1 corrections (format description is provided in Section 24.9).

As Table 10.1 shows, three types of displacement files are distinguished in *Bernese GNSS Software* Version 5.2, namely:

- atmospheric non-tidal loading,
- ocean non-tidal loading, and
- hydrological effects.

Table 10.1.: List of Vienna GRID files with allowed keywords.

Type	Description	Number of entries	Keyword in program input file
ATM-NT-LOAD	atmospheric non-tidal loading	3	ALOAD_FILES
OCN-NT-LOAD	ocean non-tidal loading	3	ONTLD_FILES
HYDR-LOAD	hydrological effects	3	HLOAD_FILES
VMF1	VMF1 troposphere model	4	VMF1_FILES

INFORMATION ON VIENNA GRID FILES :									
Filename	Type	Range of latitude			Range of longitude			Epoch	
		min	max	step	min	max	step		
VMF13068.GRD	VMF1	-90.0	90.0	2.0	0.0	360.0	2.5	2013-03-09	00:00:00
...									
VMF13068.GRD	VMF1	-90.0	90.0	2.0	0.0	360.0	2.5	2013-03-10	00:00:00
APL13068.GRD	ATM-NT-LOAD	-89.5	89.5	1.0	0.5	359.5	1.0	2013-03-09	00:00:00
APL13068.GRD	ATM-NT-LOAD	-89.5	89.5	1.0	0.5	359.5	1.0	2013-03-09	06:00:00
...									

Figure 10.1.: Example of a report concerning used GRID files in GPSEST.

The non-tidal effects may even reach up to several centimeters. The largest variations for the inland stations are expected from the atmospheric pressure loading — please be reminded of the required consistency between the tidal and non-tidal part. On the other hand, the ocean non-tidal loading effect is more important for coastal sites.

Each of the grid files with site displacements is expected to have three columns. The source of the site displacement is identified by the related TYPE string in the header section of the data record. The files are only accepted if they are given in the correct input field of the processing program GPSEST. Whether all specified grid files have been correctly accepted by the processing program, can be verified in a section of the program output from GPSEST (see Figure 10.1 for an example).

As soon as a grid file with these site displacement corrections is specified in one of the input fields for the program GPSEST, the corresponding corrections are applied as time-dependent corrections to the station coordinates. Because of the grid structure of the data files, a spatial and temporal linear interpolation has to be done.

According to the current IERS and IGS conventions, such corrections shall not be applied to any official product. On the other hand, several studies (e.g., Dach et al. 2011a; Sošnica et al. 2013) have shown advantages when applying, e.g., atmospheric pressure loading corrections directly to the observations.

In this context it might be of interest that these site displacement corrections may be allocated with scaling factor parameters. They allow to rescale or remove the non-tidal corrections at the normal equation level in ADDNEQ2 by setting up scaling factor parameters in GPSEST. A detailed discussion of the scaling factors for non-tidal loading displacements is given in Section 10.4.

10.1.6. Other Site Displacements

There are other effects causing site displacements like post-glacial rebound or post-earthquake relaxation. The *Bernese GNSS Software* Version 5.2 does not apply models for these effects, but these effects are measurable with GNSS and may be investigated in an analysis of coordinate time series using program FODITS.

10.2. Defining the Geodetic Datum for a Tracking Network

GNSS is basically a differential technique due to the fact that the measurements are related to absolute ranges between receivers and satellites through unknown clock corrections and

phase ambiguity parameters. The values of this large amount of parameters have to be estimated, either explicitly or implicitly, irrespective of whether undifferenced or double-differenced observations are processed. The only exception is PPP, where satellite clocks, known from other sources, are introduced as fixed, thereby defining the geodetic datum of the solution.

The fact that one clock bias per receiver and per satellite (implicitly in the case of double-difference processing) as well as at least one ambiguity parameter per link and satellite pass (or double-differences thereof) have to be estimated for each observation epoch, results in a loose definition of the geodetic datum of a processed network. The smaller the geometric extension of the network, the easier it is to compensate a translation of the entire network by adapting clock and ambiguity parameters. As a consequence, the geodetic datum of a network solution has to be introduced as external information.

Using coordinates of one or several reference sites given in a well-defined reference frame, the estimated coordinates can be aligned to that frame. The way this alignment is performed is called *geodetic datum definition*. In this section we discuss the different options provided by the *Bernese GNSS Software*.

Contrary to the absolute geometry, the internal geometry of the network is very well-determined by GNSS measurements because a shift of a single station in a network cannot be compensated by simply adjusting clock and ambiguity parameters. The same is true for the orientation of the network which is imposed by the reference frame in which the used GNSS satellite orbits are represented (as long as no orbit parameters are estimated).

Constraining of sites on a rotated reference frame, in fact, does not change the orientation of the estimated network if orbits are introduced as fixed, but distorts the network.

The geodetic datum has to be defined for estimated velocities, as well. Datum definition of coordinates, e.g., to ITRF, does not implicitly define the velocity datum to the same reference frame. The velocity datum may be defined, as for positions, with minimum constraints or by constraining velocity vectors of reference sites to a priori values.

10.2.1. Reference Frames Important for GNSS Analyses

The IERS Terrestrial Reference System (ITRS) is realized by the International Terrestrial Reference Frame (ITRF). The ITRF consists of 3-dimensional Cartesian coordinates and velocities for a set of globally distributed stations. The coordinates refer to a specific time epoch. The ITRF is updated on a regular basis to include recent results from contributing space techniques (GNSS, SLR, Lunar Laser Ranging (LLR), VLBI, DORIS). The ITRF web site is advisable for more information in this regard (<http://itrf.ensg.ign.fr>). Since ITRF 97, the IGS uses its own realization of the ITRF (Kouba et al. 1998). This IGS realization is not necessarily more accurate, but more consistent. In analogy, the ILRS has also started SLR-specific realizations of the ITRF to process SLR data, e.g., SLRF 08. These realizations contain historical SLR stations and they are updated on a regular basis by the ILRS as soon as a new SLR site is included to the network.

All IGS products are based on the ITRF resp. IGS realization thereof (see Table 10.2 for an overview). Consequently, the ITRF can be accessed with a sub-centimeter accuracy if IGS products are introduced in a GNSS analysis.

Table 10.2.: History of reference frames used for IGS products.

Frame	Used for IGS products between	
	GPS week	Date
ITRF 92	0730 — 0781	02 Jan. 1994 — 31 Dec. 1994
ITRF 93	0782 — 0859	01 Jan. 1995 — 29 June 1996
ITRF 94	0860 — 0947	30 June 1996 — 07 Mar. 1998
ITRF 96	0948 — 1020	08 Mar. 1998 — 31 July 1999
ITRF 97	1021 — 1064	01 Aug. 1999 — 03 June 2000
IGS 97	1065 — 1142	04 June 2000 — 01 Dec. 2001
IGS 00	1143 — 1252	02 Dec. 2001 — 10 Jan. 2004
IGS 00b	1253 — 1398	11 Jan. 2004 — 04 Nov. 2006
IGS 05 ^a	1400 — 1631	05 Nov. 2006 — 16 Apr. 2011
IGS 08	1632 — 1708	17 Apr. 2011 — 06 Oct. 2012
IGb 08	1709 —	07 Oct. 2012 —

^aThe switch to the IGS 05 reference frame was associated with the change from the relative to absolute antenna phase center modeling within the IGS. This model change has an impact on the coordinates of the reference sites, see text. The latest frames, i.e., IGS 08 and IGb 08 use the absolute antenna phase center modeling, as well.

The broadcast ephemerides of GPS satellites refer to the World Geodetic System–84 (WGS–84). This reference system can only be realized with a quality of about 1 m in geocentric position via the broadcast orbits and clock corrections. Nevertheless, the realization of the WGS–84 is close enough to the ITRF so that corresponding coordinates may be adopted for reference stations when broadcast ephemerides are used.

Since January 01, 2014 GLONASS broadcast information is given in the PZ–90.11¹ system which agrees with ITRF at the cm level. The precursor realizations PZ–90.02 and PZ–90 were shifted, and both shifted and rotated, respectively (Tatevian and Kuzin 2015). This fact must be considered when GLONASS broadcast orbits are used. However, GLONASS orbits provided by CODE (or any other analysis center of the IGS) refer to the ITRF, thus they are consistent with the GPS orbits and no further transformation is needed.

Satellite positions in precise orbit files always refer to a particular reference frame. The same reference frame should be used for the ground stations during the analysis to ensure best possible consistency. An analysis of the biases introduced into a regional solution if station positions and satellite orbits are used inconsistently may be found in Beutler et al. (1988). This means, in particular, that any solution using satellite data has to be performed in a global reference frame, e.g., ITRF 2008 or IGS 08. Thus, a transformation into regional reference frames has to be performed after a final coordinate solution is computed, e.g., using the program ETRS89. The *Bernese GNSS Software* does not allow processing of data in regional or local frames (see flags on GLOBAL, REGIONAL, or LOCAL in the “Geodetic datum” file described in Section 24.3.2).

Bernese coordinate and velocity files are available at <http://www.aiub.unibe.ch/download/BSWUSER52/STA> for the various ITRF and IGS realizations. A set of three files are provided for ITRF 2008, IGS 08, and IGb 08: coordinate and velocity files containing IGS reference stations only (e.g., IGB08_R.CRD and IGB08_R.VEL) and a station selection file listing the respective reference sites (e.g., IGB08.FIX). The selection file

¹PZ–90 (Параметры Земли 1990 года) is an Earth–centered and Earth–fixed reference frame.

can be used to easily select the reference stations for datum definition in Bernese programs.

The change to the ITRF 2005 reference frame within the IGS was associated with the switch from relative to absolute antenna phase pattern modeling (see also Section 18.1), which is a widely accepted standard today. Besides, in IGS 05 the receiver antenna phase patterns were developed for GPS, only. Consequently, the antenna phase patterns for GLONASS receivers were a copy of the GPS patterns.

The more recent IGS 08 was derived using the absolute antenna phase pattern modeling based on the first reprocessing campaign of the IGS. As opposed to the IGS 05, the IGS 08 contains the system-specific corrections (different for GPS and GLONASS systems).

Since that time, the IGS dataset has been consistently reprocessed several times by CODE AC using the most recent processing and modeling standards. The resulting products are available at `ftp://ftp.unibe.ch/aiub/REPRO_yyyy/` (where `yyyy` stands for the year of the reprocessing activity). We recommend to use the products from the most recent available reprocessing effort extended by the operational product series. This strategy promises the most consistent time series of solutions.

10.2.2. Datum Definition Types

10.2.2.1. Free Network Solution

A network solution generated without explicitly introducing any datum information is called a *free network solution* in the *Bernese GNSS Software*. The fixed orbits are then the only external information defining the geodetic datum. The network geometry is derived from the GNSS observations and not affected by (possibly bad) reference coordinates. However, the resulting coordinates do not refer to a well-defined reference frame rendering a free network solution unusable to compute precise results.

The estimated network will show considerable translations for different days leading to significant day-to-day coordinate variations. Therefore, the results of a free network solution must be transformed into an appropriate reference frame using, e.g., Helmert transformations (program HELMR1). The daily transformations, however, may accidentally remove part of a geodynamical signal from the time series. An explicit datum definition is advisable in all cases, because the network translations are the effect of correlations with other parameters and small modeling deficiencies, e.g., of troposphere delays.

There are two main applications for a free network solution. It may be used in program GPSEST to create normal equations only, regardless of other results. The geodetic datum must then be defined later in program ADDNEQ2. The second application is the PPP (see Section 10.6), where not only the satellite orbits, but also the satellite clocks are introduced. The resulting coordinates will then share the reference frame defined by the orbits and clocks. The free network solution ensures that no additional constraints are imposed on the estimated coordinates.

10.2.2.2. Minimum Constraint Solution

Conditions based on Helmert constraints on coordinates of (a subset of) sites with respect to a reference frame constitute the best suited way for the datum definition of a network.

The definition of the datum is not based on conditions imposed on single reference stations. Rather, the conditions act on the barycenter of the reference sites or the mean orientation of the network. This type of datum definition is called *minimum constraint solution* in the *Bernese GNSS Software*.

For regional or local GNSS solutions, it is sufficient to demand that the barycenter of the estimated reference coordinates coincides with the barycenter of the a priori coordinates (no-net-translation condition). Because the orientation of the network is defined by the introduced orbits, this type of datum definition is very closely related to the so-called inner constraint solution (Vaníček and Krakiwsky 1982).

In some cases, mainly when estimating GNSS satellite orbits and EOPs in a global network, it is necessary to additionally constrain the rotation of the network (no-net-rotation condition). The scale of the network must only be constrained in very rare cases, e.g., when estimating satellite antenna phase center offsets. Whether to set up the no-net-translation condition in a global network or not, depends on whether the coordinate origin of the solution shall coincide with the the coordinate origin of the reference frame or with the geocenter as it was realized by the solution (see also Section 16.4.3 for details on estimating the geocenter).

The advantage of a minimum constraint solution through three translation conditions on the network's barycenter is that (small) errors in the coordinates of a reference site do neither distort the network geometry nor significantly degrade the datum definition. It is thus the recommended method to estimate final results, when the satellite orbits and EOPs are fixed. Please note, that this option is only available in program ADDNEQ2. The detailed mathematical background is described in Section 9.3.7.

10.2.2.3. Constraining Reference Coordinates

The geodetic datum can be defined by constraining coordinates of reference stations to their a priori values. Infinitely tight constraints correspond to fixing reference coordinates whereas infinitely loose constraints are equivalent to a free network solution. By varying the constraints you may smoothly shift between these two cases. Depending on the quality of the reference site coordinates, tightly constraining of several sites may result in network distortions (“over constraining”).

A solution with a single site constrained to its reference frame position is a particular minimum constraint solution, with the disadvantage that an error in the position of the single reference site propagates into the positions of all other sites in the network.

The advantage of very tight constraints over fixing coordinates is that the constrained station coordinates still remain in the resulting normal equation system. Thus, it is possible to change the datum definition later on in ADDNEQ2.

A loose constraining is in general well suited when saving normal equations in program GPSEST.

10.2.2.4. Fixing Reference Coordinates

If the coordinates of reference stations in the observed network are not estimated but kept fixed, they define the geodetic datum for the GNSS network solution. All other estimated coordinates then refer to that reference frame.

There are certain risks involved in fixing station positions. The reference coordinates may be incorrect or less accurate than the computed GNSS solution would allow, a reference station may have tracking problems and show a bad performance. In either case, the estimated network will be distorted, decreasing the quality of all parameters. On the other hand, if you have very accurate coordinates of reference stations and your current network solution is less accurate (e.g., very short observation time), the network solution may be improved by fixing the good quality reference site coordinates.

In any case, fixing site coordinates is not recommended because the corresponding coordinate parameters are removed from the normal equation system. Thus, the datum definition is frozen and cannot be changed anymore. Use tight constraints instead (e.g., 0.01 mm).

10.2.3. Reference Site Verification

There are several reasons why the coordinates of reference stations may become invalid for datum definition, e.g., co-seismic deformations, snow coverage of the antenna, human interaction, or other influences damaging the antenna installation. Therefore, it is advisable to verify the coordinates of reference stations before using them for datum definition. This is especially important if the coordinates are to be fixed or tightly constrained.

In a minimum constraint solution, the resulting network geometry is independent from the reference sites. Thus, it is well-suited to check the coordinates of reference sites by comparing the estimated coordinates with the a priori values based on a Helmert transformation. The program HELMR1 provides a possibility of an automatized reference site verification and selection, as demonstrated in the examples of Section 9.5. A detailed program description is given in Section 10.7.2.

An abrupt change in the reference coordinates may also be detected by comparing coordinates from the current session with those from previous ones using program COMPAR (see Section 10.7.5). Be aware that a datum definition problem may affect the repeatability of all sites in the network.

10.3. Coordinate and Velocity Estimation in Practice

Before detailing on specific aspects, let us first address some general issues concerning coordinate and velocity estimation with the *Bernese GNSS Software*. There are several programs in Version 5.2 which may be used to estimate station coordinates and velocities. Table 10.3 lists these programs together with the respective estimation approach.

Station coordinates estimated by the two preprocessing programs CODSP and MAUPRP have a limited accuracy because they are based on code measurements only, or on results from an epoch-difference solution, respectively. If the PPP procedure has been executed to generate good a priori coordinates — as recommended in Section 3.8 — these preliminary coordinate results are not needed anymore. Otherwise, they may be used as a priori information in subsequent analysis steps.

If final coordinate results are to be estimated, GPSEST is mainly used to create a normal equation file. The geodetic datum is then defined in a separate step with ADDNEQ2. The

Table 10.3.: List of programs used for coordinate/velocity estimation.

Program	Location and input data type
Station Coordinates	
CODSPP	"Menu>Processing>Code-based clock synchronization" GNSS code measurements on zero-difference level
MAUPRP	"Menu>Processing>Phase preprocessing" GNSS phase measurements on epoch-difference level
GPSEST	"Menu>Processing>Parameter estimation" GNSS code and/or phase measurements on zero- or double-difference level or SLR observations
ADDNEQ2	"Menu>Processing>Combine normal equation systems" NEQs containing coordinate parameters
FODITS	"Menu>Service>Coordinate tools>Analysis of time series" time series of coordinate estimates
Station Velocities	
ADDNEQ2	"Menu>Processing>Combine normal equation systems" NEQs containing coordinate and/or velocity parameters
FODITS	"Menu>Service>Coordinate tools>Analysis of time series" time series of coordinate estimates

station coordinate solution to be used for the datum definition are verified by the program HELMR1 and the inversion of the NEQ by ADDNEQ2 is repeated with the updated list of reference frame sites. Multi-session solutions and velocity estimation are possible with ADDNEQ2 as well.

Having long time series of station coordinates, it is feasible to analyze them searching for discontinuities, velocity changes, and outliers using the program FODITS (full description in Chapter 11). FODITS computes approximated coordinates and velocities of the stations, but these results should not be taken as the final solution, because FODITS does the analysis station-by-station, so the covariance information and the impact of other estimated parameters are neglected. The output from FODITS (with extended station names and station discontinuity information) serves as a priori information in a consecutive ADDNEQ2 solution. The final multi-session should always be computed using ADDNEQ2 with full covariance information and a flexible geodetic datum definition.

The program panels dedicated to datum definition are very similar in programs GPSEST and ADDNEQ2. The only differences are the minimum constraint solution and the velocity related panel, which both are not available in GPSEST. Figure 10.2 shows the corresponding ADDNEQ2 panel.

The options let you select one of the datum definition types described in Section 10.2.2 and, if necessary, the corresponding constraints or minimum constraint conditions. The comboboxes next to each datum definition type offer several possibilities for reference site selection (stations used for the datum definition). The FIRST, LAST, or ALL stations may be selected without any additional user interaction. The other three possibilities need further specifications in a subsequent panel. Reference sites may be specified in a user-defined list of stations (MANUAL), taken from a station selection or sigma file (FROM_FILE), or selected depending on the corresponding flags (WITH_FLAG) in the input coordinate file ("Station coordinates"). If coordinates shall be constrained using the FROM_FILE option, not only the list of reference sites but also the a priori sigmas are taken from that file. Sections 24.7.13

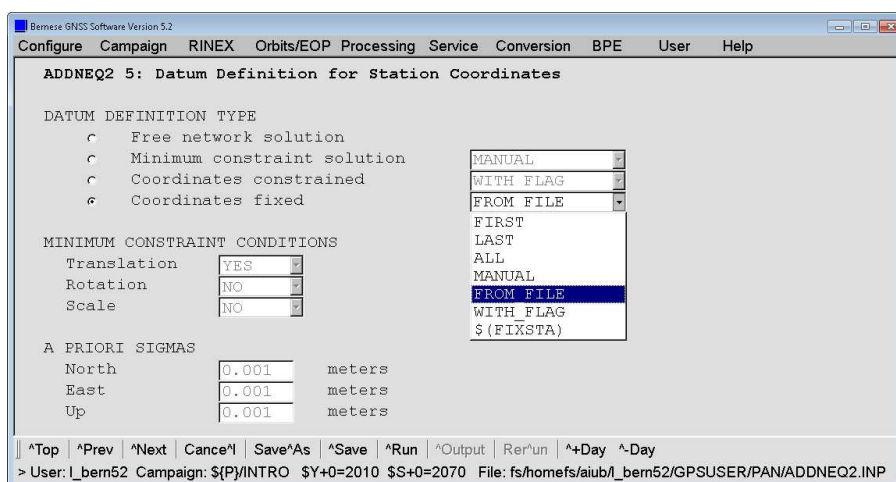


Figure 10.2.: Datum definition options in ADDNEQ2.

and 24.7.12 provide more details on station selection and station sigma files. The datum may be analogously defined for velocities in program ADDNEQ2.

The a priori coordinates of the reference sites should always refer to the current epoch of the processed session. If the reference coordinates refer to a different epoch they must be extrapolated accordingly with program COOVEL before being introduced in GPSEST. For program ADDNEQ2 this is not necessary, provided that an a priori velocity file is specified in the input panel. In that case, ADDNEQ2 internally propagates the coordinates before the normal equation system is solved. For coordinate solutions using very long sessions (longer than 7 days), it is recommended to use ADDNEQ2 instead of GPSEST, because ADDNEQ2 implicitly takes the station's velocity into account, and thus, the tectonic plate motion, as well. In some regions, site displacements due to plate motion may reach several centimeters after a few months.

10.3.1. Program Output and Result Files Related to Coordinates

GPSEST and ADDNEQ2 provide very similar coordinate and velocity² related sections in the program output files. All introduced station coordinates and velocities (if set up) are reported in the first part of the program output. A priori coordinates and velocities are tabulated in a geocentric, Earth-fixed, cartesian system, as well as in geodetic latitude, longitude, and elliptical height.

Each station is marked with one of the following flags:

- ESTIM: station coordinates/velocities are estimated,
- FIXED: fixed on their a priori values,
- HELMR: estimated and used to define the *minimum constraints condition*, or
- ECCEN: refer to an eccentric station.

The next output section lists the coordinate/velocity constraints for each station or — in case of a minimum constraint solution — the network constraints.

Figure 10.3 shows an excerpt of the result part in the program output from ADDNEQ2, including estimated velocities. Cartesian coordinates are given in units of meters,

²Velocity related information is only available in ADDNEQ2.

```

Station coordinates and velocities:
-----
Reference epoch: 2005-01-01 00:00:00
-----
Station name      Typ  A priori value  Estimated value  Correction  RMS error  3-D ellipsoid  2-D ellipse
-----
WTRZ 14201M010  X  4075580.54730  4075580.54977  0.00247  0.00233
                  Y  931853.79758  931853.79219  -0.00539  0.00095
                  Z  4801568.13018  4801568.13064  0.00046  0.00258
                  U  666.02003  666.02117  0.00114  0.00335
                  N  49.1441985  49.1441985  -0.00061  0.00102
                  E  12.8789098  12.8789097  -0.00579  0.00084
WTRZ 14201M010  VX  -0.01605  -0.01659  -0.00054  0.00038
                  VY  0.01713  0.01797  0.00084  0.00016
                  VZ  0.01009  0.00980  -0.00029  0.00042
ZIMM 14001M004  VU  -0.00011  -0.00055  -0.00044  0.00055
                  VN  0.01555  0.01561  0.00007  0.00017
                  VE  0.02028  0.02122  0.00094  0.00014
                  X  4331297.06427  4331297.06557  0.00130  0.00267
                  Y  567555.87790  567555.87985  0.00195  0.00100
                  Z  4653133.93612  4653133.93715  0.00103  0.00277
                  U  956.33330  956.33511  0.00181  0.00370
                  N  46.8770975  46.8770975  -0.00042  0.00093
                  E  7.4652768  7.4652768  0.00176  0.00114
ZIMM 14001M004  VX  -0.01353  -0.01391  -0.00038  0.00045
                  VY  0.01807  0.01778  -0.00029  0.00017
                  VZ  0.01205  0.01170  -0.00035  0.00046
                  VU  0.00123  0.00069  -0.00054  0.00062
                  VN  0.01632  0.01638  0.00006  0.00019
                  VE  0.01967  0.01943  -0.00024  0.00019
-----
(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)
    
```

Figure 10.3.: Coordinate/velocity related part of ADDNEQ2 output.

geographical coordinates in degree/minute/second, and velocities in meters per year. The output is quite self explaining, only columns (7)–(10) need further explanation:

- Column (7): Lengths of the principal axes of the 3–dimensional error ellipsoid (in meters).
- Column (8): Orientation of the error ellipsoid: zenith distance of the longest axis, azimuth (counted positive in East) and elevation angle of the second axis (in degrees).
- Column (9): Lengths of the principal axis of the 2–dimensional error ellipse in the horizontal plane (in meters).
- Column (10): Orientation of the error ellipse: azimuth of the principal axis counted positive in East (in meters).

Please note that the internal representation of coordinates and velocities is always cartesian. Where needed, they are transformed to a geodetic system based on the local geodetic datum defined in the respective a priori coordinate or velocity input file.

The estimated coordinates and velocities can be stored in corresponding result files. They are flagged according to the applied constraints (see Section 24.7.1). Stations not appearing in the current session are directly inherited from the a priori input files (but without flags). Consequently, the resulting files contain all stations from the a priori files, no matter if actually processed or not. In addition, ADDNEQ2 can write coordinate and velocity results in the SINEX format. Both programs, GPSEST and ADDNEQ2, can store the covariance information of coordinate parameters in the corresponding result files (default extension COV, see Section 24.11.10 for a detailed description).

10.3.2. Static Network Solution

A static network solution is the most common case of coordinate estimation. It is usually based on double–differenced GNSS phase observations with orbit and Earth orientation information introduced from an external source, such as the CODE or the IGS. In a static solution, one set of coordinates for each station is estimated for the entire session. This is, of course, only valid if station velocities can be neglected for the processed time interval, which is usually fulfilled for ground mounted tracking stations.

The geodetic datum of the network must be defined based on some reference sites with well known coordinates, especially for non–global networks. To ensure consistency with the orbits and EOPs, it is recommended that some nearby stations from the global IGS network are included as reference sites. The precise IGS coordinates and velocities for these stations may then be used for datum definition purposes. A no–net–translation condition or tight constraints on the individual reference stations are well–suited for a final coordinate solution.

Of course it is advisable to check the quality of the fiducial sites and — if necessary — to remove problematic stations from the list of reference sites. The typical approach is demonstrated in the RNX2SNX processing example (see Section 23.4.2) utilizing program HELMR1.

10.3.3. Multi-Session Solution

Normal equation systems from subsequent sessions can be combined in a multi-session solution with ADDNEQ2. All coordinate parameters belonging to the same station (identified by the station name) are combined to one single set of coordinates. The resulting coordinates refer then to the middle epoch of the availability of the station unless a different epoch is explicitly demanded (option “Reference epoch for station coordinates” in panel “ADDNEQ2 3.1: Options 1”).

When combining several normal equation systems, consistency is of utmost importance. If the option “Notify station inconsistencies between NEQs” in panel “ADDNEQ2 3.2: Options 2” is enabled, ADDNEQ2 reports all station equipment changes occurring in the processed time span.

It should be carefully considered whether it is still valid to combine station coordinates before and after a reported event. E.g., a receiver change is usually harmless whereas an antenna change may cause a jump in the coordinates.

Station inconsistencies:				

Station	First obs. epoch	Last obs. epoch	Receiver type	Antenna type ...
AUCK 50209M001	2005-10-08 00:00:00	2005-10-29 23:59:30	ASHTECH Z-XII3	ASH701945C_M ...
AUCK 50209M001	2005-10-30 00:00:00	2005-11-27 23:59:30	TRIMBLE NETRS	TRM41249.00 ...
...				

In the example above a completely new equipment has been installed at the station and a jump in the coordinate time series may occur. Three different choices are offered by Version 5.2 of *Bernese GNSS Software*:

- In ADDNEQ2 dedicated options are provided in panel “ADDNEQ2 3.2: Options 2” for the pre-elimination of all station-related parameters with equipment changes in the station information file (see Section 10.3.5). This is, e.g., useful because in the SINEX result files it is assumed that for each station coordinate set only one equipment description record is available.
- The station may be renamed (e.g., to AUCK 50209M001B) and treated as a completely new station as of the time of equipment change (see Section 10.3.5). ADDNEQ2 will then estimate two sets of coordinates, one for station AUCK 50209M001 with the old equipment and one for AUCK 50209M001B with the new equipment. By comparing these two coordinate sets it can be decided if the station can still be combined despite the changes (the renaming can be undone in that case).
- Utilizing the program FODITS it is possible to verify this significance testing in an automated way. The usage of this program is explained in Chapter 11. FODITS renames the stations automatically and generates all necessary input files for a consecutive ADDNEQ2 solution.

Apart from station equipment inconsistencies, the coordinate repeatabilities should be carefully monitored. Jumps or outliers will most certainly degrade the quality of the results, the more so if a reference station is affected. After computing the combined solution, program ADDNEQ2 rereads each input NEQ and processes it individually with the same options if “Compute and compare individual solutions” (see panel in Figure 9.6) is enabled.

Coordinate residuals of the individual solutions with respect to the combined solution are computed in North, East, Up and are reported in the output. In addition, they may

```

...
Helmert Transformation Parameters With Respect to Combined Solution:
-----
Sol      Rms (m)      Translation (m)      Rotation (")      Scale (ppm)
          X         Y         Z         X         Y         Z
-----
  1      0.00069      0.0003  0.0000  0.0001      ----  ----  ----  ----
  2      0.00070     -0.0003 -0.0001 -0.0001      ----  ----  ----  ----
  3      0.00107     -0.0002 -0.0001 -0.0001      ----  ----  ----  ----
  4      0.00107      0.0002  0.0001  0.0001      ----  ----  ----  ----

Statistics of individual solutions:
-----
File      RMS (m)      DOF  Chi**2/DOF  #Observations authentic  ...
-----
  1      0.00115      73006      1.33      74048  ...
  2      0.00121      72711      1.46      73694  ...
  3      0.00123      75122      1.52      76079  ...
  4      0.00122      75064      1.48      76073  ...

Comparison of individual solutions:
-----
JQZ2 12204M002  N   0.24   0.12  -0.12   0.26  -0.27
JQZ2 12204M002  E   0.43   0.45  -0.44   0.29  -0.28
JQZ2 12204M002  U   0.92  -1.07   1.14   0.19  -0.21

ZIMM 14001M004  N   0.18  -0.09   0.08   0.20  -0.22
ZIMM 14001M004  E   0.12  -0.02   0.02   0.12  -0.17
ZIMM 14001M004  U   0.64   0.56  -0.55  -0.53   0.57
...

```

Figure 10.4.: Coordinate residuals in the ADDNEQ2 program output file.

be written to a separate file specified in “Station residuals” in panel “ADDNEQ2 2.2: Output Files 2” serving as the main input source of information for the FODITS program. The residuals allow us to identify problems for individual stations or in individual input NEQs. Because the geodetic datum for each individual solution is defined in the same way as for the combined solution, residuals have to be interpreted carefully if the set of reference stations changes from solution to solution or if solutions contain no reference stations at all.

The program output file (see Figure 10.4) gives an overview on the estimated Helmert parameters of individual solutions according to the selection for the option “Compute and compare individual solutions” in panel “ADDNEQ2 3.1: Options 1”:

- HLM_ALL: a seven-parameter Helmert transformation is applied to compare each individual solution with the combined solution,
- HLM_ROT: three rotation parameters are applied to compare each individual with respect to the combined solution,
- HLM_TRA: three translation parameters are applied to compare each individual with respect to the combined solution,
- HELMERT: the same components as selected for the *minimum constraints condition* are applied,
- YES: each individual solution is directly compared to the combined solution without any transformation parameter,
- NO: no comparison is computed.

In the subsequent table of the program output the basic statistics of each individual solution such as RMS, degree of freedom, and number of observations as well as parameters

are provided (see Figure 10.4). Please check the quality of each individual solution carefully before interpreting the residuals.

The first two columns of the part `Comparison of individual solutions` in the program output file give the station name (consisting of four character ID and the DOMES code in this example) and the component. The third column gives the repeatability RMS and the following columns show the residuals for each input normal equation file. The values are given in millimeters. Repeatability RMS values for each station may also be written to a “Weekly summary file” if a filename is specified in the corresponding field in panel “ADDNEQ2 2.2: Output Files 2”.

In panel “ADDNEQ2 7: Comparison of Individual Solutions” threshold values for residuals and for repeatability RMS values may be specified, as well as a minimum number of contributing input normal equation files. These options allow us to automatically generate a list of stations for which the coordinate comparison indicates anomalous behavior. If outliers are found, they are reported directly below the aforementioned comparison section. Enabling the options, however, does not have any influence on the results but only notifies possible outliers in the program output. It might be a good idea to repeat the ADDNEQ2 run and pre-eliminate the misbehaving stations before stacking. This can easily be achieved by a corresponding entry in the station information file.

The program FODITS mentioned above already several times may be useful for an automatization of the analysis of the repeatability. However, FODITS requires sufficiently long time series of station coordinates for successful analyses. A detailed description is given in Chapter 11.

10.3.4. Velocity Estimation

If the multi-session solution covers a reasonable long time interval, e.g., 2.5 years or more, it is possible to estimate station velocities with ADDNEQ2. The technical issues of velocity estimation are described in Section 9.3.6.1.

Velocity estimation is activated by the option “Set up station velocities” in panel “ADDNEQ2 3.1: Options 1”. Estimated velocities are not automatically given in the geodetic datum defined for the station positions. As a consequence the datum has to be defined separately for positions and velocities. The corresponding panel “ADDNEQ2 6: Datum Definition for Station Velocities” is similar to the coordinate related panel and offers the same options (cf. Figure 10.2).

It is recommended that the a priori velocities are introduced (option “Station velocities” in panel “ADDNEQ2 1: Input Files”) and the velocity datum is defined using a no-net-translation condition on the velocity vectors (sum of improvements constrained to zero) for the reference sites. Alternatively, velocities may be tightly constrained if good a priori velocities are known. For small networks and for not too large displacements in the considered time interval it is possible to use a priori coordinates propagated to the middle epoch of the analyzed time period, specify no a priori velocities, and constrain the velocity vector of one site. The estimated velocities of the other sites then are relative to that specific site. In no case station coordinates should be fixed if velocities are estimated.

For short time intervals, e.g., half a year, it may make sense to estimate only the horizontal velocity components. This can be achieved by defining the geodetic datum with a station sigma file. The file should contain North, East, and Up constraints for the

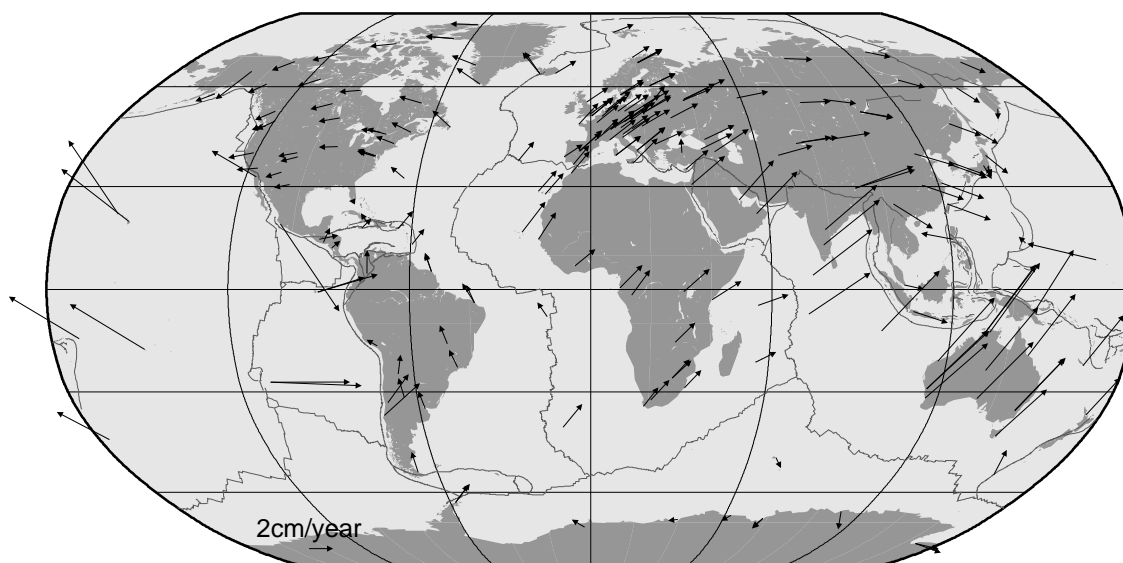


Figure 10.5.: Velocity field obtained from the weekly coordinates solutions at CODE within the years 2002 to 2006.

reference sites just as usual but in addition very tight Up constraints for all additional stations.

Program ADDNEQ2 allows saving site velocities in normal equations and then manipulate and combine velocities from input normal equations.

Figure 10.5 shows the velocity field obtained from the weekly coordinates solutions at CODE within the years 2002 to 2006.

10.3.5. Use of the Station Information File

The station information file (see Section 24.7.6) plays a central role for the coordinate estimation with ADDNEQ2. The most important applications of this file are (see also Section 9.4.6):

- *Change station names:*
Station names can be changed in the first section of the file (TYPE 001). In this way, station names from different normal equation files can be unified or a new set of coordinates can be set up, e.g., after an equipment change (see Section 10.3.3) or a displacement of the antenna. Note that ADDNEQ2, in contrary to RXOBV3, does not support wildcards in station names.

All station-related parameters are renamed immediately after reading the normal equation file. Consequently, the new name must be used for all consecutive manipulations (e.g., for datum definition or in the other sections of the station information file).

- *Define station information:*
The station information (second part of the file, TYPE 002) is mainly used to update the information written into SINEX files. If a new antenna eccentricity is specified,

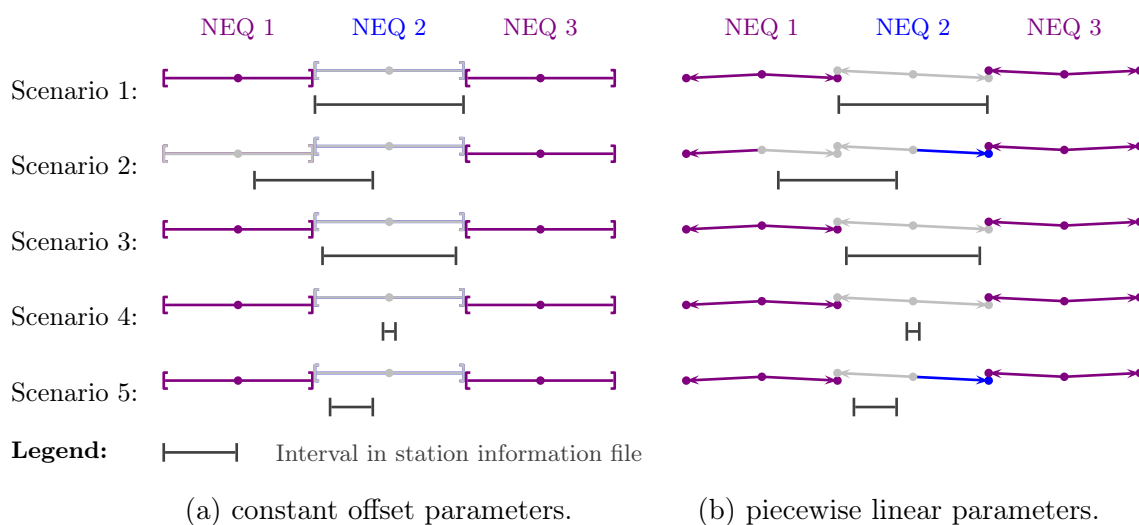


Figure 10.6.: Examples how intervals in the station information files are acting on the parameters. The light gray parameters are addressed by the intervals from the station information file.

the estimated coordinates refer to the new values. All other changes do not influence the coordinate estimation.

Only equipment changes given in this section of the station information file are relevant for the options “Remove station in case of receiver change” and “Remove station in case of antenna change” in panel “ADDNEQ2 3.2: Options 2”.

- *Handle station problems:*

Stations can be excluded from processing for a defined time interval by adding a corresponding line to section three of the station information file (TYPE 003). The coordinates and all other station specific parameters (like troposphere parameters) are then pre-eliminated before stacking without any constraints applied. This may become necessary in case of station problems (e.g., an antenna change during the session or an outlier in the time series).

Long-term monitoring parameters (scaling factors for loading grids, scaling factors for higher order ionosphere corrections, GNSS translation parameters) are excluded from the station problem handling.

- *Constraints for station coordinates and velocities:*

Section four of the file (TYPE 004) offers the possibility to set up relative coordinate and velocity constraints between different stations. As constraints apply to the estimated improvements, the a priori values for the affected parameters should be equal if the estimates shall be constrained to the same values. With this kind of relative constraints it is possible, e.g., to estimate one and the same velocity for two different stations located very close together.

An entry in the station information file is applied to the corresponding parameters in the normal equation file if two conditions are met: the station name is identical and the epochs of the parameters are touched by the time interval given in the station information file (with a ± 10 minutes margin). Some examples are given for illustration in Figure 10.6. It is in particular important to consider that only the affected part of a piecewise linear

sequence of parameters is detected, even if the beginning or end of the time interval is identical with a right or left boundary.

If option “Notify changes due to station info file” in panel “ADDNEQ2 3.2: Options 2” is enabled, a warning message is issued in the program output file, signalling each change of station information based on the station information file.

It is recommended to construct the station information file automatically by the program FODITS (description in Chapter 11) whenever possible.

10.4. Displacement Scaling Factors

The non-tidal displacement corrections discussed in Section 10.1.5 may come along with scaling factor parameters (independently for each of the three types given in Table 10.1). This allows rescaling, removing, or considering the original corrections of the non-tidal loading effects at the normal equation level in GPSEST and ADDNEQ2.

The scaling factor parameters are introduced in GPSEST (enabled by option “Scaling related to loading effects” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” and defined in panel “GPSEST 6.17: Scaling Factors Related to Loading Effects”):

- one overall:** one scaling factor applied commonly for all stations,
- per station:** independent scaling factors for each station,
- per group:** stations are grouped using the cluster number in an additional cluster file (extension CLU, description in Section 24.7.18). Scaling factors for each group are set up.

This parameter specification may be also handled in program ADDNEQ2 on normal equation level (see Figure 10.7).

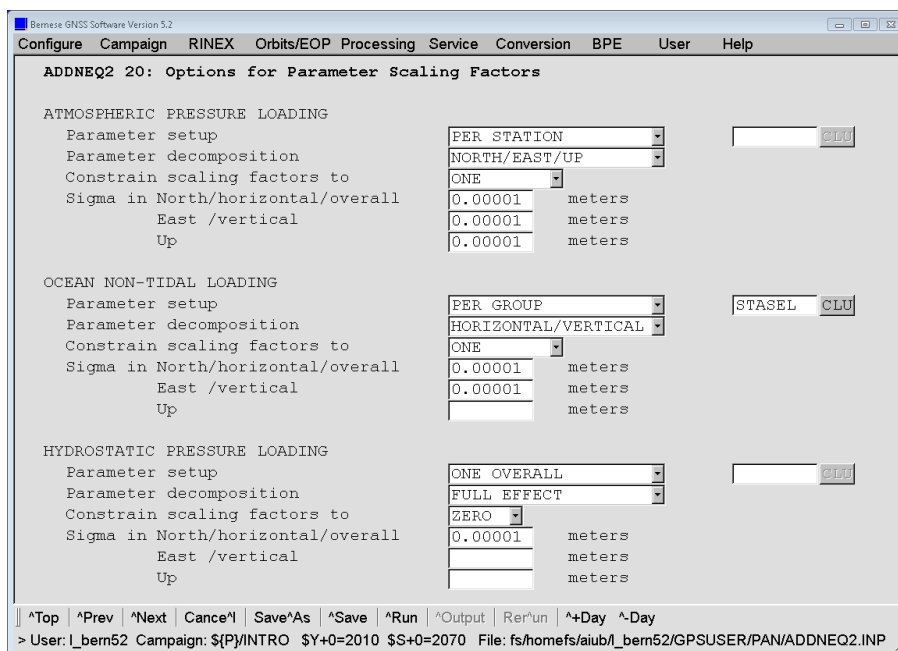


Figure 10.7.: Options for parameter scaling factors in ADDNEQ2.

In both GPSEST and ADDNEQ2 each set of scaling factors consists in fact of three parameters, one for each coordinate component in the local horizontal system (North, East, Up). Furthermore, constraints to the estimated scaling factors can be applied. There are three opportunities to define the constraints:

- NORTH/EAST/UP:** individual constraints for each of the three components of a local coordinate system for each station,
- HORIZONTAL/VERTICAL:** specific constraints for the horizontal and vertical components,
- FULL EFFECT:** one constraint applied to all three coordinate components.

It is recommended that the scaling factors in GPSEST are strongly constrained, because often, only a short interval of one single session (likely one day) is covered which is not expected to have big variations of one of these effects. The parameters can be reliably estimated only from long time series of solutions at the ADDNEQ2 level. If the grid files contain other than the loading effects, the situation may be different.

The scaling factors can be constrained in GPSEST or ADDNEQ2 (see Figure 10.7) as follows:

- forced to ONE:** in order to apply original corrections,
- forced to ZERO:** in order to remove the corrections,
- freely ESTIMATED:** in order to validate the correction by measurements (the expected estimated scaling factor should be close to unity for a perfect non-tidal loading model).

Several solution types can easily be derived from one normal equation. The program handles all correction types in the same way. This offers the opportunity to introduce, e.g., three atmospheric pressure loading models from different sources in GPSEST (with the three different keywords, see Section 10.1.5) and check them at a normal equation level.

10.5. Estimating Kinematic Coordinates

The *Bernese GNSS Software* Version 5.2 allows the estimation of kinematic, i.e., epoch-wise receiver coordinates in the zero-difference and precise point positioning mode as well as in the double-difference mode. Processing of mixed, kinematic and static stations is possible in the same solution allowing, e.g., processing data from two stations in baseline mode, one of them static, the other kinematic. Phase or (smoothed) code observations can be analyzed. For technical reasons the combined analysis of code and phase data is only possible in the zero-difference mode.

10.5.1. General Remarks on Preprocessing

In the GNSS analysis, kinematic positions are the parameters with the lowest redundancy. From, let us say, six to ten single-difference observations at a given epoch, three coordinate parameters are estimated in addition to the parameters valid for several epochs (e.g., ambiguity or troposphere parameters).

It is recommended that the user be as restrictive as possible in eliminating observations during preprocessing. The goal is to get as many epochs with reliable kinematic coordinate

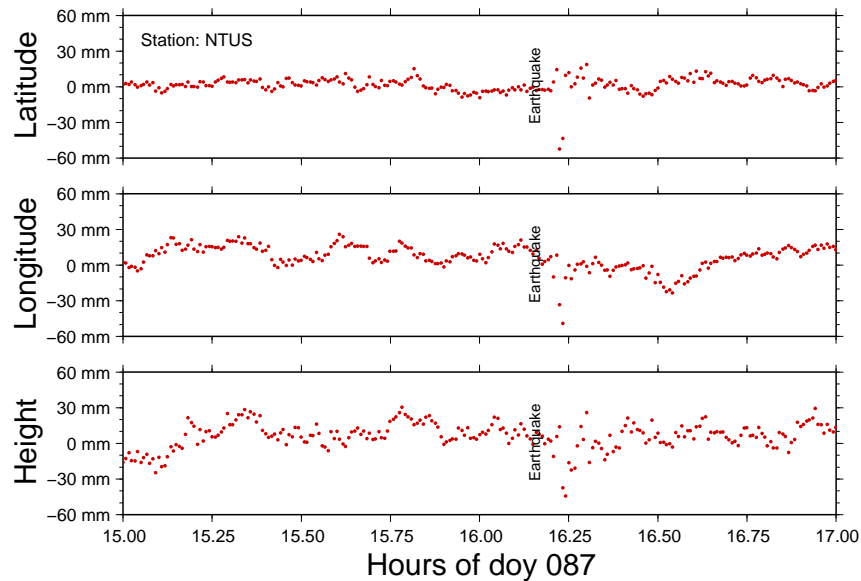


Figure 10.8.: Kinematic processing results of the data from the IGS station NTUS in Singapore during the earthquake in the Indian Ocean on March 28, 2005, at 16:09 UT.

estimates as possible. On the other hand, the low redundancy makes it difficult to detect bad observations. The results are very sensitive to data quality. This makes it difficult to give a ready-to-use recipe for a robust analysis of data from all types of kinematic stations.

In general, the best way is to follow the static procedure: Start with a precise point positioning (see Section 10.6) to get a first solution for kinematic stations. Use these kinematic (PPP-) positions as a priori values for the preprocessing of baselines. Sections 6.3.3 and 6.5.5 provide information on important issues concerning preprocessing of kinematic station data. Algorithms for resolution of phase ambiguities to integer values can be applied as described in Chapter 8 also for baselines containing kinematic stations.

If you have only short pieces of connected phase observations after preprocessing, you may find jumps in the resulting time series (especially in the vertical component) at those epochs for which the phase ambiguities to all satellites are disconnected. This effect results from the correlation between the phase ambiguity parameters and the vertical component of the kinematic coordinates. It depends on the selected elevation cutoff and on the change of the satellite configuration during the time interval that is connected by phase ambiguities.

To improve the situation, first review the option settings for the “Enable outlier rejection” and “Set ambiguities for all satellites” in program MAUPRP to check whether they are appropriate to the quality of your data. You may then add the code data to the analysis to stabilize the solution. For technical reasons, this is currently only possible when analyzing the data in zero-difference mode.

If you are interested in the subdaily movement of a static station (e.g., changes in antenna position due to an earthquake) you can follow static processing strategies. Only in the final run of GPSEST — after the ambiguity resolution — you enable the kinematic positioning for this station.

To demonstrate the performance of the *Bernese GNSS Software* for such an application we refer to Figure 10.8. It shows the results from a kinematic double-difference network solution (ambiguities are introduced as integers) with a sampling of 30 seconds for the IGS station NTUS (Singapore) during the earthquake in the Indian Ocean on March 28, 2005 at 16:09 UT. The effect of the quake on the GPS antenna's position is delayed by about 4 minutes. With a distance of about 750 km from the epicenter, this corresponds to a propagation speed of the shock waves of about 3 km/s.

10.5.2. Kinematic Positioning in GPSEST

To enable the estimation of kinematic coordinates in GPSEST simply check the option "Kinematic coordinates" in panel "GPSEST 5.1: Setup of Parameters and Pre-Elimination 1". An additional panel "GPSEST 6.9: Kinematic Coordinates" then allows you to select the stations for which kinematic coordinates are requested. The selection of stations for the kinematic positioning is independent from the station selection for the datum definition. Kinematic positions can be estimated even if the station was fixed for datum definition.

As a priori coordinates for kinematic stations one may either use

- constant coordinates from the "A priori station coordinates" file that has to be specified in panel "GPSEST 1.1: Input Files 1",
- positions for each epoch from a "Kinematic coordinates" file that may be selected in panel "GPSEST 1.2: Input Files 2" (see Section 10.5.4), or
- positions for each epoch from a "Satellite standard orbits" file for LEOs that may be selected in the Section "LEO data processing" of panel "GPSEST 1.1: Input Files 1".

For technical reasons, it is necessary to include each kinematic station in the "A priori station coordinates" file that has to be specified in panel "GPSEST 1.1: Input Files 1", even if kinematic positions are provided as input. Coordinates in the file may be zero.

Site displacements due to solid Earth tides as well as other tidal and non-tidal loading site displacements (as soon as loading coefficients are available) are considered for all types of stations (GNSS static, kinematic, PPP, and SLR stations), except for LEOs, irrespective whether they are static or kinematic. The advantage is that the position differences between roving and static receivers contain only differential effects.

Two types of constraints may be defined in panel "GPSEST 6.9: Kinematic Coordinates" for the estimated corrections to kinematic coordinates. Constraints may either be specified independently for the horizontal and vertical components in the local system or a single value may be defined for all three geocentric coordinate components.

If the a priori positions for the kinematic station are gathered from the kinematic coordinates file, coordinates are constrained only for those epochs that are labeled with flag K indicating a valid position estimate. The kinematic positions for the other epochs are computed but without constraints. Relative constraining between epochs is not supported.

Kinematic coordinates can be estimated as any other parameter without the pre-elimination. In that case the number of parameters may, however, become very large. Thus, epoch-wise pre-elimination and resubstitution of epoch parameters (for description see Section 7.7.2) is preferable for most applications. It is enabled when the option "Pre-elimination: Kinematic coordinates" in panel "GPSEST 5.1: Setup of Parameters and Pre-Elimination 1" is set to EVERY_EPOCH for kinematic coordinates.

The way formal errors of kinematic coordinates and normalized residuals are computed in the case of epoch-wise pre-elimination and resubstitution, depends on the setting for option “Var-covar wrt epoch parameters” in panel “GPSEST 6.7: General Options for Epoch Parameters”. If the option is set to SIMPLIFIED, formal errors are computed based on the epoch solution only, with the non-epoch parameters introduced without error. With the option set to CORRECT the formal errors are computed correctly, but the processing time and memory consumption may become very large. For option SIMPLIFIED, it is then preferable to scale normalized residuals with the a priori variance (NORM_APRIORI instead of NORMALIZED in option “Type of computed residuals” in panel “GPSEST 3.1: General Options 1”). We refer to Section 7.7.2 for more information.

10.5.3. Program Output and Result File

The results of the kinematic coordinate estimation are included in the GPSEST program output. An example is given in the top panel of Figure 10.9. The first line gives the a priori coordinates for the station (degrees, minutes, and seconds of arc for latitude and longitude, meters for height) as it is given in the input static coordinate file. For each epoch one line is printed containing the following information:

EPO Epoch number.
 EPOCH (MJD) Epoch of the kinematic position in modified Julian date.
 #OBS Number of observations that contributed to the epoch parameter (observations from different baselines are counted separately).
 STA First four characters of the station name.
 CORRECTION AND RMS IN METER
 Estimated correction and formal error in North, East, and Up components in meters. The corrections refer to the a priori coordinates used.
 ESTIMATED POSITION WRT. FIXED COORD.
 Estimated trajectory in North, East, and Up components in meters. The columns contain the difference between the position estimated for the particular epoch and the constant coordinate from the coordinate input file.

The output for different kinematic stations is separated by a blank line. A minimum number of observations contributing to the kinematic position of an epoch can be defined in panel “GPSEST 6.9: Kinematic Coordinates”. If fewer observations are available the corresponding value is labeled with the flag S instead of flag K in the kinematic result file and is marked in the program output by an asterisk in the column containing the number of observations.

The program output section looks slightly different for LEOs (see the bottom example in Figure 10.9). In that case only the estimated corrections in the X,Y,Z-components in the Earth-fixed system are printed together with their formal error.

Because the section on kinematic coordinate estimation may significantly increase the size of the GPSEST output file, the writing of the information may be suppressed with option “Printing: Suppression of output concerning epoch parameters” in panel “GPSEST 3.2.1.1: Extended Program Output Options”.

Estimated kinematic coordinate corrections may be extracted from the GPSEST program output into a summary file using program GPSXTR. The program writes all corrections

KINEMATIC COORDINATES: \${P}/EXAMPLE/STA/K1_03138.KIN												

EPOCHS SINCE 2003-05-18 10:00:00 (SAMPLING 300 SEC)												
EPOCH	EPOCH(MJD)	#OBS	STA	LATITUDE	CORRECTION	LONGITUDE	HEIGHT	ESTIMATED POSITION	WRT. FIXED	COORD.	UP (M)	

PTBB 14234M001												
1	52777.416667	7	PTBB	52 17 46.280644	-0.0400 +- 0.053	10 27 35.085144	130.2259	-0.0400	0.0912	0.0025	0.0025	
2	52777.420139	7	PTBB	-0.0434 +- 0.052	0.0871 +- 0.044	-0.0236 +- 0.090	-0.0434	0.0871	-0.0236	-0.0434	0.0871	
3	52777.423611	7	PTBB	-0.0615 +- 0.051	0.0866 +- 0.045	-0.0157 +- 0.088	-0.0615	0.0866	-0.0157	-0.0615	0.0866	
4	52777.427083	5 *	PTBB	-0.0374 +- 0.050	0.0857 +- 0.046	-0.0335 +- 0.081	-0.0374	0.0857	-0.0335	-0.0374	0.0857	
5	52777.430556	6	PTBB	-0.0334 +- 0.050	0.0960 +- 0.049	-0.0349 +- 0.078	-0.0334	0.0960	-0.0349	-0.0334	0.0960	
6	52777.434028	6	PTBB	-0.0282 +- 0.049	0.0938 +- 0.050	-0.0040 +- 0.073	-0.0282	0.0938	-0.0040	-0.0282	0.0938	
...												
KINEMATIC COORDINATES: \${K}/GRACE/STA/ZK104141.KIN												

EPOCHS SINCE 2004-05-19 21:00:00 (SAMPLING 30 SEC)												
EPOCH	EPOCH(MJD)	#OBS	STA	LATITUDE	CORRECTION	LONGITUDE	HEIGHT	ESTIMATED POSITION	WRT. FIXED	COORD.	UP (M)	

1	53144.875000	8	GRCA L09	-0.046 +- 0.006	0.046 +- 0.006	0.078 +- 0.027	0.006	0.078	0.027	0.046	0.006	LEO Earth-fixed XYZ
2	53144.875347	8	GRCA L09	-0.048 +- 0.006	0.046 +- 0.006	0.084 +- 0.027	0.006	0.084	0.027	0.046	0.006	LEO Earth-fixed XYZ
3	53144.875694	8	GRCA L09	-0.042 +- 0.006	0.053 +- 0.006	0.005 +- 0.027	0.006	0.005	0.027	0.042	0.006	LEO Earth-fixed XYZ
4	53144.876042	8	GRCA L09	-0.048 +- 0.006	0.047 +- 0.006	0.048 +- 0.027	0.006	0.048	0.027	0.048	0.006	LEO Earth-fixed XYZ
5	53144.876389	8	GRCA L09	-0.048 +- 0.006	0.044 +- 0.006	0.024 +- 0.027	0.006	0.024	0.027	0.048	0.006	LEO Earth-fixed XYZ
6	53144.876736	8	GRCA L09	-0.048 +- 0.006	0.044 +- 0.006	0.024 +- 0.027	0.006	0.024	0.027	0.048	0.006	LEO Earth-fixed XYZ
...												

Figure 10.9.: GPSEST program output for the estimation of kinematic coordinates (top: terrestrial station, bottom: LEO).

for which the formal error given in the GPSEST program output is smaller 0.1 m (or 10 m if no phase observations are used). The extraction program is, however, limited to one single station or one LEO. Note that for LEOs the X,Y,Z-components in the Earth-fixed system are reported instead of the North, East, and Up components. Consult the online help of GPSXTR for more information.

10.5.4. Using the Kinematic Coordinate File

Both programs CODSP and GPSEST may write estimated kinematic coordinates to a kinematic coordinates file (description in Section 24.7.4). That file may contain kinematic positions of more than one station. Three different flags indicate the quality of the individual epoch estimates:

- K kinematic coordinates estimated with enough redundancy,
- S estimated from a small number of observations or singularity in the estimation, as well as
- X no estimation, linearly interpolated.

The kinematic coordinate file may be introduced into the programs CODSP, MAUPR, and GPSEST. Each station with at least one position in the kinematic coordinates file is considered as kinematic station. The a priori positions for each epoch are taken from this file and, consequently, observations are skipped for epochs without kinematic input coordinates. Station coordinates may be fixed on the input kinematic coordinates or improvements may be estimated. It is even possible to estimate static coordinates when introducing a priori coordinates through a kinematic coordinate file.

If estimation of kinematic positions is enabled for a station in the kinematic coordinate file, all epochs from the file are processed (independently of the flag). If no kinematic coordinates are estimated, only the positions labeled with flag K (position OK) are considered. Epochs with other flags are skipped for this station.

There are two more programs that use the kinematic coordinates file:

- GPSSIM ("Menu>Service>Generate simulated observation data", description in Chapter 20) may read the file to generate synthetic Bernese observation files for kinematic stations.
- Kinematic coordinates for a LEO may be converted into the precise orbit format using the program KINPRE ("Menu>Service>LEO utilities>Convert kinematic pos. to precise orbits", description in Chapter 17).

Both programs consider only epochs labeled with flag K.

10.6. Precise Point Positioning

The Precise Point Positioning (PPP) is a special case of zero-difference processing. As opposed to other applications, the satellite clock corrections are not estimated (or differenced out) but assumed to be known. They are introduced in the processing together with orbit information and Earth orientation parameters. Parameters left to estimate are station clock corrections, coordinates, and troposphere parameters.

This modus operandi has several consequences:

- PPP is not a differential technique. The geodetic datum must not be defined by means of any constraints on reference stations. It is given by the introduced orbit and clock information and can not be changed.

- Consistency of introduced orbit, EOPs, and satellite clock information is of utmost importance to reach high accuracy. It is mandatory to use the information from the same source. Mixing of orbits and clocks from different Analysis Centers degrades the PPP results.
- The models used to estimate the orbits and clock corrections should be the same as the models implemented in the actual analysis software. This issue poses no problem when CODE or IGS products are used together with the *Bernese GNSS Software*.

The quality of the introduced information should be as good as possible for PPP as all errors directly propagate in the results. One kind of inconsistencies may arise when using orbits from other sources as CODE, e.g., from the IGS. CODE final orbits can be fitted by program ORBGEN on the sub-centimeter level whereas this can not be guaranteed for other orbit products due to slightly different orbit models employed. In such cases the orbit fit may be improved by setting up not only one but several orbital arcs per day, e.g., two or four (“ORBGEN 5: Orbital Arc Definition”) or by setting up more pseudo-stochastic pulses, which absorb satellite velocity changes.

Furthermore, the satellite clock corrections should be used as provided and not be interpolated. Thus, data processing is limited to the sampling rate of the clock corrections. I.e., using satellite clock information from IGS clock RINEX files means a data sampling of 30 sec (some of the IGS ACs only provide the corrections with a sampling of 5 min, only). On the other hand, CODE provides even ultra high-rate satellite clocks with a sampling of 5 s allowing higher sampling rates of one Hertz (Bock et al. 2009). Use these clocks together with CODE orbits. Section 15.3.1 describes the necessary steps to extract satellite clock corrections from clock RINEX files.

PPP is a very fast and efficient means to generate good station coordinates. Nevertheless, it is not possible to reach a coordinate quality as obtained from a network analysis. This is mainly due to two facts, the impossibility to resolve phase ambiguities and the neglect correlations between stations and clock corrections. The latter needs some further explanations: in a network solution all parameters are estimated to fit all observation data best possible under consideration of all correlations. This is not the case for a PPP, where the influence of the stations on the satellite clocks can not be accounted for anymore. As a consequence, in particular for local and regional networks, small modeling deficiencies (e.g., concerning troposphere modeling) may be absorbed in the satellite clocks estimated implicitly in a double-difference solution while this mechanism does not work for PPP. A network solution is therefore the first choice to obtain highest quality positioning results.

On the other hand, the disregard of correlations may also be a desired feature. Errors introduced by a misbehaving station are not disseminated throughout the whole network but only influence the results of that specific station. Thus, the PPP is well apt to identify station problems.

To run GPSEST in PPP mode some options need special attendance. The zero-difference mode must be activated in panel “GPSEST 1.1: Input Files 1”, the estimation of satellite clock corrections must be switched off (option “Pre-elimination: GNSS clock offsets” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”), and receiver clock corrections must be set up (“Pre-elimination: Receiver clock offsets”). Due to the possibly of large number of receiver clock offsets, it might be necessary to pre-eliminate them EVERY_EPOCH. Finally, the datum definition should be set to “Free network solution” in panel “GPSEST 4: Datum Definition for Station Coordinates”.

If no parameters common to several stations are set up (e.g., geocenter coordinates), there is no advantage in processing several stations in one program run compared to one individual run per station. Otherwise, it is still possible to process single stations in separate runs if normal equations are stored. They may subsequently be combined with ADDNEQ2.

The *Bernese GNSS Software* Version 5.2 is capable of PPP processing using combined GPS and GLONASS phase and code observations. PPP solutions using GPS and GLONASS phase observations are free from biases, because the phase ambiguities absorb the intersystem differences. For PPP using code data, additional frequency-dependent receiver bias parameters have to be estimated. For details concerning intersystem and interfrequency biases please refer to Section 15.2.2.

There are two BPE examples provided with the software distribution showing possible implementations of PPP procedures: one standard PPP for coordinate, troposphere, and receiver clock determination based only on GPS or combined GPS and GLONASS data and the second PPP for extended processing examples, e.g., pseudo-kinematic, high-rate troposphere, or ionosphere solutions.

10.7. Coordinate and Velocity Related Auxiliary Programs

The *Bernese GNSS Software* provides several programs dealing with coordinate and velocity files. Typical applications are, e.g., Helmert transformations, comparison of several coordinate files, velocity computation based on a model, etc. All coordinate/velocity tools can be found in "Menu>Service>Coordinate tools". The most common programs are described in the following sections.

10.7.1. Extracting Coordinates/Velocities from SINEX

Although program SNX2NQ0 ("Menu>Conversion>SINEX to normal equations") is not directly coordinate related, it should be mentioned here. Apart from the conversion of SINEX files to Bernese normal equation files, it allows extracting station coordinates and velocities from the SINEX file. This may be used in conjunction with the official ITRF SINEX file to get a complete set of ITRF station coordinates and velocities at any user-defined epoch (option "Set of CRD/VEL valid at epoch" in panel "SNX2NQ0 2: Options"). The program is described in Section 4.5.2.

10.7.2. Helmert Transformation

Program HELMR1 ("Menu>Service>Coordinate tools>Helmert transformation") allows comparing two coordinate sets after estimating up to seven parameters of a Helmert transformation (three translations, three rotations, and one scaling factor).

The program computes Helmert transformation parameters from the coordinates in the second input file to those in the first (reference) file. The coordinates of the reference file may be propagated to the epoch of the second file by specifying an input velocity file. Note, that only stations with flags in both coordinate files are used for the comparison because flags indicate coordinates, which are the result of a processing. Coordinate sets without flags are ignored.

The program may run in two different modes that can be selected in option “System of transformation, local or geocentric” in panel “HELMR1 2: Options for Helmert Transformation”:

- Transformation in geocentric system

If coordinates from large regional or global networks are compared, the option should be set to XYZ. In this case the estimated transformation parameters refer to the geocentric cartesian coordinate system:

$$\mathbf{X}' = (1 + \kappa) \cdot \mathbf{R}_z(r_z) \cdot \mathbf{R}_y(r_y) \cdot \mathbf{R}_x(r_x) \cdot (\mathbf{X} + \mathbf{X}_0) \quad (10.1)$$

where \mathbf{X}_0 is the translation vector, $\mathbf{R}_i(r_i)$ the matrix of a rotation by an angle r_i around the axis i , and κ is the scaling parameter. The transformation parameters are estimated by minimizing the sum of squared differences between the coordinates from the second input file, transformed according to Eqn. (10.1), and the coordinates in the reference file.

If no translation parameters are estimated, the two sets of coordinates are first reduced to their respective barycenter in order to allow a proper interpretation of the estimated rotation parameters.

- Transformation in local system

If the option is set to NEU, the estimated transformation parameters refer to the local horizon system in the barycenter of the second coordinate set. This option is particularly useful for local and small regional networks. The following algorithm is used:

1. The barycenter of the second coordinate set is computed according to

$$\bar{\mathbf{X}} = \frac{1}{n} \cdot \sum_{i=1}^n \mathbf{x}_i$$

where \mathbf{x}_i are the geocentric coordinates of the n stations involved.

2. With the help of the ellipsoidal coordinates $\bar{\phi}$ and $\bar{\lambda}$ of the barycenter $\bar{\mathbf{X}}$ both coordinate sets are transformed to the local horizon system using

$$\mathbf{X}_{local} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathbf{R}_y(\bar{\phi} - 90^\circ) \cdot \mathbf{R}_z(\bar{\lambda} - 180^\circ) \cdot (\mathbf{X} - \bar{\mathbf{X}}) .$$

3. Finally, the Helmert transformation parameters in the equation

$$\mathbf{X}'_{local} = (1 + \kappa) \cdot \mathbf{R}_z(r_z) \cdot \mathbf{R}_y(r_y) \cdot \mathbf{R}_x(r_x) \cdot (\mathbf{X}_{local} + \mathbf{X}_0) \quad (10.2)$$

are estimated by minimizing the square sum of the difference between the coordinates of the second set, transformed according to (10.2), and the reference coordinate set.

While the first option has to be used for large regional and global sets of coordinates, the second option is particularly useful for the interpretation of transformation parameters between small regional and local networks. Note that the residuals in the program output are given in the North, East, and Up components in both cases.

The program also allows us to estimate only a subset of the seven Helmert transformation parameters by selecting the options in panel “HELMR1 2: Options for Helmert Transformation” accordingly.

The user may select the stations which shall be used to compute the transformation parameters manually or automatically. Stations may either be marked or excluded. Marked stations are not used for computing the transformation parameters but the program provides residuals in the output file (marked with a flag **M**) while excluded stations are not considered at all. In manual mode the user may mark and exclude stations manually from a list containing all stations with a flag in both files. In automatic mode a station selection file may be specified in "File with list of stations" in panel "HELMR1 1: Input/Output Files". Only stations listed in this file are considered for computing the transformation parameters while the other stations are marked or excluded according to user selection.

The program allows us to iteratively remove stations with residuals exceeding thresholds that may be specified in panel "HELMR1 3: Outlier Rejection". A station selection output file may be written containing only those stations, which passed the thresholds. The other stations are marked with an asterisk in the output and their names and residuals may be written to a special output file. The option is useful, e.g., for an automatic reference site verification (see Section 10.2.3), i.e., to compare the coordinates of the reference sites obtained from a minimum constraint solution with the reference coordinates (e.g., IGb08) using an input station selection file listing only the reference station names. The output station selection file contains then the same station names reduced by the badly performing stations. This selection file, containing only the verified reference stations, can be used for datum definition of the final solution in an additional ADDNEQ2 run. In the RNX2SNX processing example described in Section 23.4.2 this procedure is demonstrated.

10.7.3. Apply Coordinate Transformation Parameters

Program HELMR1 may output a coordinate file that contains the station coordinates from the second input file transformed to the system of the first input file using the estimated transformation parameters. The option "System of transformation, local or geocentric" must be set to XYZ (GEOCENTRIC — global transformation).

The same transformation may also be performed with program COOSYS ("Menu>Service>Coordinate tools>Coordinate transformation") which allows to apply any set of Helmert transformation parameters according to Eqn. (10.1) to an input coordinate file (assuming small rotation angles).

10.7.4. Coordinate Transformation between ITRF and ETRF

Program ETRS89 ("Menu>Service>Coordinate tools>Transform to ETRS89") allows a transformation of site coordinates from ITRF xx to different realizations of the European Terrestrial Reference Systems, i.e., to the European Terrestrial Reference Frames (ETRF xx), which are aligned to the Eurasian tectonic plate by a set of European GNSS stations. Different target reference frames are supported: starting with TRF89 and ending with TRF2008. The epoch for the time dependent transformation is taken from the corresponding header line in the coordinate file. Use program COOVEL (see Section 10.7.9) to propagate the coordinates to a specific target epoch before using ETRS89 (the velocities are not transformed to ETRF xx, this is why the coordinate propagation has to be performed before using ETRS89). The output coordinate file does no longer refer to ITRF.

COMPARISON OF COORDINATE FILES						

Total number of stations: 162						

Station	#Days	Weekday 0123456	Repeatability (mm)			
			N	E	U	

ALBH 40129M003	7	AAAAAAA	1.2	1.0	2.4	
ALGO 40104M002	7	WWWWWWW	1.0	1.4	3.2	
ALIC 50137M001	6	A AAAAA	0.9	1.7	3.4	
ALRT 40162M001	7	AAAAAAA	1.1	0.7	3.5	
.						
.						
ZIMZ 14001M005	3	AAA	1.0	1.7	2.1	
ZWE2 12330M003	7	AAAAAAA	0.7	0.6	3.0	

# Coordinate estimates: 1070			4.7	1.6	4.7	

Figure 10.10.: Example of a weekly summary file.

The inverse transformation, i.e., from ETRF_{xx} to ITRF_{xx} can also be computed using ETRS89. If the datum from the input coordinate file is specified as ETRF_{xx}, the coordinates will be transformed to ITRF_{xx} and vice versa. The target frame option TRF_{xx} from panel “ETRS89 2: Options” denote either ITRF or ETRF, e.g., TRF89 means ETRF89 if a priori coordinates are expressed in ITRF89 or it means ITRF89 if a priori coordinates are expressed in ETRF89.

Using the option `MANUAL` it is possible to specify own transformation parameters (3 translations and 3 rotations). The output file in ETRF_{xx} must not be used as a reference frame in any further computations using satellite data: ETRF_{xx} is a regional and not a global frame and is, therefore, not consistent with the reference frame of the satellite positions in any precise orbit file.

10.7.5. Coordinate Comparisons

The main purpose of the program `COMPAR` (“Menu>Service>Coordinate tools>Coordinate comparison”) is to compare site coordinates, in accordance with a list of input files. However, `COMPAR` may also be used to compute mean station coordinates. To obtain weighted mean coordinates variance–covariance information may be introduced. It is, however, recommended that `ADDNEQ2` is used for this purpose, because it allows for much more flexibility for datum definition and parameter handling.

Stations to be used by `COMPAR` may be selected by specifying a list of coordinate flags. The program output of `COMPAR` provides the repeatability of the station coordinates without applying any transformation of the individual input coordinates to a common frame. If the coordinates refer to different epochs, they may be unified using a file with “A priori velocities”.

The respective program output looks similar to the corresponding `ADDNEQ2` output displayed in Figure 10.4. This site coordinate repeatability output allows to identify problems with particular stations. Note, however, that the input coordinate files require a consistent definition of the geodetic datum.

The repeatability (RMS) for each station may be written to a summary file (see Figure 10.10). As this file is designed as a weekly summary file, the number of columns for the flags displayed is limited to seven (to support weekly solutions). The RMS numbers, however, refer to all input coordinate files.

The program may provide repeatability information for individual baselines if the corresponding option in panel “COMPAR 3: Processing Options” is enabled. By default the statistics for all pairs of stations are provided. In order to reduce the size of the output file and the computing time, it is recommended to enter a baseline definition file (description see Section 24.7.17) in input field “INPUT FILES: Baseline definitions” in panel “COMPAR 1: Input Files” specifying the baselines of interest.

10.7.6. Velocity Comparisons

VELDIF (“Menu>Service>Coordinate tools>Velocity comparison”) is a program for computing differences between two velocity files. Alternatively, the velocities can be expressed with respect to one station or transformed by specifying a reference velocity vector. In the latter case, it is possible to transform the velocity files either using a 3 dimensional transformation or only for horizontal components (keeping the height component of the velocity vector unchanged).

10.7.7. Merging Coordinate and Velocity Files

Program CRDMERGE (“Menu>Service>Coordinate tools>Merge coordinate/velocity files”) allows merging several coordinate or velocity files into a single coordinate resp. velocity file. Using a master file it is possible to add new stations to an already existing file. If stations are present in more than one of the selected files, the corresponding flags are compared and the coordinate/velocity set with the flag of highest priority will be stored in the resulting file. Note that flags may have up to 5 characters for coordinates and up to 4 characters for velocities but only the first character is of importance for comparison.

The defined flags are listed in Section 24.7.1 with increasing default priority. The priority sequence of the flags may be adapted easily to particular needs in panel “CRDMERGE 2: Options”. A blank flag always has the lowest priority. One-character flags may be translated to longer identifiers during the merging process (e.g., N to NET). Changing the geodetic datum and reference epoch only affects the strings written to the new file, coordinates are not transformed.

10.7.8. Computing Velocities from a Model

Program NUVELO (“Menu>Service>Coordinate tools>Compute NUVEL velocities”) computes station velocities based either on the NNR–NUVEL–1 (Argus and Gordon 1991) or on the NNR–NUVEL–1A (DeMets et al. 1994) tectonic plate motion model (the boundaries of the major tectonic plates are shown in Figure 10.11). If a site is not available in the list of ITRF coordinates and velocities, the NUVEL velocities serve as good approximation for station velocities to propagate the station coordinates from the reference epoch of the reference frame to the epoch of the observation.

A subset or all stations contained in an input coordinate file may be selected. The program computes the model velocities based on a plate definition file (description in Section 24.7.16). If a station name is not listed in the plate definition file, a zero velocity vector results. The obtained velocities may be merged into an a priori velocity file. Velocities for stations already contained in this file are overwritten. Use program CRDMERGE for more flexibility in merging of velocity files. The stations for which velocities were computed are marked with the flag V.

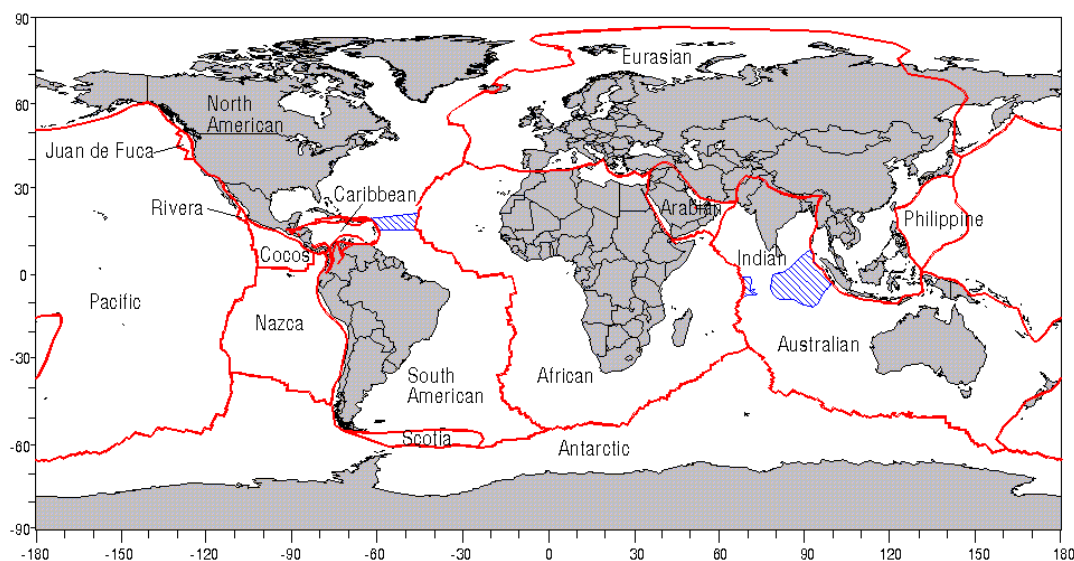


Figure 10.11.: Present-day major tectonic plate boundaries.

10.7.9. Propagating Coordinates to Specific Epochs

Program COOVEL ("Menu>Service>Coordinate tools>Extrapolate coordinates") can be used to propagate station coordinates from one epoch (reference epoch in the coordinate file) to another epoch by applying site velocities from an input velocity file. The velocities may stem from an official reference frame (e.g., ITRF 2008), from an ADDNEQ2 multi-session solution, or from a velocity field model (program NUVELO).

Usually the program is used to propagate reference station coordinates from the reference epoch to the observation epoch of the current session. If a station is not listed in the velocity file a warning message is issued and no velocities are applied.

10.7.10. Extraction of Atmospheric Tidal Loading Coefficients

For stations given in a coordinate file, the program GRDS1S2 ("Menu>Service>Coordinate tools>Extract atmospheric tidal loading coefficients") extracts the atmospheric tidal loading coefficients from a global grid for the sine and cosine terms of the S_1 and S_2 atmospheric pressure loading tidal corrections. A grid based on the Ray and Ponte (2003) model (reference in the IERS Conventions 2010) is distributed with Version 5.2 of *Bernese GNSS Software* in the file `$X/GEN/s1_s2_def_ce.dat` as an example. As already mentioned in Section 10.1.4, you should select a model that is consistent with your non-tidal atmospheric pressure loading corrections. In this context it is also important to be consistent with the reference of the loading corrections, i.e., either center-of-mass (CoM) or center-of-figure (CoF), when preparing a file with atmospheric tidal loading corrections for GNSS or SLR stations.

The result file contains the tidal atmospheric loading coefficients for all stations given in the input coordinate file. It is used in the processing programs to correct the observations for this effect. According to your reference, it may also contain the center of mass corrections (CMC). In that case it becomes additionally relevant for some of the orbit programs. An example output file containing a subset of the IGS stations is available at the anonymous FTP site http://www.aiub.unibe.ch/download/BSWUSER52/STA/ATM_VAPL.ATL. The ATL file has to be updated if new or other stations have been added to the processing.

11. Analysis of Time Series

Long time series of operational products are usually not homogeneously processed. For instance, IGS ACs update models and/or change their processing strategies on a regular basis in order to improve the quality of their products. In addition, the ACs regularly adopt new realizations of the ITRF. Such changes may induce discontinuities in the series of operational products, in particular time series of station coordinates. A prominent example is the discontinuity of up to 20 mm at GPS-week 1400 in the vertical component in nearly all coordinate time series processed at CODE. Such large discontinuities were observed, e.g., when switching from relative to absolute antenna calibration models.

Numerous reprocessing efforts of GNSS data are initialized for global, regional, and local networks. Despite homogeneously reprocessed data, coordinate time series still contain discontinuities (e.g., caused by equipment changes) and outliers (e.g., due to environmental conditions like snow coverage). More consistent accumulated multi-year solutions are obtained by cleaning the underlying coordinate time series. This requires an accurate analysis of coordinate time series.

The program Find Outliers and Discontinuities in Time Series (FODITS) ("Menu>Service>Coordinate tools>Analysis of time series"), which is embedded in the *Bernese GNSS Software Version 5.2*, has been designed to analyze and clean coordinate time series in an automated way (Ostini et al. 2008, 2010; Ostini 2012). The automated analysis and quality assessment of coordinate time series is particularly important due to the large and steadily increasing number of stations forming the GNSS networks. The program FODITS verifies the significance of lists of predefined events such as a list of equipment changes and a list of worldwide registered earthquakes, identifies discontinuities and outliers in the time series, and creates the metadata to obtain high accuracy multi-year solutions and cleaned coordinate time series. All three components of coordinate time series are processed together in a fully combined mode. As an additional feature to analyze coordinate time series, FODITS is able to identify discontinuities in station velocities and may estimate periodic functions. The analysis, however, is not restricted to station coordinates — it can also be applied to many other time series (e.g., for DCB parameters).

11.1. Basic Principle and Functional Model

The analysis of GNSS or SLR coordinate time series is a key procedure in a reprocessing context, especially when NEQs are accumulated to derive multi-year solutions. The algorithm of the program FODITS adapts step-by-step a functional model to the time series containing sets of discontinuities, outliers, velocity changes, and periodic functions.

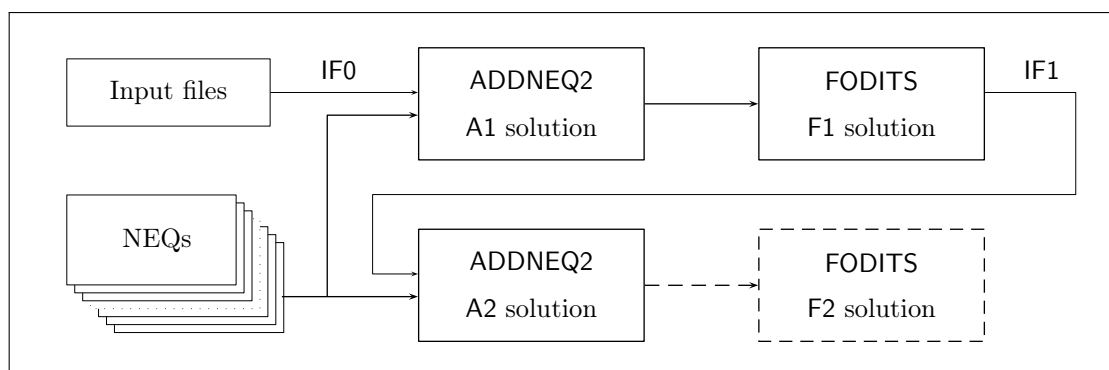


Figure 11.1.: Principle of coordinate time series in the *Bernese GNSS Software*. A_x refers to ADDNEQ2 solutions, F_x to FODITS time series evaluations, and IF_x to a certain set of station-related input files.

11.1.1. Coordinate Time Series Generation with Bernese GNSS Software

Figure 11.1 contains the general overview of the generation of long-term coordinate time series in the *Bernese GNSS Software*. The program ADDNEQ2 generates a first cumulative solution A1 as well as time series of coordinate residuals based on a series of normal equation files and a set of input files (labeled IF0). The relevant set of input files consists of an a priori reference frame (coordinate and velocity files, default extensions CRD and VEL) being the datum of the network solution, the station information file (default extensions STA, see Section 9.4.6), and a list of reference frame stations (given in a station selection file with the default extension FIX).

The coordinate time series from ADDNEQ2 solution A1 is analyzed by FODITS (solutions F1). It checks for significant discontinuities, outliers, velocity changes, and periodic functions according to a functional model. The results from the time series evaluation are used to update the set of input files IF0 automatically to a new set of input files (yielding IF1 — the filenames are specified in panel “FODITS 7: Options to generate files for ADDNEQ2”). If these input files are introduced together with the series of normal equation files, a cleaned time series solution (named A2 in Figure 11.1) results from the subsequent ADDNEQ2 solution.

At this stage, the final solution is already generated. Of course, it can again be introduced for validation or other purposes into a second run of the program FODITS (named F2).

11.1.2. The Functional Model

The coordinate time series are parameterized in the North, East, and Up components as

$$\begin{aligned}
 \mathbf{f}(t_i) = & \mathbf{d}_0(t_0) + \mathbf{v}_0(t_i - t_0) + \sum_{k=1}^{n_d} \mathbf{d}_k \eta_{d,k}(t_i) + \sum_{k=1}^{n_s} \mathbf{s}_k \eta_{s,k}(t_i) + \\
 & \sum_{k=1}^{n_v} \mathbf{v}_k(t_i - t_k) \eta_{v,k}(t_i) + \sum_{k=1}^{n_p} [\mathbf{p}_{a,k} \cos(\omega_k(t_i - t_0)) + \mathbf{p}_{b,k} \sin(\omega_k(t_i - t_0))] \eta_{p,k}(t_i) ,
 \end{aligned} \tag{11.1}$$

where

- $i = 1, \dots, N$ is the index of epoch t_i of the series of N elements,
- \mathbf{d}_0 and \mathbf{v}_0 are the initial coordinate and velocity,
- $\eta_{d,k}(t_i)$, $\eta_{s,k}(t_i)$, $\eta_{v,k}(t_i)$, and $\eta_{p,k}(t_i)$ are functions returning either 0 or 1 to indicate the validity of the related component,
- \mathbf{d}_k is the list of n_d discontinuities,
- \mathbf{s}_k is the list of n_s outliers,
- $\mathbf{v}_k(t_i - t_k)$ is the list of n_v velocity changes, and
- $\mathbf{p}_{a,k}$, $\mathbf{p}_{b,k}$ are the phase and out-of-phase components for the n_p periodic functions.

The analysis of coordinate time series by the program FODITS is supported by a list of predefined elements of the functional model. Such a list is created based on an external list of earthquakes, from the history of equipment changes, from the test of the datum definition, and from a list of user-defined elements (see Section 11.2.1).

After having added step-by-step all significant predefined elements in the functional model, the program FODITS searches for possible elements that help to significantly improve the representation of the analyzed time series. Such a search procedure is performed for discontinuities, outliers, velocity changes, and periodic functions (see Section 11.1.3).

Changes in the horizontal coordinate components (i.e., North and East) after big earthquakes may have an impact on the vertical component (Up) as well. Alternatively, if primarily the vertical component is affected by a change, e.g., after an equipment change, horizontal components (e.g., the centering of an antenna) may likely experience a change as well. It is preferable to consider the time series as a three-dimensional vector defined by Eqn. (11.1) rather than analyzing the vectors component-wise because station coordinates are eventually estimated in the geocentric Earth-fixed Cartesian coordinate system.

Coordinate time series of different stations are assumed to be independent in order to simplify the analysis and to reduce the processing time. The time series are, therefore, analyzed station by station. The functional model given by Eqn. (11.1) refers to a single station. Furthermore, no time correlation is assumed between the data points of the time series. Only the space correlations (between the North, East, and Up component) are taken into account. The full covariance matrix can be considered in a consecutive solution using ADDNEQ2 after the time series analysis with FODITS.

The program FODITS treats outliers separately from other elements. Observations identified as outliers are excluded and the time series is reprocessed. This implies that the outliers are not set up as parameters in the functional model. The exclusion of outliers is reasoned by the fact that coordinate time series are often contaminated by a significant number of outliers (compared to other events asking for additional elements in the functional model) yielding a NEQ containing a large number of parameters. The inversion of a NEQ without outliers significantly reduces the computing efforts and the overall processing time as compared to a NEQ that describes the full functional model. However, no outlier estimates are obtained in such an analysis. For FODITS this is not relevant: outliers are derived from the *observed minus computed* values after the functional model has been applied to the time series. The uncertainties of the outliers, however, are inherited from the previous step, i.e., from the estimation performed by ADDNEQ2.

11.1.3. The Fundamental Algorithm in Program FODITS

The algorithm of the program FODITS is illustrated in Figure 11.2. Its steps are summarized in the following:

1. Coordinate time series are either
 - a) read from a list of coordinate files (CRD) or
 - b) reconstructed from the residual file (PLT) in conjunction with the coordinate and velocity result files (CRD, VEL).

The covariance information of the coordinate in the time series is only provided via the residual file (PLT) and is for that reason only available for option (b).

The selection of the files is done in panel “FODITS 1: Input Files”.

2. A list of predefined elements may be proposed to the functional model:
 - a) discontinuities due to equipment changes from the station information file (STA),
 - b) discontinuities and velocity changes because of seismic events from a list of earthquakes (given in file with extension ERQ),
 - c) periodic functions according to option “Propose seasonal signals” in panel “FODITS 4: Model definition”, or
 - d) all types of events manually defined in “Input event list file” (EVL).

All files contributing to the list of predefined events are specified in panel “FODITS 1: Input Files”.

3. An epoch-by-epoch test of the datum definition is performed as described in Section 11.2.1.5.
4. The analysis is performed independently for each station (station by station).
5. The procedure enters the loop to identify new elements in the time series.
6. The procedure enters the loop to insert a priori elements into the functional model and to remove insignificant elements from it.
7. Elements are removed from the functional model until all remaining elements are significant. No elements are removed during the first iteration step and the first screening step because the functional model consists solely of the initial offset and of the initial velocity.
8. Based on the statistical test (Eqn. 11.17) and the test value (Eqn. 11.16), the element which contributes least to the description of the time series is removed from the functional model. Simultaneously, all insignificant outliers are removed from the functional model as well (see Eqn. 11.18 for the statistical test).
9. The predefined elements are checked in the functional model one after the other using the statistical test (Eqn. 11.17) that is based on the test value (Eqn. 11.15). The condition of a minimum interval length between successive velocity changes, Δt_v , must be met for velocity change candidates. Moreover, all significant predefined outlier candidates are added to the functional model according to the statistical test (Eqn. 11.18). Further, all elements must meet the additional criteria.
10. The search for discontinuities (see Section 11.2.2.1), outliers (see Section 11.2.2.2), velocity changes (see Section 11.2.2.3), and periodic functions (see Section 11.2.2.4) proposes elements that reduce the discrepancy between the functional model and the time series. The proposed elements are collected in a list of candidate elements. In

Step and description

- 1 **Input:** Read input time series from a set of coordinate files (CRD) or use result files from ADDNEQ2 for reconstruction (CRD, VEL, PLT).
- 2 **Input:** Read predefined elements and events from station information file (STA), earthquake list (ERQ), and/or event list (EVL)
- 3 **Identify outliers** in the datum definition and add these stations as outliers to the list of predefined elements
- 4 **for all** *station time series* **do**
- 5 **repeat** identify new elements — iteration loop
- 6 **repeat** model screening — screening loop
- 7 **repeat** remove elements
- 8 Remove the non-significant element from the functional model, which obtained the smallest value of the statistical test
- 9 **until** *all elements in the functional model are significant*
- 10 Insert in the functional model the significant a priori element candidate, which obtained the largest value in the statistical test and meets the minimum interval length between successive velocity changes
- 11 **until** *functional model agrees with a setup of a previous step in the screening loop*
- 12 Identify in the post-fit residuals the most probable
 - epochs of discontinuities
 - epochs of outliers
 - epoch of a velocity change
 - period of periodic functions
 Collect all identified elements in a list of candidates
- 13 Insert the identified element candidate into the functional model, which obtained the largest value of the statistical test
- 14 **until** *functional model agrees with a setup of a previous step in the iteration loop*
- 15 **end**
- 16 **Output:** Write list of events (EVL) and the program output (OUT) files
- 17 **Output:** Update the set of input files for a subsequent run of the program ADDNEQ2 (CRD, VEL, STA, FIX)

Figure 11.2.: The algorithm of FODITS. Acronyms: files containing station coordinates (CRD), station velocities (VEL), residual time series (PLT), station information (STA), earthquakes (ERQ), event list (EVL), and output file (OUT).

this way, it is possible that the search proposes more than one candidate per element type. This feature is exploited by the algorithm in three cases. First, the time series is divided into sub-intervals for the search for discontinuities; for each sub-interval the search proposes one candidate. This is particularly efficient when time series are contaminated by colored noise (see Section 11.2.2.1). Second, the maximum number of outlier candidates is user-defined, i.e., more than only one outlier may be added to the functional model (see Section 11.2.2.2). Third, a velocity change candidate may be proposed in conjunction with each known discontinuity of unknown origin. For the analysis of coordinate time series this feature might help, e.g., to model induced effects such as snow on top of the antenna.

11. The candidate elements collected in step 10 are checked one by one in the functional model. Then, the most probable element, which is the element that removes the largest discrepancy between the functional model and the time series, is added to the functional model. Such an element has to meet the statistical test based on the test value and the minimum interval length between successive velocity changes Δt_v . At the same time, significant outlier candidates are added to the functional model according to Eqn. (11.18). In addition, all elements must meet the additional criteria described in Section 11.2.3.3.
12. Output files are created. All elements of the functional model of the entire set of analyzed stations are reported in the event list (EVL).
13. The metadata files for a follow-up ADDNEQ2 run are updated. Metadata can be specified in panel "FODITS 2: Output files" (STA file) and in panel "FODITS 7: Options to generate files for ADDNEQ2" (CRD, VEL, FIX, and SIG files).

11.2. Detailed Description of the Algorithm

11.2.1. Introducing Known Elements

The support of predefined information allows us to carry out a reliable analysis of the time series. The a priori information considered by FODITS consists of the history of equipment changes, of a file containing information about registered earthquakes, of potential periodic functions, and of a list of user-defined events.

11.2.1.1. Earthquakes

The list of earthquakes introduced in the analysis of the program FODITS is derived from the database of the U. S. Geological Survey (USGS) Earthquake Hazards Program (see Section 24.7.21 for the description). The earthquake list file can be selected in panel "FODITS 1: Input Files".

Not all tracking stations are affected by the worldwide registered earthquakes. According to Delle Donne et al. (2010), a station at a distance d_{erq} (in meters) from the epicenter of an earthquake of magnitude M_{erq} has a co-seismic displacement associated with the earthquake if

$$M_{erq,1} \geq -6.40 + 2.17 \cdot \log_{10} d_{erq} . \quad (11.2)$$

This condition, however, is only roughly representing the mean effect of an earthquake event. In the context of FODITS, where a significance test is added for each potential discontinuity caused by an event, we prefer a waver for this condition by shifting the offset in Eqn. (11.2) by +0.8. In this way, we obtain a more representative expression for permanent co-seismic displacements yielding

$$M_{erq,2} \geq -5.60 + 2.17 \cdot \log_{10} d_{erq} . \quad (11.3)$$

The values can also be adjusted by the user via the options “Earthquake factor A” and “Earthquake factor B” in panel “FODITS 1.2: General Variables”.

For each earthquake that meets the condition defined in Eqn. 11.3, both a discontinuity and a velocity change is added to the list of predefined elements. The discontinuity aims at modeling the permanent co-seismic displacement caused by the event. The velocity change, on the other hand, shall model the actual long-term change of the station velocity after the event.

Large earthquakes are usually followed by a series of aftershocks lasting weeks or even months. Hence, the list of predefined elements would possibly contain the main earthquake as well as several large aftershocks if we stick to the selection criterion given by Eqn. (11.3). Currently, for geodetic tasks such as the realization of a terrestrial reference frame, there is no need to model post-seismic relaxation phases of earthquakes. Therefore, aftershocks succeeding large earthquakes might be removed from the list of predefined elements in order to avoid modeling these phases by sequences of frequent discontinuities.

The screening procedure concerning aftershocks is as follows: starting from the largest (in terms of magnitude) earthquake of the list, all smaller earthquakes taking place after the user-defined time interval Δt_{erq} are removed from the list. As a result, we obtain a list of predefined elements containing only the major earthquakes. From the experience gained in analyzing long time series we can tell that a value of $\Delta t_{erq} = 60$ days optimally removes the events related to post-seismic relaxation phases (option “Minimal time span between earthquakes” in panel “FODITS 1.2: General Variables”).

11.2.1.2. Equipment Changes

Equipment changes at permanent tracking stations may induce systematic offsets and changes in the noise behavior of the coordinate time series. Whether these changes are significant or not depends on the assumptions of the statistical tests described in Section 11.2.3.1. Typically discontinuities are induced by antenna or radome changes or by imaging effects due to changes in the near field environment. Other events such as changing the receiver or updating the receiver firmware introduce in most cases only a small discontinuity but they may change significantly the noise characteristics of the measurements.

The history of equipment changes in the *Bernese GNSS Software* is documented in the station information file (default extension *STA*, description in Section 24.7). The program FODITS reads the equipment information from the related input file (to be specified in panel “FODITS 1: Input Files”) and updates the list of predefined elements. The type of events that shall be considered may be selected in panel “FODITS 3: Handling of information coming from the input files” displayed in Figure 11.3.

For each type of event three options are available:

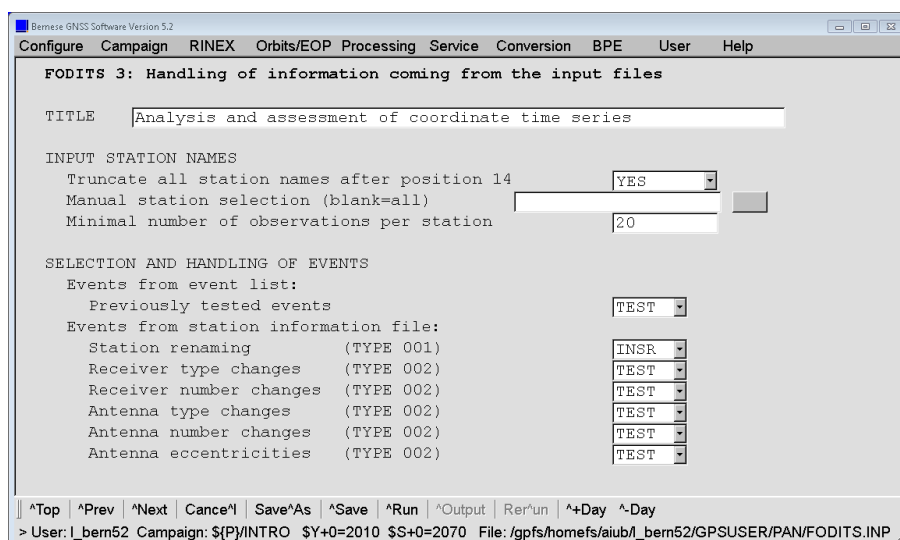


Figure 11.3.: Handling of a priori information from the event list or from particular parts of the station information file by FODITS.

INSR: introduce discontinuity to the functional model without testing for significance,
 TEST: introduce discontinuity only if it significantly improves the functional model,
 NONE: ignore the entry.

After an equipment change no station velocity change is expected.

11.2.1.3. User-Defined List of Events

A general opportunity to introduce a priori events (i.e., a discontinuity, an outlier, a velocity change, or a periodic function) into the algorithm is offered via the “Input event list file” (see Section 24.7.20 for the description). Using this file is optional; it may be selected in panel “FODITS 1: Input Files”.

As for equipment changes the proposed elements from the event list file may be introduced only if they are significant or without any condition (option “Events from event list file” in panel “FODITS 3: Handling of information coming from the input files” displayed in Figure 11.3). These options allow the user to manipulate the resulting functional model in a very flexible way.

This feature offers for instance the opportunity to introduce officially confirmed discontinuities adopted by both IGS¹ and EUREF².

11.2.1.4. Periodic Functions

Coordinate time series of both global and regional networks show in many cases seasonal signals. According to Dong et al. (2002) the primary contribution of such apparent signals, with 40% of the power, has been identified in surface mass redistribution due to atmosphere, ocean, snow, and soil moisture. Since these are not strong periodic signals (indicated by the expression “quasi-seasonal”) the harmonics of an annual period should be considered as well.

¹<ftp://igs-rf.ign.fr/pub/discontinuities/soln.snx>

²ftp://epncb.oma.be/pub/station/coord/EPN/EPN_discontinuities.snx

Independent from these effects, orbit modeling deficiencies or multipath effects result in harmonics related to the draconitic year of the GPS or GLONASS constellation with a length of approximately 351 days and 353 days, respectively. Also deficiencies in modeling sub-daily signals may propagate in a draconitic signal because of the daily processing scheme typically applied for GNSS data processing.

In panel “FODITS 4: Model definition” the inclusion of seasonal signals (annual and semi-annual periods added if the option “Propose seasonal signals” is enabled) and/or additional user-specified periods may be proposed for the functional model. The related components are checked for significance. Further significant periods may be added as well from an automated search if the option “Selection of new elements, periodic functions” in panel “FODITS 6: Identification step” is enabled (see Section 11.2.2.4).

11.2.1.5. Outliers from the Test of the Datum Definition

A series of station coordinates is typically compared epoch by epoch against a second set of coordinates using the Helmert transformation. For each epoch, estimates of the Helmert parameters are obtained as well as residuals for each station contributing to the adjustment. This procedure is thus well-suited to identify stations that should not contribute to the datum definition in the multi-year solution. For each epoch, stations with residuals larger than user-defined thresholds in the north, east, and vertical components are first rejected from the computation of the Helmert transformation. Such stations may be added to a list of predefined outliers. The options in panel “FODITS 4.1: Test datum definition by Helmert transformation” are dedicated for this purpose. Their usage is equivalent to the use of the program HELMR1.

11.2.2. Searching for New Elements to Improve the Functional Model

The algorithms described in this section detect the most probable element (discontinuity, outlier, periodic function, or velocity change) in step 10 of the algorithm described in Section 11.1.3 and illustrated in Figure 11.2. The options in panel “FODITS 6: Identification step” (see Figure 11.4) allow to select the type of event to be considered.

11.2.2.1. Searching for Discontinuities

The search for the epoch of the most probable discontinuity in the time series of the residuals aims at validating the assumptions for the modification of functional and stochastic models. There are two assumptions related to the linear Gauss–Markov model. It is assumed (1) that the time series contains only white noise and (2) that the functional model is correct, i.e., the model is defined adequately for the time series. Only the second assumption has to be validated because only the epoch of the discontinuity with the largest discrepancy between the functional model and the time series shall be identified. According to Teunissen and Kleusberg (1998b), an error in the functional model can be verified by formulating the following null hypothesis and alternative hypothesis (see also Section 7.2):

$$\begin{aligned} H_0 & : \mathbf{E}(\mathbf{y}) = \mathbf{A}\mathbf{p}, & \mathbf{D}(\mathbf{y}) & = \mathbf{Q}_{yy} \\ H_A & : \mathbf{E}(\mathbf{y}) = \mathbf{A}\mathbf{p} + \mathbf{C}\nabla, & \mathbf{D}(\mathbf{y}) & = \mathbf{Q}_{yy} . \end{aligned} \quad (11.4)$$

Whereas the null hypothesis H_0 states that the functional model is free of errors, the alternative hypothesis H_A states that the functional model contains a bias $\mathbf{C}\nabla$, with \mathbf{C}

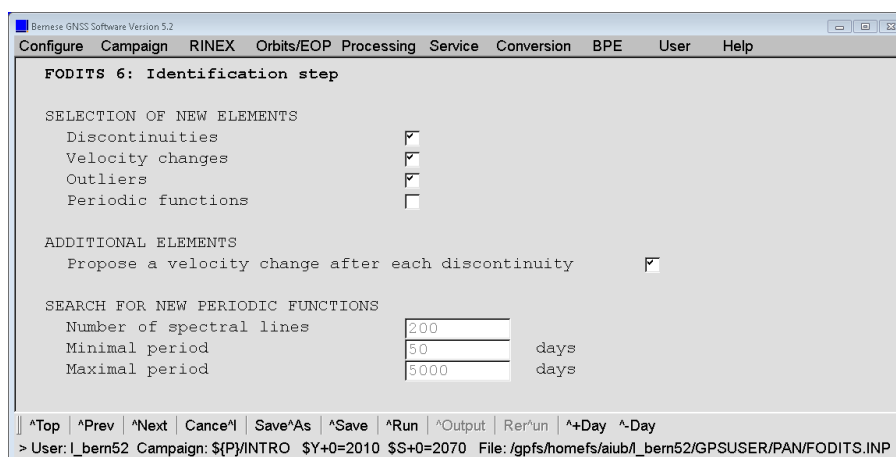


Figure 11.4.: Setup for detection of additional events: discontinuities, velocity changes, and periodic functions in FODITS.

being the known error and ∇ being the unknown size. The statistical test to infer whether H_0 has to be rejected in favor of H_A has its roots in the generalized likelihood ratio. The ratio test compares the likelihood function of H_0 with that of H_A . The test quantity T_d is

$$T_d = \frac{1}{d} \mathbf{v}^T \mathbf{Q}_{yy}^{-1} \mathbf{C} [\mathbf{C}^T \mathbf{Q}_{yy}^{-1} \mathbf{Q}_{vv} \mathbf{Q}_{yy}^{-1} \mathbf{C}]^{-1} \mathbf{C}^T \mathbf{Q}_{yy}^{-1} \mathbf{v}, \quad (11.5)$$

where d is the dimension of the test, \mathbf{v} are the residuals, and \mathbf{Q}_{yy} and \mathbf{Q}_{vv} is the variance–covariance matrix of the observations and of the residuals, respectively. The d –dimensional matrix \mathbf{C} defines the error considered by Eqn. (11.5). The null hypothesis H_0 is rejected in favor of the alternative hypothesis H_A if

$$T_d \geq F_\alpha(d, \infty, 0), \quad (11.6)$$

where α is the user–defined level of significance given in option “Significance test: threshold for relative improvement” (panel “FODITS 5: Statistical tests” displayed in Figure 11.7). $F_\alpha(d, \infty, 0)$ corresponds to the F–distribution, with d and ∞ being the degree of freedoms. According to Teunissen and Kleusberg (1998b), the n_{obs} observations are checked for the existence of a significant discontinuity at epoch t_k by defining the one–dimensional test vector

$$\mathbf{c}_k = \begin{cases} 0 & \text{for } i = 1, \dots, k-1 \\ 1 & \text{for } i = k, \dots, n_{obs} \end{cases} \quad (11.7)$$

The identification step of the procedure finds the most probable discontinuity by (1) testing the alternative hypothesis (Eqn. 11.4) for all n_{obs} epochs of the time series and (2) proposing the epoch with the largest value in the statistical test (Eqn. 11.5) as the most probable discontinuity (if statistically significant). This implies that the epoch $t_{A,j}$ of the identified discontinuity satisfies the criterion

$$g(t_{A,j}) = \max(T_{A,1}, \dots, T_{A,n_{obs}}), \quad (11.8)$$

where T_A is the one–dimensional test (see Eqn. 11.5). For the three–dimensional case, Eqn. (11.7) is set up with an identity matrix $I_{3 \times 3}$.

The analysis of the time series by means of the algorithm introduced in Section 11.1.3 together with the search for discontinuities (see Eqn. 11.8) is CPU-time intensive. This is particularly true when daily coordinate time series spanning more than ten years are analyzed for more than 500 stations. This is why an optimized statistical test for discontinuities has been introduced by starting from the one-dimensional case of Eqn. (11.5):

$$T_1 = \mathbf{v}^T \mathbf{Q}_{yy}^{-1} \mathbf{c} [\mathbf{c}^T \mathbf{Q}_{yy}^{-1} \mathbf{Q}_{vv} \mathbf{Q}_{yy}^{-1} \mathbf{c}]^{-1} \mathbf{c}^T \mathbf{Q}_{yy}^{-1} \mathbf{v} . \quad (11.9)$$

The optimization is based on a heuristic approach. If a coordinate time series is not provided along with its covariance information (as described in step 1 of the algorithm in Figure 11.2), the covariance matrix of the observations is assumed to be an identity matrix, i.e., $\mathbf{Q}_{yy}^{-1} = \mathbf{E}$. This assumption reduces Eqn. (11.9) to

$$T_1 = \mathbf{v}^T \mathbf{c} [\mathbf{c}^T \mathbf{Q}_{vv} \mathbf{c}]^{-1} \mathbf{c}^T \mathbf{v} , \quad (11.10)$$

with $\mathbf{Q}_{vv} = \mathbf{I} - \mathbf{A} \mathbf{Q}_{\hat{p}\hat{p}} \mathbf{A}^T$. As the F-distribution in Eqn. (11.6) refers to the covariance information of the observations, the original statistical meaning of the test is lost. The denominator $\mathbf{c}^T \mathbf{Q}_{vv} \mathbf{c}$ can therefore be set to one and Eqn. (11.10) is reduced to

$$T_1 = \mathbf{v}^T \mathbf{c} \mathbf{c}^T \mathbf{v} = (\mathbf{v}^T \mathbf{c})^2 , \quad (11.11)$$

where $(\mathbf{c}^T \mathbf{v})^T = \mathbf{v}^T \mathbf{c}$ was used. Because the only interest of the test is to find which alternative hypothesis H_A in Eqn. (11.4) obtains the largest value, Eqn. (11.11) may be further simplified to

$$T_1 = |\mathbf{v}^T \mathbf{c}| .$$

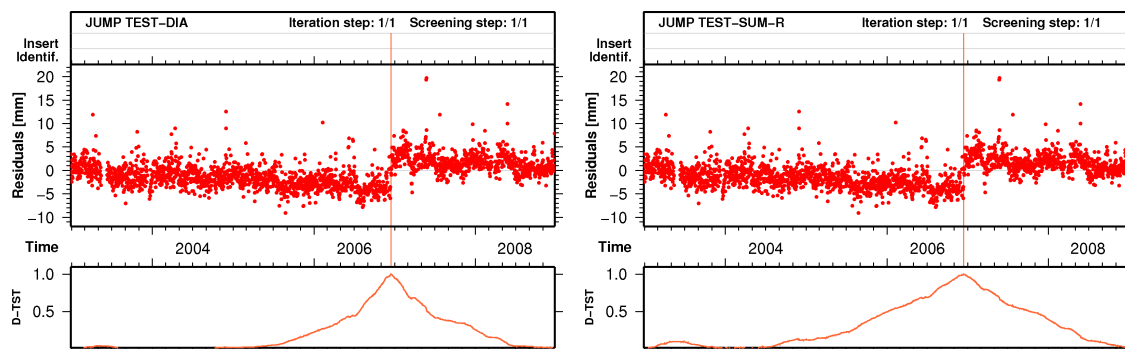
By using the test matrix \mathbf{c} , which is given in Eqn. (11.7), we obtain

$$T_{1,k} = \left| \sum_{i=k}^{n_{obs}} \mathbf{v}_i \right| . \quad (11.12)$$

The new search based on the optimized test (Eqn. 11.12) results in the discontinuity epoch $t_{B,j}$ with

$$g(t_{B,j}) = \max(T_{B,1}, \dots, T_{B,n_{obs}}) \quad \text{with} \quad T_{B,k} = \left| \sum_{i=k}^{n_{obs}} \mathbf{v}_i \right| . \quad (11.13)$$

Figure 11.5 illustrates the normalized search (D-TST) for the most probable discontinuity in the one-dimensional daily coordinate time series with the original test (see Eqn. 11.8 and Figure 11.5a) and with the optimized test (see Eqn. 11.13 and Figure 11.5b). Although the two search algorithms result in slightly different normalized search series, both identified the same epoch for the most probable discontinuity, namely December 15, 2006. The optimized search $t_{B,j}$ is more than 100 times faster than the original one $t_{A,j}$ (1 s versus 160 s). Both search algorithms identified the correct epoch despite of outliers and despite of the discontinuity not being a step function.



(a) Search with space VCI. Identified discontinuity: December 15, 2006. Processing-time: about 160 sec. (b) Search with simplified equation. Identified discontinuity: December 15, 2006. Processing-time: about 1 sec.

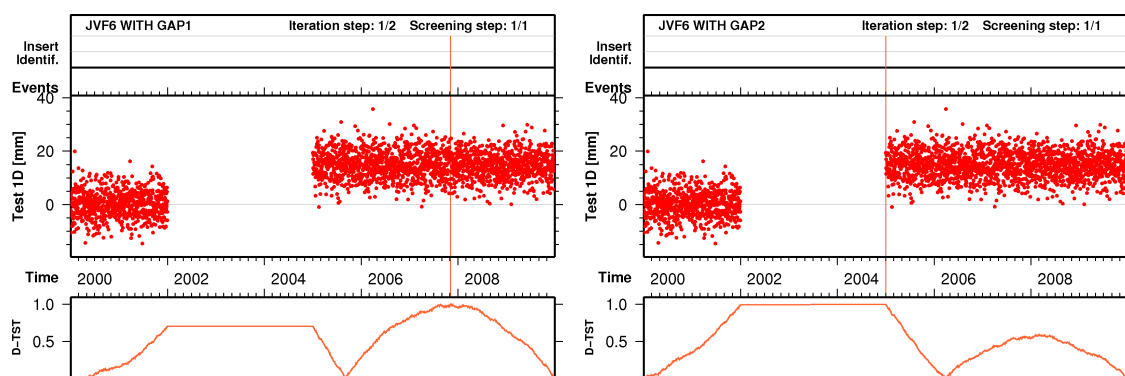
Figure 11.5.: Search for discontinuities in simplified form. Time series: North component of CODE daily coordinates, station PDEL 31906M004.

The performance of the test (Eqn. 11.13) is reduced in case long gaps occur. To improve the robustness of the test we use

$$g(t_{C,j}) = \max(T_{C,1}, \dots, T_{C,n_{obs}}) \quad \text{with} \quad T_{C,k} = \left| \sum_{i=k}^{n_{obs}} \mathbf{w}_i \right| \quad (11.14)$$

to find the epoch $t_{C,j}$ of the discontinuity; \mathbf{w} is the time series of residuals obtained from a linear regression through the original time series of the residuals \mathbf{v} , but with the peculiarity $t_i = i$ for $i = 1, \dots, n_{obs}$. In other words, before the fit to obtain new residuals \mathbf{w} , pseudo-observations (i.e., the residuals \mathbf{v}) are artificially spaced in time by a constant unitary amount. According to the derivation of the test, no covariance information is taken into account.

Figure 11.6 shows the search (D-TST) for both cases, (a) without new sampling ($t_{B,j}$) and (b) with new sampling ($t_{C,j}$). It is evident that the former test fails and the latter succeeds. For this reason, the implemented search for discontinuities in the algorithm FODITS is $t_{C,j}$ (see Eqn. 11.14).



(a) Search $t_{B,j}$ without time re-sampling. Identified discontinuity: November 3, 2007. (b) Search $t_{C,j}$ with time re-sampling. Identified discontinuity: January 1, 2000.

Figure 11.6.: Search for discontinuities without (a) and with (b) time re-sampling. Time series: synthetic data $\sim N(0,25)$ with a discontinuity of 15 mm.

Last but not least, the search (Eqn. 11.14) exploits the fact in the context of the least squares that if $\sum_{i=k}^{n_{obs}} \mathbf{w}_i^2 = \min$, then $\sum_{i=k}^{n_{obs}} \mathbf{w}_i = 0$. Broadly, such an implication might be interpreted as a "first derivative of the minimum principle".

11.2.2.2. Searching for Outliers

An epoch $t_{O,i}$ is assumed to be associated with an outlier if

$$T_{O,i} = \frac{|\mathbf{v}_i|}{\delta v_i} \geq U_s \quad \text{for } i = 1, \dots, n_{obs} ,$$

where U_s is the user-defined level of significance for outliers ("Significance test: N*sigma criterion for outliers" in panel "FODITS 5: Statistical tests" displayed in Figure 11.7), $\delta v = m_0 \sqrt{\mathbf{T} \mathbf{Q}_{yy}(\mathbf{v}) \mathbf{T}^T}$ is the RMS error of the outlier candidate (residual) \mathbf{v} with \mathbf{T} being the transformation matrix and m_0 describing the a posteriori RMS of unit weight.

The search for outliers accounts for the covariance information of the observations (i.e., $\mathbf{Q}_{yy}(\mathbf{v})$) instead of the cofactor matrix derived from the adjustment (i.e., $\mathbf{Q}_{\hat{p}\hat{p}}(\mathbf{v})$). If, however, the covariance information of the observations is not available, δv is equal to σ_0 , i.e., the user-defined a priori RMS of unit weight (by convention: 1 mm).

11.2.2.3. Searching for Velocity Changes

To identify the epoch of the most likely velocity change in a sub-interval of N observations (epochs), we adopt the following deterministic model:

$$\mathbf{f}_{vc}(t) = \begin{cases} \mathbf{a}_0 + \dot{\mathbf{a}}_0 t & \text{for } t \leq t_k \\ \mathbf{a}_0 + \dot{\mathbf{a}}_0 t + \dot{\mathbf{a}}_{0k}(t - t_k) & \text{for } t \geq t_k, \end{cases}$$

i.e., the model is linear within the entire sub-interval, but features different slopes before and after the epoch t_k , namely $\dot{\mathbf{a}}_0$, $\dot{\mathbf{a}}_0 + \dot{\mathbf{a}}_{0k}$. The first design matrix associated with the observations in the selected sub-interval reads as

$$\mathbf{A}_k = \begin{bmatrix} 1 & t_{a,1} & 0 \\ 1 & t_{a,2} & 0 \\ \vdots & \vdots & \vdots \\ 1 & t_{a,k-1} & 0 \\ 1 & t_{a,k} & t_{b,1} \\ \vdots & \vdots & \vdots \\ 1 & t_{a,N} & t_{b,N-k} \end{bmatrix} \begin{array}{l} \rightarrow t_{a,1} = t_1 \\ \rightarrow t_{a,2} = t_2 \\ \vdots \\ \rightarrow t_{a,k-1} = t_{k-1} \\ \rightarrow t_{a,k} = t_k, \quad t_{b,1} = t_k - t_k = 0 \\ \vdots \\ \rightarrow t_a = t_N, \quad t_{b,N-k} = t_N - t_k . \end{array}$$

The most likely epoch $T_{V,k}$ is found by systematically varying k in the range $k = 2, 3, \dots, N - 1$ and by using the a posteriori RMS $m_{0,k}$ of the observations associated with the estimates assuming the velocity change at $t = t_k$. We use the following condition to identify $t_{a,k} = t_{V,j}$:

$$g(t_{V,j}) = \max\left(\frac{1}{m_{0,2}}, \dots, \frac{1}{m_{0,N-1}}\right) .$$

The search of the maximum velocity change is implemented in order to speed up the computation time by assuming that the observations are neither time-correlated nor cross-correlated, i.e., the least squares method does not take into account the covariance information. Furthermore, instead of re-computing \mathbf{A}_k and its associated NEQ for each epoch k , the $N - 2$ NEQs to be solved,

$$\mathbf{N}_k = \begin{bmatrix} N & \sum t_{a,i} & \sum t_{b,j} \\ \sum t_{a,i} & \sum t_{a,i}^2 & \sum t_{a,i}t_{b,j} \\ \sum t_{b,j} & \sum t_{a,i}t_{b,j} & \sum t_{b,j}^2 \end{bmatrix}, \quad \mathbf{b}_k = \begin{bmatrix} \sum y_i \\ \sum t_{a,i}y_i \\ \sum t_{b,j}y_i \end{bmatrix},$$

are computed in a time-saving manner by updating $\{\mathbf{N}, \mathbf{b}\}_k$ using $\{\mathbf{N}, \mathbf{b}\}_{k-1}$.

11.2.2.4. Searching for Periodic Functions

The search for the most probable periodic function in the post-fit residual time series is based on the Fourier analysis by least squares adjustment. The Fourier analysis consists of n_{per} spectral lines starting from the initial period p_{beg} to the final period p_{end} . Spectral lines are evenly spaced in the frequency domain. For each spectral line k , the following first design matrix (here only for one component) is defined:

$$\mathbf{A}_k = \begin{bmatrix} \cos(\omega_k t_1) & \sin(\omega_k t_1) \\ \cos(\omega_k t_2) & \sin(\omega_k t_2) \\ \vdots & \vdots \\ \cos(\omega_k t_N) & \sin(\omega_k t_N) \end{bmatrix}.$$

Parameters are estimated by least squares adjustment and the a posteriori sigma of unit weight $m_{0,k}$ is computed. The most probable period P_j among the residuals is found by

$$g(\omega_{P,j}) = \max\left(\frac{1}{m_{0,k}}, \dots, \frac{1}{m_{n_{per},k}}\right).$$

11.2.3. Controlling the Algorithm

Without an external control, the algorithm would add more and more elements to the functional model as long as the degree of freedom of the adjustment remains positive. The procedure is controlled by user-defined significance levels in order to terminate the analysis at a reasonable point, i.e., when the functional model describes the time series in an acceptable way.

Since outliers are treated separately from the other elements, there exist two statistical tests: one for outliers and one for all other elements of the functional model. The drawback of performing two statistical tests with two levels of significance is compensated to a large extent by the advantage of carrying out the analysis in a faster and more flexible way.

In order to adapt the algorithm in an easy way to the expected noise level of the time series, additional criteria are defined to stop the algorithm at a reasonable magnitude for the detected elements.

The options to control the algorithm are available in panel "FODITS 5: Statistical tests" displayed in Figure 11.7.

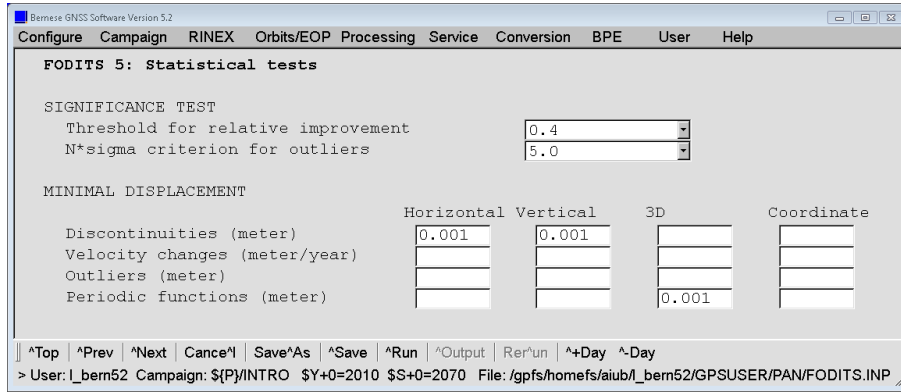


Figure 11.7.: The panel controlling the termination of the algorithm detecting new events with minimum thresholds.

11.2.3.1. Test for Discontinuities, Velocity Changes, and Periodic Functions

All elements of the functional model are checked for significance by means of a statistical test that is based on the sum of weighted square residuals. A new element is added to the functional model based on the test value

$$T_t = \left(\frac{v_n^T P v_n}{v_p^T P v_p} - 1 \right) \cdot \frac{n_{obs}}{n_{obs,a}}, \quad (11.15)$$

with $v_n^T P v_n$ being the new weighted sum of square residuals (i.e., after the new element has been added) and $v_p^T P v_p$ being the previous weighted sum of square residuals (i.e., before adding the element). The last term of Eqn. 11.15 is introduced to harmonize the test value for all analyzed time series (e.g., of the campaign). Similarly, for the removal of an element from the functional model the test value is defined as

$$T_t = \left(\frac{v_p^T P v_p}{v_n^T P v_n} - 1 \right) \cdot \frac{n_{obs}}{n_{obs,a}}. \quad (11.16)$$

An element is added or removed, respectively, if

$$T_t \geq U_t, \quad (11.17)$$

where U_t is the user-defined level of significance for the elements. The test (Eqn. 11.17) tells whether the impact of the added or removed element is significant or not. The test values (Eqn. 11.15 and 11.16) are also used to identify the element that removes the largest discrepancy between the functional model and the time series.

11.2.3.2. Test for Outliers

Outliers are considered significant if

$$T_s = \frac{|\mathbf{s}_c|}{\delta s_c} \geq U_s, \quad (11.18)$$

where δs_c is the formal error of the outlier candidate \mathbf{s}_c , and U_s is the user-defined level of significance for outliers (“Significance test: N*sigma criterion for outliers” in panel “FODITS 5: Statistical tests”).

11.2.3.3. Additional Criteria for All Parameters

Weekly coordinate solutions produced from a global network analysis are usually consistent at the level of $\lesssim 1$ mm and ≈ 3 mm for horizontal and vertical components, respectively. Therefore, elements of the functional model with absolute values smaller than these values do not have a reliable physical meaning although they have possibly passed the statistical tests. This is why minimal values may be defined by the user for horizontal, vertical, or 3D-displacement as well as for a single coordinate component (see Figure 11.7 showing the panel “FODITS 5: Statistical tests”). Elements that do not satisfy these additional criteria are not considered even if they are significant in terms of the conditions from Eqs. (11.17) and (11.18). It is obvious that these values need to be adjusted according to the noise behavior of the solution under consideration (network extension, daily or weekly solutions, GNSS- or SLR-based solutions etc.).

11.2.3.4. Minimum Interval Length for Velocities

Within FODITS, station velocities are assumed to be linear in time. Reliable estimates of station velocities emerge from continuous GNSS observations over a time span of more than 2.5 years. Changes of the station velocity are typically induced by earthquakes. Prominent examples are earthquake cycles; the GNSS technique is often used to monitor inter-seismic, co-seismic, and post-seismic deformations due to earthquakes. Post-seismic phases, often characterized by aftershocks, are associated with the viscoelastic relaxation of the Earth lasting for 6 months or longer.

The algorithm considers a user-defined *minimum interval length between successive velocity changes* variable Δt_v with a default value of 2.5 years in order to obtain reliable station velocities (option “Minimal interval length for all rate intervals” in panel “FODITS 4: Model definition”). Additional velocity change candidates (e.g., proposed to model a post-seismic phase of a large earthquake) that do not satisfy the minimum interval length criterion are ignored.

11.3. Output and Result Files

11.3.1. Program Output from FODITS

As an example, one year of weekly coordinate solutions for the IGS stations in Arequipa, Peru (AREQ 42202M005) have been used. The differences between the functional model and the coordinates are plotted in Figure 11.8. The corresponding program output reporting the time series analysis is shown in Figure 11.9.

In the first section of the program output (not shown here), all input options are reported. All proposed elements for the functional model are listed according to the specification (see Section 11.2.1) in a subsequent section of the program output (upper table in Figure 11.9). In this case, an annual and semi-annual period function (checkbox for “Propose seasonal signals” in panel “FODITS 4: Model definition” was selected) and two earthquakes (Section 11.2.1.1) were selected. After the second earthquake no further solution is available for Arequipa which means that it is not relevant here. There was no equipment change during this period.

The differences between a functional model only consisting of these proposed a priori elements and the coordinate time series are shown in Figure 11.8a. In a first iteration, the algorithm detects four outliers in the vertical component (indicated with light gray instead of dark dots in Figure 11.8b). The algorithm then checks for an additional discontinuity or velocity change in the time series. It proposes the element leading to the biggest reduction of the RMS of the differences between the time series and the model. In this case, this discontinuity is obviously not significant. So the second iteration only adds the four outliers. This reduces the RMS between the time series and the functional model from (2.5, 2.0, 1.7) mm to (2.0, 2.0, 1.6) mm for the vertical, north and east components respectively. Finally in an additional iteration another outlier is identified that becomes significant due to the reduced RMS in the north component. The RMS is now reduced further to (1.9, 1.9, 1.6) mm for the three coordinate components.

By selecting the option “Enable detailed program output” in panel “FODITS 2: Output Files” the program reports on each processing step with a very high level of detail, as described above. The algorithm introduced in Section 11.1.3 can be followed nicely through this detailed output. This mode is helpful to help tuning the input options to a specific scenario. This part of the output is not displayed in Figure 11.9.

The lower part in Figure 11.9 shows the final results from the time series analysis. All elements have been identified or introduced as a priori elements by the current program run. The following elements are reported as contributions to the functional model in the column `Evnt` of the program output:

RATE: linear velocity, term $v_0(t_i - t_0)$ in Eqn. (11.1)

DISC: discontinuity element, term $d_k \eta_{d,k}(t_i)$ in Eqn. (11.1)

OUTL: outlier element, term $s_k \eta_{s,k}(t_i)$ in Eqn. (11.1)

VELO: linear velocity after a velocity change, term $v_k(t_i - t_k) \eta_{v,k}(t_i)$ in Eqn. (11.1)

PERI, PERP: amplitude and phase of a periodic function corresponding to the term $[\mathbf{p}_{a,k} \cos(\omega_k(t_i - t_0)) + \mathbf{p}_{b,k} \sin(\omega_k(t_i - t_0))] \eta_{p,k}(t_i)$ in Eqn. (11.1)

The column `Remark` indicates at which level the event has been introduced into the algorithm:

OFFST-TS, DRIFT-TS: basic component corresponding to station coordinate and linear velocity, automatically added to each functional model.

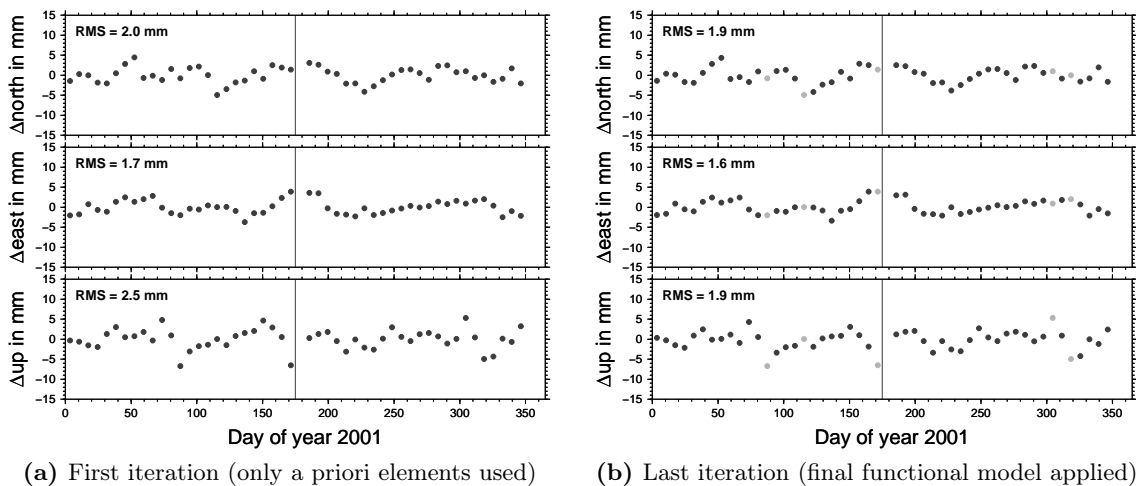


Figure 11.8.: Results of a time series analysis on weekly coordinates for station Arequipa.

```

INPUT: A PRIORI INFORMATION (FROM FILES OR FROM INPUT PANEL)
-----
Reasons for equipment changes:
A: Station renaming
B: Receiver type changes
C: Receiver number changes
D: Antenna type changes
E: Antenna number changes
F: Antenna eccentricity changes
-----

```

Nr Station	Event	Flg	Epoch (From)	Epoch (To)	Period [days]	Remark	Estimates [m,m/year]	Up	StdDev	Stat
							North East		All	test S KYWD
1 AREQ 42202M005	PERI	TST	2001-06-23 20:19:53	182.625	PAN-PERI	0.34257E-02 0.21618E-02	0.43769E-02	0.60942E-03	9.79	Y AP0S
1 AREQ 42202M005	PERI	TST	2001-04-28 12:00:00	182.625	PAN-PERI	-0.43870E+02 -0.66150E+02	0.29211E+02	0.00000E+00	0.00	Y AP0S
1 AREQ 42202M005	PERI	EST	2001-04-28 12:00:00	365.250	PAN-PERI	0.89261E-02 0.14531E-01	0.73760E-02	0.79644E-03	23.33	Y AP0S
1 AREQ 42202M005	PERI	EST	2001-06-23 20:19:53	365.250	PAN-PERI	-0.50674E+02 -0.46324E+02	0.92001E+02	0.00000E+00	0.00	Y AP0S
1 AREQ 42202M005	VELD	TST	2001-12-04 05:34:18	9999.999	DRIFT-TS	0.52494E+00 0.73906E+00	0.42491E-01	0.42015E-02	0.00	N AP0S
1 AREQ 42202M005	VELD	TST	2001-12-04 05:34:18	9999.999	DRIFT-TS	0.52494E+00 0.73906E+00	0.42491E-01	0.42015E-02	0.00	N AP0S
1 AREQ 42202M005	DISC	EST	2001-01-03 12:00:00	9999.999	OFFST-TS	0.43786E+00 0.61557E+00	0.40180E-01	0.35078E-02	0.00	N AP0S
1 AREQ 42202M005	DISC	EST	2001-03-28 12:00:00	9999.999	NEW-OUTL	-0.25269E+00 -0.35011E+00	-0.41770E-01	0.10000E-02	433.79	Y AP0S
1 AREQ 42202M005	OUTL	EST	2001-04-25 12:00:00	9999.999	NEW-OUTL	-0.25456E+00 -0.34311E+00	-0.36935E-01	0.10000E-02	428.82	Y AP0S
1 AREQ 42202M005	OUTL	EST	2001-06-20 12:00:00	9999.999	NEW-OUTL	-0.24664E+00 -0.34420E+00	-0.30021E-01	0.10000E-02	424.51	Y AP0S
1 AREQ 42202M005	DISC	EST	2001-06-23 20:19:53	9999.999	ERQ-DISC	-0.32667E+00 -0.46189E+00	-0.35170E-01	0.26003E-02	218.43	Y AP0S
1 AREQ 42202M005	VELD	EST	2001-10-31 12:00:00	9999.999	NEW-OUTL	-0.15959E+00 -0.19090E+00	-0.68528E-01	0.37546E-01	6.81	N AP0S
1 AREQ 42202M005	OUTL	EST	2001-10-31 12:00:00	9999.999	NEW-OUTL	-0.2730E+00 -0.39463E+00	-0.12180E-01	0.10000E-02	483.89	Y AP0S
1 AREQ 42202M005	DISC	EST	2001-11-14 12:00:00	9999.999	NEW-OUTL	-0.27730E+00 -0.39041E+00	-0.25587E-01	0.10000E-02	479.55	Y AP0S
1 AREQ 42202M005	DISC	EST	2001-12-04 05:34:18	9999.999	ERQ-DISC	0.35868E-03 -0.24634E-02	0.15392E-02	0.21749E-02	1.35	N AP0S
1 AREQ 42202M005	VELD	EST	2001-12-04 05:34:18	9999.999	ERQ-VELD	-0.10504E+00 -0.12294E+00	0.17111E+00	0.11240E+00	2.09	N AP0S

Figure 11.9.: Program output for the time series analysis, example station Arequipa (1).

```

SUMMARY OF RESULTS
-----
General summary:
-----
R: Y = Reference site before analysis
-----
Nr Station      R #Epoch  | signf #staF #evlF #erqF #panF | #disc #velo #outl #peri | Total #disc #velo | Total #Itr | A posteriori |
-----
1 AREQ 42202M005  49 | 0 0 0 1 2 | 0 0 0 5 0 | 1 0 | 8 | 3 | 0.193883E-02 | Z
-----
Summary total      | 0 0 0 1 2 | 0 0 0 5 0 | 1 0 | 8 | 3 |
-----

MODEL UPDATE FOR ADDNEQ2
-----
Update of reference stations:
-----
Number of fiducial sites before FODITS analysis      : 0
Number of rejected fiducial sites                    : 0
Number of fiducial sites after FODITS analysis        : 0
Number of resulting fiducial sub-interval sites       : 0
Number of renamed stations in STA file                : 2
Number of outliers in STA file                      : 5
Number of relative velocity constraints in STA file    : 0

Update details concerning reference stations:
-----
Legend:  Group of relative velocity constraints (Gr), 1..nGr
R: reference station (Y), reference station rejected (N), (A) no original reference station,
Year G: interval length of the group of sub-intervals with same relative velocity constraints,
perc G: percentual observations in the group of sub-intervals with same relative velocity constraints,
-----
Nr Station Sub-Int. | From              | To              | Gr | R | year G | perc G | KYWD
-----
1 AREQ 42202M005ZZ | 2001-01-03 11:45:00 | 2001-07-04 11:44:59 | 1 | A | 0.000 | 0.00 | USTF
1 AREQ 42202M005   | 2001-07-04 11:45:00 | 2001-12-12 11:44:59 | 2 | A | 0.000 | 0.00 | USTF
-----
>>> CPU/Real time for pgm "FODITS": 0:00:00.197 / 0:00:00.233
>>> Program finished successfully

```

Figure 11.10.: Program output for the time series analysis, example station Arequipa (2).

- ERQ-DISC, ERQ-VELO: discontinuity and velocity change due to a potential crustal deformation related to an earthquake event (see Section 11.2.1.1).
- STA-DISC: potential discontinuity because of an equipment change indicated in the station information file (see Section 11.2.1.2).
- EVL-DISC, EVL-OUTL, EVL-VELO, EVL-PERI: an event introduced by an “Input event list file” (see Section 11.2.1.3).
- PAN-PERI: periodic function introduced by the user in option “Propose seasonal signals” or “Propose additional periods” (see Section 11.2.1.4).
- DDF-OUTL: outlier for a datum reference station was found according to the description in Section 11.2.1.5.
- NEW-DISC, NEW-OUTL, NEW-VELO, NEW-PERI: a new element proposed by the algorithm in order to improve the functional model’s representation of the time series (see Section 11.2.2).

In this time series analysis example for station Arequipa in Figure 11.9, all elements have been included in the significance tests during the different iterations. This is indicated by **EST** in the column **Flg**. Alternatively, **SET** indicates an element that was defined as a priori information but not further confirmed by a significance test.

All lines of this table end with **APOS** to allow a simple search or extraction by any external script. Directly before the keyword you can find the significance indicator **Y** or **N**. This allows for instance to simply extract the significant elements by searching for **Y APOS**.

In the example of Figure 11.9, the annual and semi-annual periodic function introduced by the user in panel “FODITS 4: Model definition” was found to be significant. From the first earthquake only the discontinuity was found to be significant where there was no significant change in the velocity. Because the second earthquake occurred after the end of the coordinate time series, it is listed but flagged as not significant. The procedure from FODITS detected 5 outliers and one additional discontinuity in the time series. This discontinuity was introduced as a potential improvement of the functional model but it was found to be not significant. This is summarized in one line per station to give a general overview of the time series analysis in the table in Section **SUMMARY OF RESULTS** of the program output that is displayed in Figure 11.10.

11.3.2. Event List File

The event list file reports the result from the time series analysis in a dedicated file format. The file is located in the **STA** directory of the campaign and has the default extension **EVL**. With the explanation of the program output file in the previous section, the content of this file is also explained. The example in Figure 11.11 corresponds to the program output shown in Figure 11.9.

The file can also be used as an input file for running the program FODITS as described in Section 11.2.1.3.

11.3.3. Station Information File

The results from the time series analysis have to be transferred to an updated station information file (to be specified in panel “FODITS 2: Output Files”). The aspects discussed in Section 9.4.6 are introduced automatically:

```

# FODITS - TIME SERIES EVENT LIST FILE
# -----
# Title: Analysis of weekly coordinates (AREQ)
# Description:
# -----
# Flg : - TST, tested by FODITS, removed if non-significant.
#       - SET, tested by FODITS, but always significant.
#       - MOT, interval of no event.
#       - EST, estimated by FODITS.
#       - DISC, discontinuity (use "Form Epoch").
#       - VELO, velocity change (use "Form Epoch").
#       - OUTL, outlier (use "From Epoch" for one outlier, use both "From Epoch" and "To Epoch" for a sequence).
#       - PERI, functional period ("From Epoch" and "To Epoch" are optional, "Period" must be defined).
#       - Y significant, N non-significant.
# S:
# -----
# From Epoch          To Epoch          Period          Amplitude [m]          Remark
# STATION NAME      Flg Evt      YYY-MM-DD HH:MM:SS  YYY-MM-DD HH:MM:SS  DDDD.DDDD  North  East  Up  S RRRRRRRR
# -----
AREQ 42202M005      EST PERI          2001-01-03 12:00:00  2001-03-31 23:45:00  182.6250  0.0034  0.0022  0.0044  Y PAN-PERI
AREQ 42202M005      EST PERI          2001-01-03 12:00:00  2001-04-28 23:45:00  365.2500  0.0089  0.0145  0.0074  Y PAN-PERI
AREQ 42202M005      EST RATE          2001-01-03 12:00:00  2001-06-23 23:45:00  9999.9999  0.5249  0.7391  0.0425  N DRIFT-TS
AREQ 42202M005      EST DISC          2001-03-25 00:15:00  2001-04-28 23:45:00  9999.9999  0.4379  0.6156  0.0402  N OFFST-TS
AREQ 42202M005      EST OUTL          2001-04-22 00:15:00  2001-06-23 23:45:00  9999.9999  -0.2527  -0.3501  -0.0418  Y NEW-OUTL
AREQ 42202M005      EST OUTL          2001-06-17 00:15:00  2001-06-23 23:45:00  9999.9999  -0.2546  -0.3431  -0.0369  Y NEW-OUTL
AREQ 42202M005      EST DISC          2001-06-23 20:19:53  2001-06-23 20:19:53  9999.9999  -0.3287  -0.4619  -0.0352  Y ERQ-DISC
AREQ 42202M005      EST VELO          2001-06-23 20:19:53  2001-11-03 23:45:00  9999.9999  -0.1559  -0.1909  -0.0685  N ERQ-VELO
AREQ 42202M005      EST OUTL          2001-10-28 00:15:00  2001-11-17 23:45:00  9999.9999  -0.2798  -0.3946  -0.0122  Y NEW-OUTL
AREQ 42202M005      EST OUTL          2001-11-11 00:15:00  2001-11-17 23:45:00  9999.9999  -0.2773  -0.3904  -0.0256  Y NEW-OUTL
AREQ 42202M005      EST DISC          2001-12-04 06:34:18  2001-12-04 06:34:18  9999.9999  0.0004  -0.0025  0.0015  N ERQ-DISC
AREQ 42202M005      EST VELO          2001-12-04 06:34:18  2001-12-04 06:34:18  9999.9999  -0.1050  -0.1229  0.1711  N ERQ-VELO

```

Figure 11.1.1.: Event list file for the time series analysis example for station Arequipa.

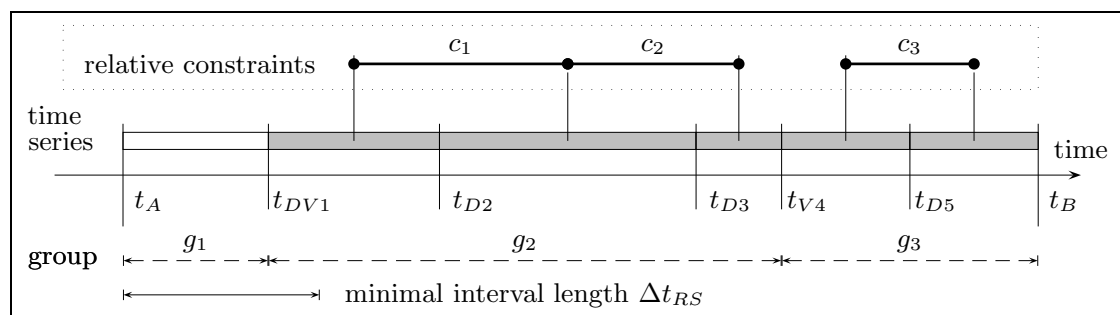


Figure 11.12.: A typical scenario of sub-intervals and relative velocity constraints for a reference site.

- Outliers are added to Section TYPE 003: HANDLING OF STATION PROBLEMS.
- Discontinuities and velocity changes are introduced by renaming the station in Section TYPE 001: RENAMING OF STATIONS.
- Discontinuities without velocity changes are also introduced by a renaming of the station name but the velocity estimates are attached to each other by introducing constraints in Section TYPE 004: STATION COORDINATES AND VELOCITIES (ADDNEQ).

The related changes are also reported in the program output file (last section in Figure 11.10).

Figure 11.12 illustrates the representation of the FODITS results in the station information file. The time series spans from t_A to t_B . Sub-intervals emerge from discontinuities (t_{D_n}) and velocity changes (t_{V_n}).

Δt_{RS} is the minimum interval length for reference sites. Relative velocity constraints such as c_1 , c_2 , and c_3 are applied to sub-intervals to model discontinuities. As a result, groups of sub-intervals such as g_1 , g_2 , and g_3 with identical station velocities are formed.

Initially, all groups of sub-intervals are considered for a reference frame station. In a second step, all groups are checked whether a group of sub-intervals exceeds the *minimum interval length* Δt_{RS} and whether the number of observations within a group has a *minimum percentage of data* p_{RS} . Groups that do not meet both requirements are declared as “non-reference” and, as a consequence, the associated sub-intervals are rejected from the list of reference sites. In the example of Figure 11.12, only the second and third group meet the first requirement and are kept as reference frame stations (indicated by the gray bar). For this reason, not all sub-intervals of this group are considered for reference sites in subsequent ADDNEQ2 runs.

The renaming of a station also requires an update of other input files for the program ADDNEQ2, namely station coordinate and velocity files (CRD, VEL) as well as station selection and sigma files (FIX, SIG) for the datum definition.

12. Troposphere Modeling and Estimation

12.1. Subdivision of the Atmosphere

The Earth's atmosphere is usually subdivided into two main shells, the troposphere and the ionosphere, since the signal propagation conditions are quite different in these two parts:

- The troposphere (neutral atmosphere) is the lower part of the atmosphere and extends from the Earth's surface up to an altitude of about 20 kilometers. The signal propagation depends mainly on temperature, pressure, and water vapor content of the atmospheric layers. At microwave wavelength the neutral atmosphere is not dispersive, while it is dispersive at optical wavelengths (SLR). For spaceborne receivers the troposphere is irrelevant.
- The ionosphere is the upper part of the atmosphere. It is located approximately between 70 and 1000 kilometers above the Earth. The signal propagation is mainly affected by free charged particles. The ionosphere is dispersive for microwave signals. The ionosphere and relevant issues are described in detail in Chapter 13.

12.2. Troposphere for GNSS Measurements

12.2.1. Motivation

Due to the availability of high accuracy orbits from the IGS (see Section 2.2.1), orbit errors need no longer to be considered as an important error source. Propagation delays of the GNSS code and phase signals caused by the neutral atmosphere (i.e., the troposphere) are certainly one of the ultimate accuracy-limiting factor for GNSS-based geodetic applications. The ZPD due to tropospheric refraction is of the order of 2.3 m (or about 8 ns) for a station at sea level and standard atmospheric conditions.

Let us first distinguish two kinds of troposphere biases:

- Relative troposphere biases caused by errors of (mismodeled) tropospheric refraction at one endpoint of a baseline relative to the other endpoint.
- Absolute troposphere biases caused by errors of (mismodeled) tropospheric refraction common to both endpoints of a baseline.

Both error sources are dealt with in detail in Beutler et al. (1988). In conclusion, the relative troposphere biases cause primarily biased station heights whereas absolute troposphere biases produce scale biases of the estimated network solution.

For local and small regional campaigns, relative troposphere errors are much more important and more difficult to model. To a first order, the station height bias due to a relative troposphere error may be computed as

$$\Delta h = \frac{T_r^0}{\cos z_{max}}, \quad (12.1)$$

where

- Δh is the induced station height bias,
- T_r^0 is the relative tropospheric ZPD error, and
- z_{max} is the maximum zenith angle of the observation scenario.

In this approximation formula, it is assumed that the satellites are uniformly distributed over the sky above the observing sites. Due to the fact that GNSS orbits have an inclination of 55° (or 65° in case of GLONASS) with respect to the Earth's equator, this assumption is not true, actually: in the polar regions there are no satellites close to the zenith for instance. Santerre (1991) studies the implications of a non-uniform satellite distribution.

In any case, Eqn. (12.1) indicates that a relative troposphere bias of only 1 cm leads to an error of approximately 3 cm in the estimated relative station height for an elevation cutoff angle of 20° . This error increases to 19 cm for an elevation cutoff angle of 3° .

According to Beutler et al. (1988) the corresponding formula for the impact of an absolute troposphere error reads as

$$\frac{\Delta \ell}{\ell} = \frac{T_a^0}{R_e \cos z_{max}}, \quad (12.2)$$

where

- ℓ , $\Delta \ell$ are the baseline length and the associated bias,
- T_a^0 is the absolute troposphere bias in zenith direction (common to both endpoints of the baseline), and
- R_e is the Earth's radius.

Eqn. (12.2) implies that an absolute troposphere bias of 10 cm induces a scale bias of 0.05 ppm for an elevation cutoff angle of 20° and of 0.3 ppm for a cutoff angle of 3° , a relatively small effect compared to the height error caused by a relative troposphere bias. Nevertheless, this effect should be taken into account for baselines longer than about 20 km. Again, a uniform satellite distribution in a spherical shell centered above the stations down to a maximum zenith distance of z_{max} was assumed when deriving Eqn. (12.2).

These raw estimates underline the importance of a sufficient troposphere modeling to derive high-accuracy results from GNSS microwave data.

In a certain sense, an absolute troposphere error is very similar to an error caused by the ionosphere. The main difference between the two effects is due to the circumstance that tropospheric refraction occurs in the lowest levels of the atmosphere (99% below 10 km) whereas the ionospheric shell height is about 400 km. As a consequence of this, tropospheric refraction tends to be much more site-specific than ionospheric refraction.

12.2.2. Theory

Tropospheric refraction is the path delay caused by the neutral (non-ionized) part of the Earth's atmosphere. The troposphere is a non-dispersive medium for radio waves up to frequencies of about 15 GHz (see, e.g., Baueršima 1983). Tropospheric refraction is thus identical for both GNSS carriers, L_1 and L_2 (and both phase and code measurements — see Eqn. (2.20)). The tropospheric path delay T is defined by

$$T = \int (n - 1) ds = 10^{-6} \int N^{trop} ds ,$$

where n is the refractive index and N^{trop} the so-called refractivity. The integration has to be performed along the actual signal path through the atmosphere. According to Hopfield (1969) it is possible to separate N^{trop} into a dry and a wet component

$$N^{trop} = N_{dry}^{trop} + N_{wet}^{trop} ,$$

where the dry component (N_{dry}^{trop}) is due to the hydrostatic and the wet component (N_{wet}^{trop}) is due to the non-hydrostatic part of the atmosphere. About 90% of the tropospheric path delay stem from the dry component (Janes et al. 1989). On the other hand, the path delay originating from the wet component shows a much higher variability (see, e.g., Langley 1996). Using the previous equation we may write

$$T = T_{dry} + T_{wet} = 10^{-6} \int N_{dry}^{trop} ds + 10^{-6} \int N_{wet}^{trop} ds .$$

According to Essen and Froome (1951) we have

$$\begin{aligned} N_{dry,0}^{trop} &= 77.64 \frac{\mathfrak{p}}{\mathfrak{T}} \left[\frac{\text{K}}{\text{mb}} \right] && \text{and} \\ N_{wet,0}^{trop} &= -12.96 \frac{\mathfrak{e}}{\mathfrak{T}} \left[\frac{\text{K}}{\text{mb}} \right] + 3.718 \cdot 10^5 \frac{\mathfrak{e}}{\mathfrak{T}^2} \left[\frac{\text{K}^2}{\text{mb}} \right] , \end{aligned}$$

where \mathfrak{p} is the atmospheric pressure in millibars, \mathfrak{T} the temperature in Kelvin, and \mathfrak{e} is the partial pressure of water vapor in millibars. The coefficients were determined empirically.

Instead of such an approximation based on surface meteorological data, it is preferable to directly solve the integral for the refractivity using a ray tracing technique based on global numerical weather models (e.g., ECMWF — European Centre for Medium-Range Weather Forecasts). This technique was, e.g., successfully applied to VLBI data by Eriksson et al. (2014). Even if both space geodetic techniques are comparable regarding their properties for tropospheric refraction, the analysis of GNSS measurements involves many more individual observations resulting in a much higher computational load to perform a ray tracing for every station to each satellite in view.

Therefore, in the processing of GNSS data the troposphere is usually handled in an alternative way: the tropospheric delay depends on the distance traveled by the radio wave through the neutral atmosphere and is therefore also a function of the satellite's zenith distance z . To emphasize this elevation-dependence, the tropospheric delay is written as

the product of the delay in zenith direction T^0 and a so-called mapping function $f(z)$:

$$T = f(z) T^0 .$$

According to, e.g., Rothacher (1992) it is better to use different mapping functions for the dry and wet part of the tropospheric delay:

$$T = f_{dry}(z) T_{dry}^0 + f_{wet}(z) T_{wet}^0 . \quad (12.3)$$

Nowadays, several different and well-established mapping functions are available (and supported by the *Bernese GNSS Software*). It is worth mentioning, however, that to a first order all mapping functions may be approximated by:

$$f_{dry}(z) \simeq f_{wet}(z) \simeq f(z) \simeq \frac{1}{\cos z} .$$

For a long time one of the most popular models to compute the tropospheric refraction was the model by Saastamoinen (1972) based on the laws associated with an ideal gas:

$$T = \frac{0.002277}{\cos z} \left[\mathbf{p} + \left(\frac{1255}{\mathfrak{T}} + 0.05 \right) \boldsymbol{\epsilon} - \tan^2 z \right] , \quad (12.4)$$

where the atmospheric pressure \mathbf{p} and the partial water vapor pressure $\boldsymbol{\epsilon}$ are given in millibars, the temperature \mathfrak{T} in Kelvin; the result is given in meters. Be aware that the model described in Eqn. (12.4) implicitly contains a mapping function (zenith dependence). Baueršima (1983) proposed special correction terms B and δR :

$$T = \frac{0.002277}{\cos z} \left[\mathbf{p} + \left(\frac{1255}{\mathfrak{T}} + 0.05 \right) \boldsymbol{\epsilon} - B \tan^2 z \right] + \delta R . \quad (12.5)$$

The correction term B is a function of the height of the observing site, the second term δR depends on the station height and on the elevation of the satellite. Only the B -term is implemented in *Bernese GNSS Software*.

The input values \mathbf{p} , \mathfrak{T} , and $\boldsymbol{\epsilon}$ for a priori models are traditionally derived from a standard atmosphere model. In this case, the following height-dependent values for pressure, temperature, and humidity are assumed (Berg 1948):

$$\mathbf{p} = \mathbf{p}_r \cdot (1 - 0.0000226 \cdot (h - h_r))^{5.225}$$

$$\mathfrak{T} = \mathfrak{T}_r - 0.0065 \cdot (h - h_r)$$

$$\mathfrak{H} = \mathfrak{H}_r \cdot e^{-0.0006396 \cdot (h - h_r)}$$

where \mathbf{p} , \mathfrak{T} , \mathfrak{H} are pressure (millibar), temperature (Celsius), and humidity (%) at height h of the site; \mathbf{p}_r , \mathfrak{T}_r , \mathfrak{H}_r are the corresponding values at reference height h_r . The reference height h_r , and the reference values \mathbf{p}_r , \mathfrak{T}_r , \mathfrak{H}_r are defined in the file `$(X)/GEN/CONST`. and we do not recommend to change these values:

$$h_r = 0 \text{ meter}$$

$$\mathbf{p}_r = 1013.25 \text{ millibar}$$

$$\mathfrak{T}_r = 18^\circ \text{ Celsius}$$

$$\mathfrak{H}_r = 50\% .$$

From the humidity the partial water vapor pressure is derived by

$$e = \mathfrak{H} \frac{1}{100} e^{-37.2465+0.213166 \mathfrak{T}-0.000256908 \mathfrak{T}^2},$$

where the temperature \mathfrak{T} is given in Kelvin.

In the early days of GPS/GNSS analysis the troposphere models from Saastamoinen (1972) or Hopfield (1969) were used. With the mapping function developed by Niell (1996), for the first time a troposphere model developed for VLBI was used also for GNSS data processing. Because the VLBI technique is forced to observe also quasars at very low elevations, these mapping functions are valid down to 3° elevation (the old ones only to 20°). The importance of this extension will be demonstrated in Section 12.2.3.

Instead of using a standard atmosphere as a priori information, Böhm et al. (2006b) proposed to use European Centre for Medium-Range Weather Forecasts (ECMWF)–based information on the troposphere to adjust the dry ZPD T_{dry}^0 and the mapping functions for the dry and wet components ($f_{dry}(z)$ and $f_{wet}(z)$). The wet part of the ZPD T_{wet}^0 is estimated together with other parameters of interest. The advantage of this approach is that the troposphere model is well adjusted by a numerical weather model. The disadvantage is that the related information must be continuously updated before the data analysis can be started.

For that reason, Böhm et al. (2007) developed a long-term average representation of the global pressure and temperature distribution in a so-called Global Pressure Temperature model (GPT). From this model the a priori information is derived. The mapping function is provided on a similar basis as Global Mapping Function (GMF).

Both approaches are available in Version 5.2 of the *Bernese GNSS Software*. A comparison between both strategies is given in Steigenberger et al. (2009), which can be summarized by the confirmation that the use of more realistic meteorological information from a global numerical weather model provides better results than using the GPT-/GMF–based information.

In summary of this section, we may state that troposphere biases are orders of magnitude above the noise level of the phase observable. To make full use of the accuracy of the observable, their influence must thus be reduced by either of the following two methods:

- Model tropospheric refraction without using the GNSS observable (e.g., by ray tracing using sufficiently developed numerical weather models).
- Estimate troposphere parameters (e.g., zenith path delay) in the general GNSS parameter estimation process.

The first of the two approaches would be preferable because no troposphere parameters need to be estimated, which is beneficial regarding the correlations within the GNSS analysis system. At the same time one should not forget that the troposphere parameters constitute typically the second largest number of parameters after the ambiguity parameters in a double-difference solution.

However, in particular the humidity information is typically not sufficient today. For that reason, troposphere parameters are usually estimated when analyzing GNSS measurements for highest accuracy requirements.

Table 12.1.: Correlation of height estimation and troposphere parameter estimation and ratio between formal accuracy of height estimation with (σ_1) and without (σ_2) estimation of troposphere parameters as a function of cutoff angle. Homogeneous distribution of satellites above the elevation cutoff angle is assumed. See Rothacher and Beutler (1998).

Elevation cutoff angle	30°	25°	20°	15°	10°	5°
Correlation	-0.985	-0.976	-0.964	-0.943	-0.907	-0.830
σ_1/σ_2	31.2	20.6	13.8	9.2	6.1	3.9

12.2.3. Correlation Between Troposphere and Other Parameters in the GNSS Analysis

If troposphere ZPD parameters are estimated together with station height and receiver clock parameters, large correlations between these three parameter types are found. They depend on the elevation cutoff angle applied in the data analysis. Table 12.1 gives numbers for the correlation between troposphere ZPD and station height estimates assuming a uniform distribution of the GNSS satellites over the sky above the cutoff angle. If this is not the case (e.g., due to the lack of GNSS satellites in the polar regions) the numbers are even more dramatic (Rothacher and Beutler 1998).

Table 12.1 impressively shows that if troposphere parameters and station height are estimated together (clock parameters have to be estimated in any case; in the double-difference processing mode they are estimated implicitly), the situation may be considerably improved by lowering the elevation cutoff angle, i.e., by observing satellites close to the horizon. The correlations are decreased further by estimating one set of station coordinates over a longer time interval, e.g., several days by combining several sessions on the normal equation level (see Section 9.5).

12.2.4. Horizontal Tropospheric Gradients

Going down to low elevations, the azimuthal asymmetry of the local troposphere at an observation site becomes more and more important and must be accounted for. Estimating horizontal tropospheric gradients is a common way to cope with these asymmetries. The station coordinate repeatability may be considerably improved by this measure, as shown by Rothacher et al. (1998) and Meindl et al. (2004).

One way to represent azimuthal asymmetries is a tilting of the zenith the mapping function is referred to (see Figure 12.1).

The troposphere gradient parameters then comply with the fact that the direction to the so-called tropospheric zenith (i.e., the direction with minimal tropospheric delay) and the corresponding tropospheric zenith distance \tilde{z} might not be identical to the geometrical (or ellipsoidal) zenith distance z . Having introduced the tropospheric zenith angle as a parameter of the mapping functions, the tropospheric delay would be given by

$$T_k^i(t, A_k^i, z_k^i) = T_k^0(t) f(\tilde{z}_k^i). \quad (12.6)$$

Assuming a small angle β between the tropospheric and geometrical zenith, the two zenith angles are related to each other by the equation

$$\tilde{z}_k^i = z_k^i + \beta = z_k^i + x_k \cos(A_k^i) + y_k \sin(A_k^i),$$

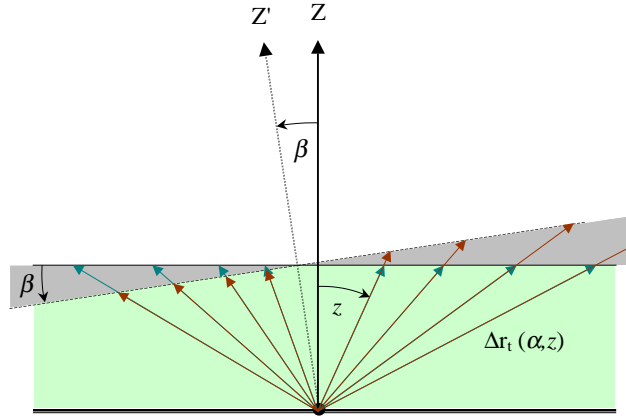


Figure 12.1.: Tilting of the tropospheric zenith by the angle β .

where A_k^i is the azimuth of the direction station–satellite and x_k, y_k are two station–dependent parameters. Using this equation and applying a Taylor expansion to first order, Eqn. (12.6) may be written as

$$\begin{aligned} T_k^i(t, A_k^i, z_k^i) &= T_k^0(t) f(z_k^i + x_k \cos(A_k^i) + y_k \sin(A_k^i)) \\ &= T_k^0(t) f(z_k^i) + T_k^0(t) \frac{\partial f}{\partial z} x_k \cos(A_k^i) + T_k^0(t) \frac{\partial f}{\partial z} y_k \sin(A_k^i). \end{aligned}$$

Introducing the notation

$$\begin{aligned} {}^n T_k(t) &= T_k^0(t) x_k && \text{gradient parameter in north–south direction, and} \\ {}^e T_k(t) &= T_k^0(t) y_k && \text{gradient parameter in east–west direction,} \end{aligned}$$

we end up with the following refined tropospheric model:

$$T_k^i(t, A_k^i, z_k^i) = T_k^0(t) f(z_k^i) + {}^n T_k(t) \frac{\partial f}{\partial z} \cos A_k^i + {}^e T_k(t) \frac{\partial f}{\partial z} \sin A_k^i.$$

For a more detailed derivation, the reader is referred to Meindl et al. (2004).

12.3. Troposphere for SLR Measurements

The order of magnitude for the total tropospheric delay is comparable between the optical SLR and the microwave–based GNSS technique. Nevertheless, there are two important differences:

- For optical measurements the tropospheric delay is dispersive. It depends on the wavelength of the signal.
- The contribution of the wet component is much less important for optical than for microwave signals.

Two models are implemented in the *Bernese GNSS Software* Version 5.2 to consider the tropospheric delay for SLR measurements: Mendes and Pavlis (2004), which is currently recommended and used by the ILRS, and Marini and Murray (1973), which was already available in previous versions of the *Bernese GNSS Software*.

Both models are empirical. They are based on meteorological data which is taken at the SLR sites and which is distributed together with the ranging measurements (see Chapter 19). Contrary to the microwave techniques, the modeling of the tropospheric delay for SLR data does not require the estimation of troposphere ZPD parameters.

The models need the wavelength of the SLR signal, which is provided by the frequency information file (description in Section 24.3.8).

12.4. Troposphere Modeling in the Bernese GNSS Software

In this section we give a detailed overview of the troposphere representation used in the *Bernese GNSS Software* Version 5.2. Let us expand the tropospheric refraction term T_k^i of observation equations (2.20) into the following three components:

$$T_k^i(t, A_k^i, z_k^i) = \underbrace{^{apr}T_k(t, z_k^i)}_{\text{a priori model}} + \underbrace{^hT_k^0(t) f(z_k^i)}_{\text{estimated model}} + \underbrace{^nT_k(t) \frac{\partial f}{\partial z} \cos A_k^i + ^eT_k(t) \frac{\partial f}{\partial z} \sin A_k^i}_{\text{horizontal gradients}}, \quad (12.7)$$

where

T_k^i	is the total tropospheric path delay between station k and satellite i ,
t	is the observation time,
z_k^i, A_k^i	are the zenith and azimuth of satellite i as observed from station k ,
$^{apr}T_k(t, z_k^i)$	is the slant delay according to an a priori model, and
$^hT_k^0(t) f(z_k^i)$	is a (time-dependent) ZPD parameter and its mapping function.
$^nT_k(t), ^eT_k(t)$	are the (time-dependent) horizontal north and east troposphere gradient parameters.

The a priori ZPD $^{apr}T_k^0(t)$ may also be constant in time if only a standard atmosphere is assumed. As mentioned above, the troposphere path delay and the mapping function may depend on the site location and the day of the year. In global solutions, Eqn. (12.7) should reflect the composition of Eqn. (12.3) with

$$\begin{aligned} ^{apr}T_k(t, z_k^i) &= T_{dry}^0 f_{dry}(z) \\ ^hT_k^0(t) f(z_k^i) &= T_{wet}^0 f_{wet}(z), \end{aligned}$$

meaning that the dry component of the tropospheric delay is completely absorbed by the a priori model and the wet component is estimated by the troposphere ZPD parameters based on the corresponding mapping function $f_{wet}(z)$. In addition, gradient parameters must be estimated during the processing, see Section 12.2.4. The following sections provide more details on the different parts of Eqn. (12.7), the related programs, and relevant options.

12.4.1. The A Priori Model

The *Bernese GNSS Software* offers several a priori models and corresponding mapping functions to take into account the tropospheric refraction. In Version 5.2 the following models are available for analyzing GNSS microwave data:

- the (dry and wet) Vienna Mapping Function (VMF1) of Böhm et al. (2006b) together with ECMWF-based ZPD corrections,
- the (dry and wet) Global Mapping Function (GMF) of Böhm et al. (2006a) where ZPD corrections are computed based on Global Pressure Temperature model (GPT) as provided by Böhm et al. (2007),
- the (dry and wet) Niell model (Niell 1996), i.e., the Saastamoinen ZPD together with the Niell mapping functions (recommended for GNSS data analysis with low elevation cutoff angle),
- the Saastamoinen model (Saastamoinen 1972) as shown in Eqn. (12.5),
- the modified Hopfield model (Goad and Goodman 1974),
- the model based on formulae by Essen and Froome (Rothacher et al. 1986).

For optical SLR measurements the following models are available:

- the Mendes–Pavlis model (Mendes and Pavlis 2004), and
- the Marini–Murray model (Marini and Murray 1973).

Each of the mapping functions is assigned to a certain a priori troposphere model. Hence, only the combination of T_{dry}^0 $f_{dry}(z)$ may be selected in the input field “ZPD model and mapping function (GNSS)” (or “ZPD model and mapping function (SLR)”) in panel “GPSEST 3.2: General Options 2”.

The a priori model requires some input parameters (pressure, temperature, and humidity). These values are usually derived from a standard model atmosphere or, in case of VMF1, from a numerical weather model. For SLR it is the usual practice to introduce measured meteo values for the stations (option “Meteorological data” in GPSEST, Section 12.3). The corresponding file description may be found in Sections 12.5.2 and 24.8.3. In general, the same can be done for correcting GNSS data as well. Here, it is even possible to introduce the meteorological measurements only for a subset of stations. For stations without explicitly introduced values, the standard model is used automatically.

Let us clarify the requirements on the accuracy of the meteorological measurements. Table 12.2, together with Eqn. (12.1), gives an impression of the dependence of the estimated station height (independent of the baseline length) on biases in surface meteorological measurements for different atmospheric conditions. We see, e.g., that in a hot and humid environment (last line in Table 12.2) an error of only 1% in the relative humidity will induce a bias of 4 mm in the tropospheric ZPD, which will in turn produce (using Eqn. (12.1)) a height bias of more than one centimeter for an elevation mask of 20°, even increasing to about 4 cm for an elevation mask of 5°. It is virtually impossible to measure the relative humidity to that accuracy (let alone using a standard atmosphere model); moreover, the measured humidity is usually not representative for the entire environment of a site. This is why experience tells that estimation of troposphere parameters is a necessity if high accuracy is required and if only ground meteorological data are available. Similar remarks are true for temperature measurements. It should be possible, on the other hand, to measure surface pressure to the accuracy level necessary to render pressure-induced height errors harmless.

You should always keep in mind the orders of magnitude reflected in Table 12.2 when using ground meteorological data to correct GNSS measurements. Our conclusion is,

Table 12.2.: Tropospheric ZPD T as a function of temperature \mathfrak{T} , pressure \mathfrak{p} , and relative humidity \mathfrak{h} .

\mathfrak{T} °C	\mathfrak{p} mbar	\mathfrak{h} %	$\left \frac{\partial T}{\partial \mathfrak{T}} \right|$ mm/°C	$\left| \frac{\partial T}{\partial \mathfrak{p}} \right|$ mm/mbar	$\left| \frac{\partial T}{\partial \mathfrak{h}} \right|$ mm/%
0°	1000	50	3	2	0.6
30°	1000	50	14	2	4
0°	1000	100	5	2	0.6
30°	1000	100	27	2	4

that only if you are able to provide meteorological values stemming from Water Vapor Radiometers you have a chance to avoid the estimation of tropospheric ZPDs. There is one exception to that rule: if you are working in a rapid static mode with short observation times (less than 1 hour — depending on the number of available satellites, e.g., whether you have a GPS-only or combined GPS/GLONASS scenario), you may be best advised not to estimate troposphere parameters, but to use only an a priori model together with the standard atmosphere. Otherwise the correlations discussed in Section 12.2.3 may not allow a numerical stable solution.

Usually, the tropospheric refraction is not taken into account by an a priori model alone, but always together with estimating additional parameters. Although it is possible to use only an a priori model, it is by no means recommended if high accuracy is aimed for. On the other hand, in the context of preprocessing programs like CODSP and MAUPRP, it may be reasonable to correct for the total tropospheric delay by using only a priori models.

12.4.2. Site-Specific Troposphere Parameters

In addition to an a priori troposphere model, the program GPSEST offers the possibility to set up and estimate so-called site-specific troposphere parameters. These parameters are station- and time-dependent corrections to the a priori model and are represented in a piecewise linear, continuous way (see Section 7.6.1). In Eqn. (12.7) the estimated parameter is given as ZPD ${}^h T_k^0(t)$; the corresponding mapping function $f(z_k^i)$ is used as the related partial derivative. You will have to estimate these parameters in virtually all observation scenarios. For small networks, where troposphere parameters are highly correlated between sites, you have the possibility to estimate relative troposphere parameters with respect to the a priori model parameters of a selected station.

Option “Parameter setup: site-specific troposphere parameters” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” activates the estimation of these parameters.

In panel “GPSEST 6.1.1: Site-Specific Troposphere Parameters 1” (see Figure 12.2) the user must select an appropriate mapping function $f(z_k^i)$ and the desired time resolution (option “Zenith path delay: Parameter spacing”). The available mapping functions are dry and wet mapping functions from VMF1, GMF, and Niell models, the Hopfield wet mapping function, and directly $\cos z$. In addition, you may impose absolute and relative constraints (see Section 7.5). Usually, a dry (hydrostatic) a priori model is used (e.g., DRY_GMF) with the corresponding wet mapping function (e.g., WET_GMF) to map the estimated part.

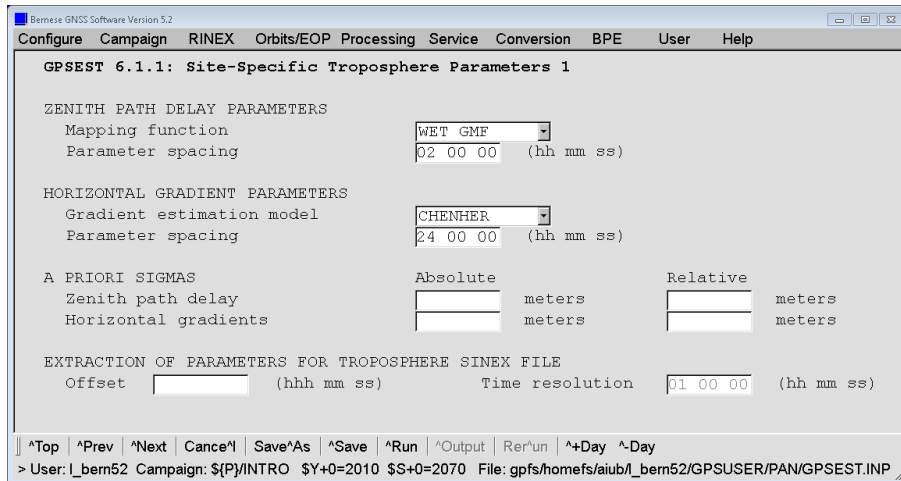


Figure 12.2.: Troposphere-related options in GPSEST (1).

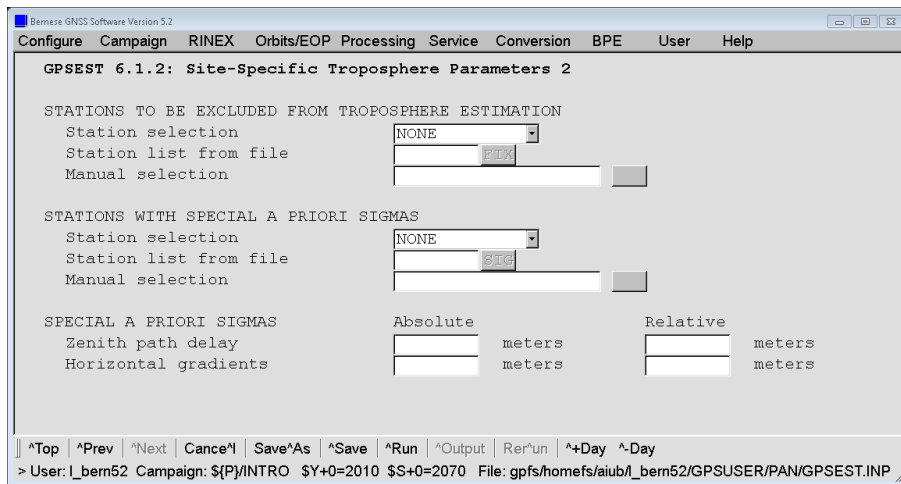


Figure 12.3.: Troposphere-related options in GPSEST (2).

Note that $12 + 1 = 13$ parameters per station will be set up if you choose a parameter spacing of 2 hours for a one-day session. This is due to the piecewise linear representation.

Figure 12.3 shows the second troposphere-specific panel in program GPSEST (“GPSEST 6.1.2: Site-Specific Troposphere Parameters 2”). The user may choose stations which should be excluded from troposphere estimation or stations for which differing absolute and/or relative sigmas should be setup. This is primarily intended to select the reference for a relative troposphere modeling in small-sized networks.

In addition, the entry WITH_TROPO for option “Tropo: list of stations with no troposphere estimation” allows to exclude stations from the estimation of troposphere parameters if troposphere delays are available in an input troposphere file specified in option “Troposphere estimates” (panel “GPSEST 1.2: Input Files 2”). All troposphere parameters are set up for stations with missing troposphere values in the file. It is important to know that if option WITH_TROPO is selected, the a priori model and the mapping function specified in the input file are applied for consistency reasons and the corresponding options in panels

“GPSEST 3.2: General Options 2” and “GPSEST 6.1.1: Site-Specific Troposphere Parameters 1” are ignored.

We refer to the corresponding help panels for further details on all options and possible applications.

12.4.3. Tropospheric Gradient Parameters

The use of low elevation data (together with an elevation-dependent weighting, see Section 7.4.3) is essential to improve the accuracy of GNSS analyses and to decorrelate station heights and tropospheric ZPD corrections. In this context also the estimation of tropospheric gradient parameters becomes important.

The gradient model from Eqn. (12.7) may be selected with option TILTING for the gradient estimation model in panel “GPSEST 6.1.1: Site-Specific Troposphere Parameters 1” (displayed in Figure 12.2). More advanced models have been proposed by Chen and Herring (1997) (to be selected by option CHENHER) and MacMillan (1995) (to be selected by option TANZ). Another possibility, LINEAR, is not recommended.

Horizontal tropospheric gradients are represented in a piecewise linear way, too. The user input options related to the tropospheric gradient parameters are similar to those of the ZPD parameters. They are all accessible through the two troposphere related panels in the program GPSEST (see Figures 12.2 and 12.3). Consult the corresponding help panels for more information.

The number of gradient parameters estimated per session is usually much lower than the number of ZPD parameters. Typically, one set of gradient parameters is estimated for a 24-hour session. Note that for technical reasons the parameter spacing for the gradients must be a multiple of the spacing for the vertical parameters. For a significant estimation of troposphere gradients, the cutoff elevation angle should be as low as possible, at most 10 degrees.

12.5. Troposphere Data Input and Output

12.5.1. Bernese Troposphere Files

The most important and mainly used troposphere-related file in the *Bernese GNSS Software* is the Bernese-formatted troposphere file. It is an output as well as an input file and contains ZPD and gradient estimates for multiple stations. In addition, it lists information on the a priori model and time resolution used during the creation process. A detailed file description is provided in Section 24.8.1, Figure 24.60 shows an example.

Two programs in the *Bernese GNSS Software* are able to create Bernese troposphere files, namely GPSEST and ADDNEQ2. If you are estimating troposphere parameters and want to store them for later use or archiving, simply specify a filename under “Troposphere estimates” (in GPSEST panel “GPSEST 2.1: Output Files 1” or in ADDNEQ2 panel “ADDNEQ2 2.1: Output Files 1”, respectively).

An important application of this file type is the introduction of estimated troposphere corrections into your processing. These estimates may stem from earlier processing steps or from an external source (such as CODE). Troposphere files may be used as input for the

programs GPSEST, CODSPP, MAUPRP, and GPSSIM. If you are introducing troposphere estimates in the program GPSEST, it is possible to estimate troposphere parameters on top of them. In that case it is forbidden to store the re-estimated troposphere parameters in an output file. Such a file is not usable anymore. Set option “Tropo: list of stations with no troposphere estimation” to WITH_TROPO (see Figure 12.3) if you are introducing a Bernese troposphere file to prevent a re-estimation of troposphere parameters. In that case the troposphere output file is usable but it will only contain the estimated parameters for the additional stations.

Using troposphere values in program ADDNEQ2 results in fixation of the corresponding troposphere parameters to the introduced estimates and deletion from the normal equation system (see Section 9.3.8). Consequently, the output troposphere file will contain no troposphere values or an incomplete set for these stations.

CODE daily troposphere estimates in the form of Bernese troposphere files are available through anonymous ftp (<http://www.aiub.unibe.ch/download/BSWUSER52/ATM/>) for all the global sites processed by CODE.

12.5.2. Files Containing Meteorological Data

As already mentioned in Section 12.4.1 the input values for the troposphere a priori model may stem from meteorological measurements (instead of using a standard atmosphere model). These values must be introduced into the software in the form of so-called meteo files. You may either prepare these files manually (e.g., by using an ASCII editor) or they may be converted from RINEX meteo files using the program RXMBV3 (see Section 4.11). One file contains the information for a single station.

There are three different types of meteo files supported by the *Bernese GNSS Software* Version 5.2 (see Section 24.8.3, Figure 24.62). The first type contains pressure, temperature, and humidity values; the second contains pressure, and dry and wet temperature; the last type is somewhat different because it does not contain surface meteorological measurements per se but directly the total tropospheric ZPDs (e.g., as obtained from Water Vapor Radiometers).

Be aware that if meteo files of type 3 are introduced, no a priori troposphere model is used and the tropospheric delay in Eqns. (2.20) will be simply the value given in the files (interpolated to the current epoch) divided by $\cos z$ as mapping function.

Note that troposphere result files cannot be re-introduced if the a priori model is based on introduced meteorological data.

12.5.3. Troposphere SINEX Files

This format is internationally adopted and may be used to exchange station-related total ZPDs and gradients, optionally, together with station coordinates. This option is a clear indicator for the high correlation between both parameter types. The corresponding format specifications are available at ftp://ftp.igs.org/pub/data/format/sinex_tropo.txt (see also Section 24.8.2 and Kouba et al. 1996). Troposphere SINEX files may be written by the programs GPSEST and ADDNEQ2 (do not forget to choose the correct SINEX header file in the “GPSEST 1.4: General Files” or “ADDNEQ2 1.3: General Files” panel).

To write a troposphere SINEX file you have to define the offset and time resolution you want to use for the parameters written to the file (option “EXTRACTION OF PARAMETERS FOR TROPOSPHERE SINEX FILE” in “GPSEST 6.1.1: Site-Specific Troposphere Parameters 1” and in “ADDNEQ2 9: Options for Atmospheric Parameters”, respectively). The offset and time resolution specified is independent of the offset and spacing of the parameters. This options simply define at which epochs the piecewise linear function shall be evaluated.

The program TROTRO (“Menu>Conversion>Manipulate troposphere SINEX files”) may be used to remove certain stations from an output file before distributing it for any reasons. You have to list those stations in TYPE 003: HANDLING OF STATION PROBLEMS of a “Station information” file specified in panel “TROTRO 1: Filenames”.

In the *Bernese GNSS Software* Version 5.2 the troposphere SINEX format is an output file format only. There is no way to directly introduce troposphere SINEX files.

12.6. Remarks and Hints on Troposphere Estimation

Let us close this chapter with some general remarks and recommendations concerning the troposphere estimation in the *Bernese GNSS Software*:

1. It is recommended to always estimate site-specific troposphere parameters. Usually, the dry part of the troposphere is accounted for by the a priori model (DRY_VMF or DRY_GMF) and the remaining wet part is estimated and mapped with the corresponding mapping function (WET_VMF or WET_GMF). A time resolution of 1 or 2 hours is reasonable for standard analyses.
2. The only exception to the previous point are “rapid static” scenarios with short observation times (below 1 hour). In this case it may be best to just use an a priori model (VMF or GMF) to account for both, the dry and the wet part, of the troposphere.
3. The estimation of horizontal troposphere gradients is recommended, even in small networks. An exception may be the processing of single baselines. Usually, the time resolution for gradients is much smaller than for ZPD parameters (e.g., one set of gradients per day). For the estimation of reasonable gradient parameters, data gathered at low elevations is absolutely essential.
4. The use of low elevation data (below 10°) is strongly recommended to decorrelate troposphere estimates and station heights (particularly in small local campaigns).
5. For parameter intervals longer than, let us say, 1 hour, it is usually not necessary to impose relative constraints. If kinematic coordinates are estimated, relative troposphere constraints may be helpful to increase the time intervals to improve the numerical stability of the GNSS analysis system. Things are of course different with fast moving objects, like airplanes, where the tropospheric conditions change very quickly. In that case shorter intervals with relative constraints are the better choice.
6. For small local campaigns it makes sense to estimate troposphere parameters for all but one station (due to strong correlations between the troposphere parameters of the stations included). Another possibility is to absolutely constrain the parameters for one station.

7. If tropospheric delays from global solutions are available for some stations (e.g., from CODE, see input files in previous section), it may be a good idea to introduce these values in your processing and estimate troposphere corrections only for the remaining stations. When making consistent use of the CODE coordinates, orbits, Earth orientation parameters, and troposphere estimates for the IGS stations included in your network, you are able to get results that are almost identical to those you would obtain by processing your (local) network data together with the global data set.
8. When processing subnetworks in clusters (see Section 9.5.1) it is very important to keep the troposphere parameters in the normal equation files when computing the cluster solutions with the program GPSEST. In that way they will be combined when stacking the normal equations in ADDNEQ2 — resulting in one and the same troposphere parameters for a station contained in more than one cluster.

Of course the few points above are generalized and not universally valid. As always, it is left to the user to evaluate the options which work best for his needs.

Consult Chapter 19 for a description of the troposphere handling for the processing of SLR observations.

13. Ionosphere Modeling and Estimation

13.1. Motivation and Introductory Remarks

You have to deal with ionospheric refraction, to be more specific, with the term I_k^i of the observation equation (Eqn. (2.20)), in the following processing steps:

1. single-point positioning (program CODSP), if you do not use the ionosphere-free (L_3) linear combination,
2. preprocessing (program MAUPRP),
3. ambiguity resolution (program GPSEST), if you do not make use of the Melbourne–Wübbena (L_6) linear combination (see Section 2.3.6.4),
4. parameter estimation (program GPSEST), if you do not use the ionosphere-free (L_3) linear combination, and
5. ionosphere mapping (programs GPSEST and IONEST).

There are also higher order terms from the ionospheric refraction that are relevant even if you are going to use the ionosphere-free linear combination. They will be discussed in a separate section 13.6.

13.1.1. Choice of the Linear Combination

You have to be aware that the choice of the linear combination to be analyzed in your final GPSEST analysis sets the course for your final results! This choice cannot be undone any more at the stage of ADDNEQ2 analyses. By the way, the same is also true concerning elevation cut-off angle, weighting of observations, tropospheric mapping function, antenna phase center corrections, and so on.

If you have only single-frequency (L_1) data available, there is nothing to choose at all. However, if you consider dual-frequency (L_1/L_2) data you cannot avoid making a decision. On one hand, in case of long baselines, you will certainly use the ionosphere-free (L_3) linear combination. On the other hand, it is known that on very short baselines, in particular in the extreme case of so-called “zero-baselines”, L_1/L_2 -based solutions perform significantly better. As a consequence of this, there must be a trade-off between L_3 and L_1/L_2 solutions. Unfortunately, because of the pronounced variability of the ionosphere, it is quite impossible to generally specify the baseline length where both kind of solutions perform similarly well. A “critical” length of, let us say, 1–10 kilometers is likely applicable — or may give at least an idea of the order of magnitude. This length is, however, valid only for mid-latitude regions. Finally, if you decide to use the basic carriers in their original form, it is better, from our experience, to ignore L_2 and to use L_1 only (see also Section 13.1.3).

Table 13.1.: Ionosphere-induced scale factor (per TECU) when neglecting the ionosphere for different linear combinations (LC).

LC	Scale factor in ppm/TECU			
	$z_{\max} = 80^\circ$	$z_{\max} = 75^\circ$	$z_{\max} = 70^\circ$	$z_{\max} = 65^\circ$
L1	-0.15	-0.10	-0.08	-0.06
L2	-0.24	-0.16	-0.12	-0.10
L3	0.00	0.00	0.00	0.00
L5	+0.19	+0.13	+0.10	+0.08

13.1.2. Impact of Unmodeled Ionosphere on Single-Frequency GNSS Solutions

If you process a network analyzing single-frequency data and disregard ionospheric refraction, you get an apparent contraction of your network. The scale bias introduced in a GNSS network by unmodeled ionospheric refraction is given in Table 13.1 (according to Beutler et al. 1988) as a function of the linear combination and the maximum zenith distance z_{\max} considered. This scale bias is proportional to the Total Electron Content (TEC), the total number of electrons in a rotation cylinder centered around the line of sight receiver-satellite with a cross section of one square meter. The TEC is expressed in so-called TEC Units (TECU). Example: for L_1 solutions with an elevation cut-off angle of 15° and a prevailing TEC of 10 TECU, you may expect a baseline shrinking of about $10 \cdot 0.10 = 1.0$ ppm (or 1.0 mm/km).

13.1.3. How to Treat Small-Area High-Precision Arrays

If only single-frequency data is available, GNSS-derived ionosphere models are very efficient in removing or greatly reducing the ionosphere-induced scale bias under homogeneous and moderate ionospheric conditions (see, e.g., Wild 1994). For small-area high-precision arrays (with a maximum extent of about 10 kilometers), we recommend to use — even if dual-frequency data is available — L_1 -only data in combination with a GNSS-derived ionosphere model (see, e.g., Beutler et al. 1995). Such ionosphere models are also useful for other applications, like ambiguity resolution (see Chapter 8).

The user of the *Bernese GNSS Software* has the possibility to derive his own ionosphere models. This chapter gives an overview of the related problems. Alternatively, he may revert to the Global Ionosphere Models (GIMs) produced by CODE and made available at <http://www.aiub.unibe.ch/download/BSWUSER52/ATM> (see Section 4.13.1). The use of these GIMs may be recommended for *local* applications, too (see, e.g., Schaer et al. 2000).

13.2. Theory

13.2.1. Introduction

The ionosphere may be characterized as that part of the upper atmosphere where a sufficient number of electrons and ions are present to affect the propagation of radio waves.

The spatial distribution of electrons and ions is mainly determined by photo-chemical processes and transportation processes.

Both processes create different layers of ionized gas in different altitudes. The diagram indicating the number of ions produced as a function of altitude is called a *Chapman profile*. This profile, which is a function of the solar zenith angle, is illustrated in Figure 13.1. Due to the influence of different transportation processes in the ionosphere, the actual electron concentrations may differ considerably from those estimated from the production layers.

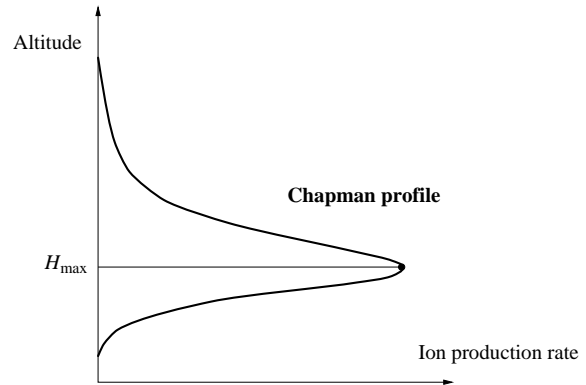


Figure 13.1.: Chapman curve of ionization rate.

The degree of ionization shows large variations which are correlated with the solar activity; the geomagnetic activity plays an important role too. The solar activity may be characterized, e.g., by the sunspot number, where one observes an 11-year cycle besides an 80–100-year super-cycle. Figure 13.2 shows the monthly and smoothed sunspot numbers from 1956 to 2015 (as obtained from <http://sidc.be/silso>). We see that the most recent ionospheric maximum must have happened during the years 2011–2014 and that currently (2015) we are approaching again a minimum. The situation will get worse again afterwards, with increasing sunspot cycle phase.

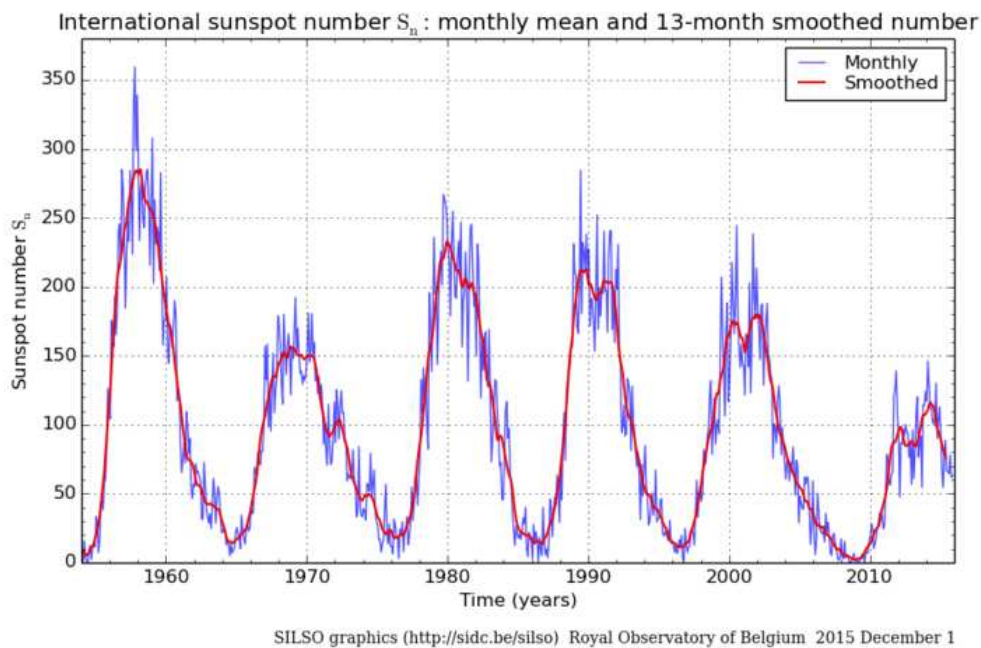


Figure 13.2.: Monthly and smoothed sunspot numbers.

13.2.2. Characterizing the Ionosphere

The state of the ionosphere may be described by the electron density n_e in units of electrons per cubic meter. The impact of the state of the ionosphere on the propagation of radio waves is characterized by the TEC E :

$$E = \int_k^i n_e(s) ds . \quad (13.1)$$

The integral gives the total number of free electrons included in a rotation cylinder with a cross-section area of one square meter, aligned along the signal path s between receiver k and satellite i . In geodetic applications, the TEC E is measured in so-called TECU, where one TECU corresponds to 10^{16} electrons per square meter ($10^{16}/\text{m}^2$). For comparisons, the vertical TEC E_v is formed as

$$E_v = E \cos z' , \quad (13.2)$$

where z' is the zenith distance of the signal path with respect to the vertical in a mean altitude of the ionospheric shell.

The ionosphere is a dispersive medium in the radio-band — as opposed to the troposphere (see Chapter 12). This implies that ionospheric refraction depends on the frequency of the signal observed. Neglecting higher-order terms at this stage, we may write the ionospheric refraction coefficient for carrier phase measurements as

$$n_I = 1 - \frac{a n_e}{f^2} , \quad (13.3)$$

where a is a constant, n_e is the electron content along the signal propagation path, and f is the carrier frequency. The integration of Eqn. (13.3) along the entire propagation path s , taking into account Eqn. (13.1), yields the total effect of ionospheric refraction on phase measurements

$$\Delta\varrho_I = \int_s (n_I - 1) ds = -\frac{a E}{f^2} \quad \text{with} \quad a = 4.03 \cdot 10^{17} \text{ m s}^{-2} \text{ TECU}^{-1} , \quad (13.4)$$

where E is the slant TEC.

Eqns. (13.3) and (13.4) indicate that the refractivity $n_I - 1$, and thus the refraction effect, is proportional to the inverse of the frequency squared. Consequently, if two frequencies are available, the ionospheric delay may be eliminated by forming the so-called ionosphere-free (L_3) linear combination according to Eqns. (2.22) and (2.23).

In the observation equation (Eqn. (2.20)), we defined a term I_k^i that is synonymous with the ionospheric delay on L_1 , e.g., for GPS:

$$I_k^i(f_{1G}) = \frac{a E}{f_1^2} \quad \text{with} \quad f_{1G} = 1.57542 \cdot 10^9 \text{ s}^{-1} . \quad (13.5)$$

Hence, the ionospheric delay may be written as

$$I_k^i(f_X) = \mp \frac{f_1^2}{f_X^2} I_k^i(f_{1G}) , \quad (13.6)$$

where we have to use the negative sign for phase observations and the positive sign for code observations.

Eqn. (13.6) shows that from an ionosphere term I_k^i referring to a specific reference frequency (here $f_{1G} = L_1$ from GPS) the effect on any other GNSS frequency f_X can be derived. As long as the correct frequencies are used, also the various frequencies of the GLONASS satellites (resulting from the FDMA principle) can be handled with this formulae. The magnitude of the one-way range error $I_k^i(f_X)$ from Eqn. (13.6) may vary from less than one meter to more than 100 meters.

The neglected higher-order terms include the actual higher-order terms of the Taylor series, the ray path bending effect, and the effect of the geomagnetic field. According to Brunner and Gu (1991), these terms may reach — on zero-difference level — a few centimeters for low-elevation angles and a very high electron content. Nevertheless, the ionosphere-free linear combination eliminating the first-order term is an excellent approximation for many applications, especially on the double-difference level, where the Residual Range Error (RRE), the difference between the ionosphere-free linear combination and the true range, is smaller than a few millimeters even for long baselines. Because significant systematic (latitude-dependent) effects may result in global network solutions, the *Bernese GNSS Software* Version 5.2 also supports the correction for higher-order terms, what will be discussed in Section 13.6.

13.2.3. Influence of the Ionosphere on Various Linear Combinations

Table 13.2 gives an overview of the influences of two categories of errors on various linear combinations of GNSS observations: the basic carriers (L_1 and L_2), the ionosphere-free linear combination (L_3), the geometry-free linear combination (L_4), and the wide-lane linear combination (L_5). We may distinguish between systematic and random errors. Systematic errors may be further divided into geometrical errors caused, e.g., by the limited accuracy of troposphere and orbit representations (“geometry”) and ionosphere-induced errors (“ionosphere”). The “noise” of the measurements falls obviously into the category of random errors.

Table 13.2.: Influences of the important error sources on various linear combinations.

LC	λ [m]	κ_1 [m/m]	κ_2 [m/m]	Geometry		Ionosphere [TECU]		Noise	
				[m]	[cycles]	6.05	1.15	[m]	[cycles]
						[m]	[cycles]		
L1	0.190	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
L2	0.244	0.00	1.00	1.00	0.78	1.65	1.28	1.00	0.78
L2'	0.122	0.00	1.00	1.00	1.56	1.65	2.57	1.00	1.56
L3	–	2.55	–1.55	1.00	–	0.00	–	2.98	–
L3 with N_5	0.107	2.55	–1.55	1.00	1.78	0.00	0.00	2.98	5.30
L4	–	1.00	–1.00	0.00	–	–0.65	–	1.41	–
L4 with N_5	0.054	1.00	–1.00	0.00	0.00	–0.65	–2.28	1.41	4.99
L5	0.862	4.53	–3.53	1.00	0.22	–1.28	–0.28	5.74	1.27
L5'	0.431	4.53	–3.53	1.00	0.44	–1.28	–0.57	5.74	2.54

Linear combinations labeled with a dash (e.g., L_2') are formed when data from a squaring-type receiver is processed, where L_2 is available with half the wavelength λ_2 only. In this case, the wide-lane (L_5) ambiguities N_5 are formed according to

$$N_5' = 2N_1 - N_2' \quad \text{with} \quad \lambda_5' = \lambda_5/2 = 0.431 \text{ m} .$$

Note that the above linear combination is superior to, e.g., $N_5'' = N_1 - N_2'$ (with $\lambda_5'' = 0.341 \text{ m}$) regarding the ionospheric influence. “ L_3 with N_5 ” denotes the so-called narrow-lane linear combination, where we introduce the previously resolved ambiguities N_5 (or N_5'). κ_1 and κ_2 are the factors to form the particular linear combinations based on L_1 and L_2 as they have been introduced in Section 2.3.6. All errors are given in meters and cycles, scaled to the error on the first carrier L_1 from GPS. The information concerning the “noise” is based on two assumptions: the measurement noise of L_1 and L_2 expressed in meters is of the same order, and L_1 and L_2 are not correlated.

In this chapter, errors related to the ionosphere are of major interest. We may recognize in Table 13.2 by comparing the ionospheric errors expressed in cycles that the wide-lane (L_5) linear combination is much less ionosphere-sensitive for ambiguity resolution than L_1 and L_2 (see also Chapter 8). The relation between an ionospheric error on a particular linear combination and TEC (in TECU) is also given in this Table. Example: an ionospheric bias of one cycle in L_5 corresponds to $1.15/0.28 = 4.14$ TECU.

13.2.4. Ionospheric Effects on GNSS Signals

On one hand, irregularities in the ionosphere produce short-term signal variations. These scintillation effects may cause a large number of cycle slips because the receiver cannot follow the short-term signal variations and fading periods. Scintillation effects mainly occur in a belt along the Earth’s geomagnetic equator and in the polar auroral zone.

On the other hand, a high electron content produces strong horizontal gradients and affects the ambiguity solution using geometrical methods. The only reliable strategy to solve the ambiguities in this case is the Melbourne–Wübbena approach using in addition the P-code measurements. The success of this method very much depends on the quality of the P-code measurements, which is often unsatisfactory under Anti-Spoofing (AS) conditions. Maximum electron content and correspondingly pronounced gradients may be expected for regions close to the (geomagnetic) equator.

As a consequence, we classify ionospheric refraction for our purposes into a stochastic part and a deterministic part.

13.3. Ionosphere Modeling

13.3.1. Deterministic Component

GNSS-derived ionosphere models describing the deterministic component of the ionosphere are usually based on the so-called Single-Layer Model (SLM) as outlined in Figure 13.3. This model assumes that all free electrons are concentrated in a shell of infinitesimal thickness. The SLM mapping function F_I may be written using Eqn. (13.2) as

$$F_I(z) = \frac{E}{E_v} = \frac{1}{\cos z'} \quad \text{with} \quad \sin z' = \frac{R}{R+H} \sin z , \quad (13.7)$$

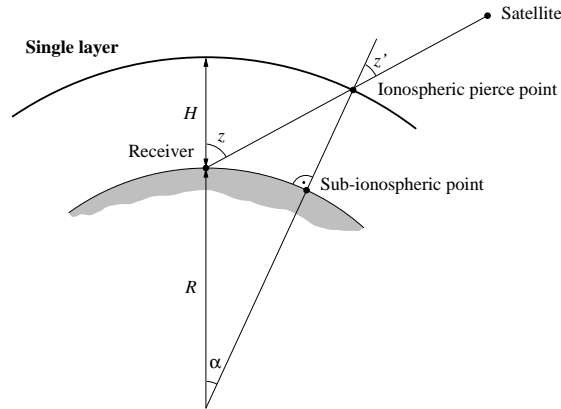


Figure 13.3.: Single-layer model.

where

- z, z' are the zenith distances at the heights of the station and of the single layer, respectively,
- R is the mean radius of the Earth, and
- H is the height of the single layer above the Earth's surface.

Based on Figure 13.3, it can be easily verified that the geocentric angle α equals $z - z'$.

The height of this idealized layer is usually set to the expected height of the maximum electron density. Furthermore, the electron density E — the surface density of the layer — is assumed to be a function of geographic or geomagnetic latitude β and sun-fixed longitude s .

The “modified” SLM (MSLM) mapping function includes an additional constant, α (Schaer 1999):

$$F_I(z) = \frac{E}{E_v} = \frac{1}{\cos z'} \quad \text{with} \quad \sin z' = \frac{R}{R + H} \sin(\alpha z). \quad (13.8)$$

Best fit of Eqn. (13.8) with respect to the JPL extended slab model (ESM) mapping function is achieved at $H = 506.7$ km and $\alpha = 0.9782$ (when using $R = 6371$ km and assuming a maximum zenith distance of 80 degrees). The resulting mapping function is used in the ionosphere analysis at CODE. For computation of the ionospheric pierce points, $H = 450$ km is assumed for ground stations.

To map TEC, the so-called geometry-free (L_4) linear combination (2.27) is used, which is designed to contain ionospheric information. The particular observation equations for undifferenced phase and code observations read as

$$L_4 = -a \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) F_I(z) E(\beta, s) + B_4 \quad (13.9a)$$

$$P_4 = +a \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) F_I(z) E(\beta, s) + b_4, \quad (13.9b)$$

where

- L_4, P_4 are the geometry-free phase and code observables (in meters),
 a is a constant with $a = 4.03 \cdot 10^{17} \text{ ms}^{-2} \text{ TECU}^{-1}$,
 f_1, f_2 are the frequencies associated with the carriers L_1 and L_2 ,
 $F_I(z)$ is the mapping function evaluated at the zenith distance z' ,
 $E(\beta, s)$ is the vertical TEC (in TECU) as a function of geographic or geomagnetic latitude β and sun-fixed longitude s , and
 $B_4 = \lambda_1 B_1 - \lambda_2 B_2$ is a constant bias (in meters) due to the initial phase ambiguities B_1 and B_2 with their corresponding wavelengths λ_1 and λ_2 .

For each receiver and satellite pass, at least one parameter B_4 has to be solved for because it contains the phase ambiguities.

13.3.1.1. Ionosphere Mapping on Zero- and Double-Difference Level

Eqns. (13.9) are valid for *zero-difference* observations. In the double-difference case, the “ionospheric” observation equations look similar, with the exception that B_4 , the phase bias term, equals now $\lambda_1 N_1 - \lambda_2 N_2$ and that b_4 , the code bias term, vanishes. In the “ambiguity-fixed” case, where the integers N_1 and N_2 are known, it is obviously no longer necessary to solve for B_4 .

Ionosphere mapping on both zero- and double-difference level may be performed using the program GPSEST, considering GPS, GLONASS, or GPS/GLONASS-combined observations. There is a second program for ionosphere mapping, IONEST. This program, however, works only on the basis of GPS zero-difference observations and, moreover, does not take into account DCBs.

The *Bernese GNSS Software* supports three types of ionosphere models to represent the deterministic component of the ionosphere:

1. local models based on two-dimensional Taylor series expansions,
2. global (or regional) models based on spherical harmonic expansions, and
3. station-specific models, represented like (2).

Note that the numbers enclosed in brackets correspond to the model type numbers internally used (see Figures 13.7 and 13.17).

13.3.1.2. Local TEC Model

The local TEC model — applicable in the vicinity of one or more dual-frequency station(s) — is represented by

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} E_{nm} (\beta - \beta_0)^n (s - s_0)^m, \quad (13.10)$$

where

- n_{\max}, m_{\max} are the maximum degrees of the two-dimensional Taylor series expansion in latitude β and in longitude s ,
 E_{nm} are the (unknown) TEC coefficients of the Taylor series, i.e., the local ionosphere model parameters to be estimated, and
 β_0, s_0 are the coordinates of the origin of the development.

β is the geographic latitude of the intersection point of the line receiver–satellite with the ionospheric layer and s is the sun–fixed longitude of the ionospheric pierce point (or sub–ionospheric point). s is related to the local solar time (LT) according to

$$s = \text{LT} - \pi \approx \text{UT} + \lambda - \pi . \quad (13.11)$$

UT is Universal Time and λ denotes the geographical longitude of the sub–ionospheric point. For satellites at elevation angles of $15^\circ/20^\circ$ with widely different azimuth, these sub–ionospheric points can be separated by up to 3000/2000 kilometers. Nevertheless, the representation (13.10) is not well suited for regional or even global applications because of limitations in the (β, s) –space. More information concerning local ionosphere modeling may be found in Wild (1994).

13.3.1.3. Global TEC Model

The global TEC model — which may be used for regional applications also — may be written as

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^n \tilde{P}_{nm}(\sin \beta) (a_{nm} \cos(m \cdot s) + b_{nm} \sin(m \cdot s)) , \quad (13.12)$$

where

- n_{\max} is the maximum degree of the spherical harmonic expansion,
- $\tilde{P}_{nm} = \Lambda(n, m) P_{nm}$ are the normalized associated Legendre functions of degree n and order m , based on normalization function $\Lambda(n, m)$ and Legendre functions P_{nm} , and
- a_{nm}, b_{nm} are the (unknown) TEC coefficients of the spherical harmonics, i.e., the global ionosphere model parameters to be estimated.

Here, we may use the geographic latitude β and the sun–fixed longitude s , or an equivalent set in a solar–geomagnetic frame, as independent arguments. Further information concerning global and regional ionosphere modeling may be found in Schaer et al. (1995), Schaer et al. (1996), and Schaer (1999).

13.3.1.4. Station–Specific TEC Models

Station–specific TEC models are treated exactly in the same way as global models. One full set of ionosphere parameters is estimated with respect to each station involved, however.

13.3.2. Stochastic Component

Short–term TEC variations are not modeled by Eqns. (13.10) and (13.12). When evaluating these observation equations, they are interpreted as noise of the geometry–free observable.

To model the stochastic component of the ionosphere, you have the possibility to directly set up the ionospheric term I_k^i of the double-difference observation equation (Eqn. (2.21)) rewritten in a simpler way:

$$L_{1k}^i = \varrho_k^i - I_k^i + \dots + \lambda_1 n_{1k}^i \quad (13.13a)$$

$$L_{2k}^i = \varrho_k^i - \frac{f_1^2}{f_2^2} I_k^i + \dots + \lambda_2 n_{2k}^i \quad (13.13b)$$

as an unknown parameter. This type of parameter, called Stochastic Ionosphere Parameter (SIP), represents the double-difference ionospheric delay on L_1 according to Eqn. (13.5). One SIP per epoch and satellite (or satellite-pair) has to be estimated. To handle the usually huge number of SIPs, an epoch-wise parameter pre-elimination has to be performed (see Section 7.6.2 for the handling of epoch parameters in GPSEST).

This parameter type is particularly useful for “dual-band” ambiguity resolution when using strategies like the General-Search or the QIF strategy, which directly solve for L_1/L_2 ambiguities (see also Chapter 8). In the ambiguity-unresolved case, where neither L_1 and L_2 ambiguities (N_1 and N_2) nor L_5 ambiguities ($N_5 = N_1 - N_2$) are known, you have to impose a priori constraints on the SIPs to retain the integer nature of the L_1/L_2 ambiguities, otherwise you will implicitly get real-valued ambiguity parameters B_3 according to Eqns. (2.24) and (2.25).

In addition, SIPs allow to smoothly switch between a pure L_1/L_2 solution and an ionosphere-free (L_3) solution. This is demonstrated in Figure 13.4 for a 20-kilometer baseline observed in a rapid-static mode (Schaer 1994). The formal accuracy of the coordinates/ambiguities is plotted with solid/dotted lines. The conclusions from Figure 13.4 are that

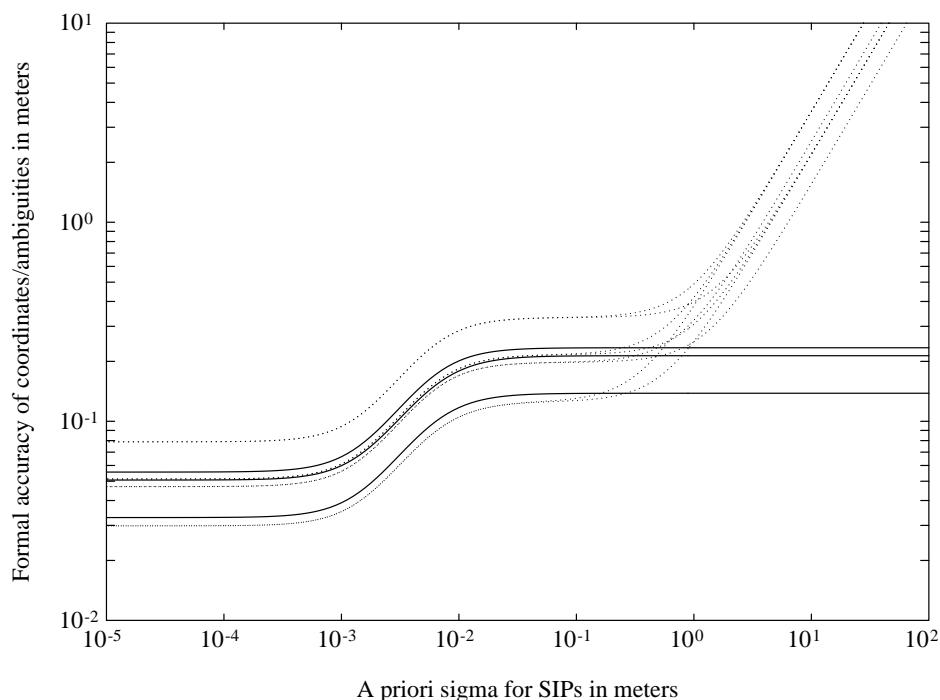


Figure 13.4.: Formal accuracies of the coordinate (solid lines) and ambiguity (dotted lines) parameters as function of SIP constraining.

1. the transition essentially takes place when the a priori sigma of the SIPs is of the same order of magnitude as the a priori measurement noise (assumed to be 4 millimeters).
2. for a very big a priori sigma, the 8 dotted curves showing the formal accuracy of the L_1/L_2 ambiguities go to infinity.

Note that this particular scenario is based on a five-satellite constellation.

13.4. Estimation of Deterministic Ionosphere Models

13.4.1. Local Ionosphere Models

Local ionosphere models (type-1 models) according to Eqn. (13.10) may be estimated with program IONEST ("Menu>Service>Ionosphere tools>Local ionosphere model estimation"). The processing steps RXOBV3 and CODSP are presupposed.

In panel "IONEST 1: Filenames" (Figure 13.5), you decide whether you want to analyze the geometry-free linear combination of either CODE or PHASE observations. We recommend to analyze PHASE observations. At "Phase observations" or "Code observations", one or more zero-difference observation files may be selected.

In panel "IONEST 2: Options" (Figure 13.6), you may define some preprocessing options to mark outliers when processing code measurements, or, to set up a new ambiguity parameter B_4 (according to observation equation, Eqn. (13.9)) for each cycle slip detected when processing phase measurements. The model-specific options include

- "Elevation cutoff angle": the minimum elevation to be processed,
- "Height of the single layer": the single-layer height H (see mapping function in Eqn. (13.7) and Figure 13.3),
- "Degree of development in latitude" and "Degree of development in hour angle": n_{\max} and m_{\max} of the TEC representation displayed in Eqn. (13.10), and

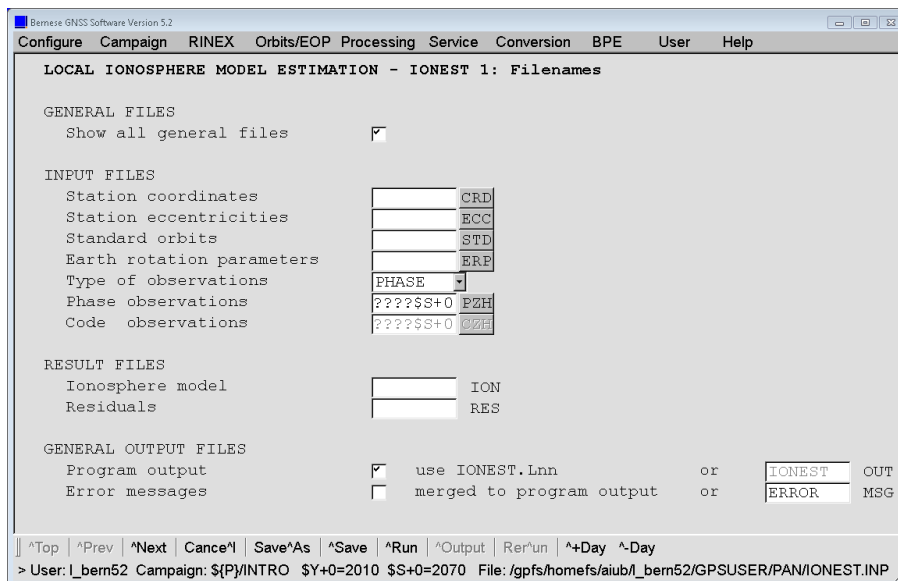


Figure 13.5.: Filenames for IONEST.

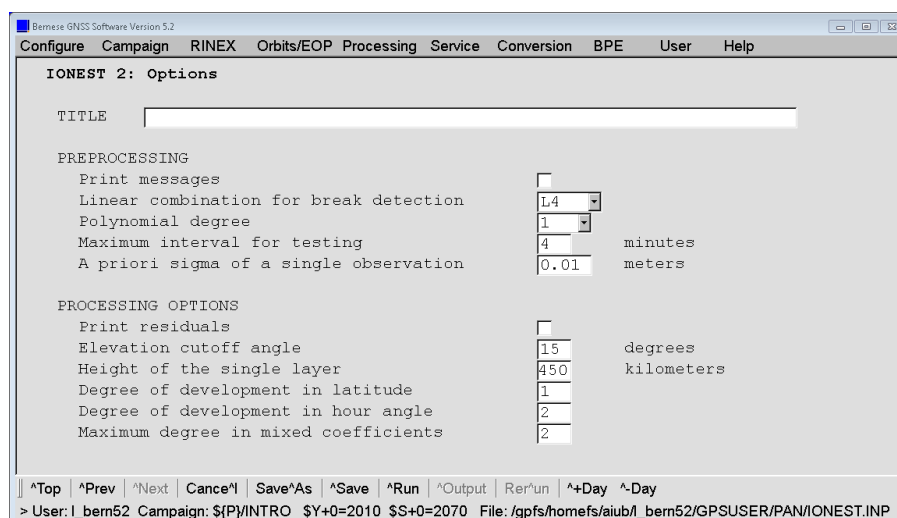


Figure 13.6.: Options for IONEST.

- “Maximum degree in mixed coefficients”: the maximal allowed sum ($n+m$) of both indices of the TEC parameters E_{nm} to be set up.

Note that the values given in this panel are the recommended ones.

The estimated ionosphere models may be used in further processing steps, therefore it makes sense to specify a filename at “Ionosphere model” in panel “IONEST 1: Filenames” (displayed in Figure 13.5). The ionosphere files (default extension ION) are stored in the campaign-specific ATM directory. It is recommended to create a “Residuals” output file (default extension RES) containing L_4 residuals, if you wish to study short-term TEC variations like scintillations or Traveling Ionospheric Disturbances (TIDs). Use the program REDISP (“Menu>Service>Residual files>Display residual file”, description in Section 6.6.1) to browse through these files.

As simple the usage of the program IONEST is, it has a big disadvantage: if you want to derive more than one ionosphere model per session, you have to concatenate/split up the observation file(s) into the desired sub-sections because IONEST always takes all available observations. This can be done either on RINEX level (program CCRINEXO, “Menu>RINEX>Cut/concatenate RINEX files>Observation files”) or on Bernese-binary-format level (program OBSSPL, “Menu>Service>Bernese_observation files>Split observation files”). Furthermore, you have to combine manually (or using a script) the individual ionosphere model files created into one common file. Figure 13.7 gives an example of an ionosphere file containing a two-session model. When joining individual models, you have to make sure that all models end with -1 and that additional models directly start with IONOSPHERE MODEL NUMBER, i.e., without title lines. For longer sessions (e.g., 24-hour sessions), it is much easier to generate a regional ionosphere model than a local one.

A series of zero-degree TEC parameters E_{00} extracted from local ionosphere models is plotted in Figure 13.8. These parameters roughly describe the TEC over the reference station(s) as processed in the program IONEST. In this case, the phase data of the Zimmerwald IGS permanent station has been used to estimate 4-hour ionosphere models. These models were then taken into account when processing the 3-dimensional GPS test network in Turtmann, Switzerland (Beutler et al. 1995). In both subfigures, you notice the typical diurnal variation in TEC. The ionospheric conditions may vary considerably, as visualized by the plots drawn with the same scale at one year interval (see also Figure 13.2).

```

IONOSPHERE MODELS FOR TURTMANN                                     8-FEB-93 10:59
-----
IONOSPHERE MODEL NUMBER : 1
TYPE OF IONOSPHERE MODEL : 1
ORIGIN OF DEVELOPMENT: TIME (UT) (Y M D H) : 1992 10 28 14.8
                        LATITUDE (DEGREES) : 46.8771
                        LONGITUDE (DEGREES) : 7.4651
                        HEIGHT OF LAYER (KM) : 350
DEGREE OF DEVELOPMENT: TIME : 2
                        LATITUDE : 1
                        MIXED : 2
NORMALIZATION FACTORS: LATITUDE (DEGREES) : 6.00
                        TIME (HOURS) : 2.00
                        ELECTRON CONTENT : 0.10D+18
APPLICABILITY FROM EPOCH : 1992 10 28 12.0
                  TO EPOCH : 1992 10 28 17.5
COEFFICIENTS:
DEG. LAT DEG. TIME COEFFICIENT RMS
  0 0 0.26313868E+01 0.18961230E-01
  0 1 -0.11226929E+01 0.82974723E-02
  0 2 0.90513909E-02 0.10480726E-01
  1 0 -0.53071964E+00 0.10746679E-01
  1 1 0.88148393E-01 0.15985126E-01
  -1
IONOSPHERE MODEL NUMBER : 2
TYPE OF IONOSPHERE MODEL : 1
ORIGIN OF DEVELOPMENT: TIME (UT) (Y M D H) : 1992 10 29 14.8
                        LATITUDE (DEGREES) : 46.8771
                        LONGITUDE (DEGREES) : 7.4651
                        HEIGHT OF LAYER (KM) : 350
DEGREE OF DEVELOPMENT: TIME : 2
                        LATITUDE : 1
                        MIXED : 2
NORMALIZATION FACTORS: LATITUDE (DEGREES) : 6.00
                        TIME (HOURS) : 2.00
                        ELECTRON CONTENT : 0.10D+18
APPLICABILITY FROM EPOCH : 1992 10 29 12.0
                  TO EPOCH : 1992 10 29 17.5
COEFFICIENTS:
DEG. LAT DEG. TIME COEFFICIENT RMS
  0 0 0.25439429E+01 0.11467723E-01
  0 1 -0.40731147E+00 0.50130496E-02
  0 2 -0.69612034E-01 0.64961719E-02
  1 0 -0.25940186E+00 0.64259418E-02
  1 1 0.48364446E+00 0.10364515E-01
  -1
    
```

Figure 13.7.: Example of an ionosphere file containing (two) local TEC models.

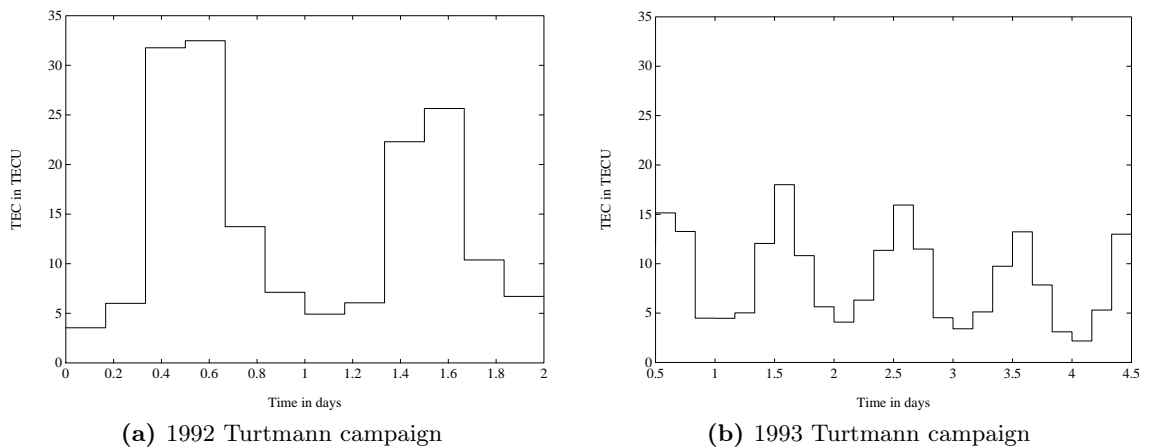


Figure 13.8.: Zero-degree TEC parameter E_{00} extracted from local ionosphere models.

13.4.2. Global, Regional, or Station–Specific Ionosphere Models

The estimation of global, regional, or station–specific ionosphere models, better addressed as maps, is supported by the main parameter estimation program GPSEST ("Menu >Processing>Parameter estimation"). It is then the user's decision to do the ionosphere analysis on either zero– or the double–difference level. We may make two recommendations:

- If you favor the zero–difference approach, the following preprocessing steps are pre-supposed:

1. RNXSMT ("Menu>RINEX>RINEX utilities>Clean/smooth observation files"),
2. RXOBV3 ("Menu>RINEX>Import RINEX to Bernese format>Observation files"), and
3. CODSPP ("Menu>Processing>Code-based clock synchronization").

The use of smoothed code observations in program GPSEST is preferred.

- If you follow the “traditional” double–difference approach, you should undertake the following preparing steps

1. RXOBV3 ("Menu>RINEX>Import RINEX to Bernese format>Observation files"),
2. CODSPP ("Menu>Processing>Code-based clock synchronization"),
3. SNGDIF ("Menu>Processing>Create baseline files"), and
4. MAUPRP ("Menu>Processing>Phase preprocessing").

The use of phase observations in GPSEST is strongly recommended. Ionosphere mapping on double–difference level is, however, not recommended until your ground network is of large size.

In the following, we discuss the most important options for the estimation of global or regional ionosphere model parameters on the basis of zero–difference smoothed code observations. We will highlight aspects which are relevant if double–difference phase observations are processed.

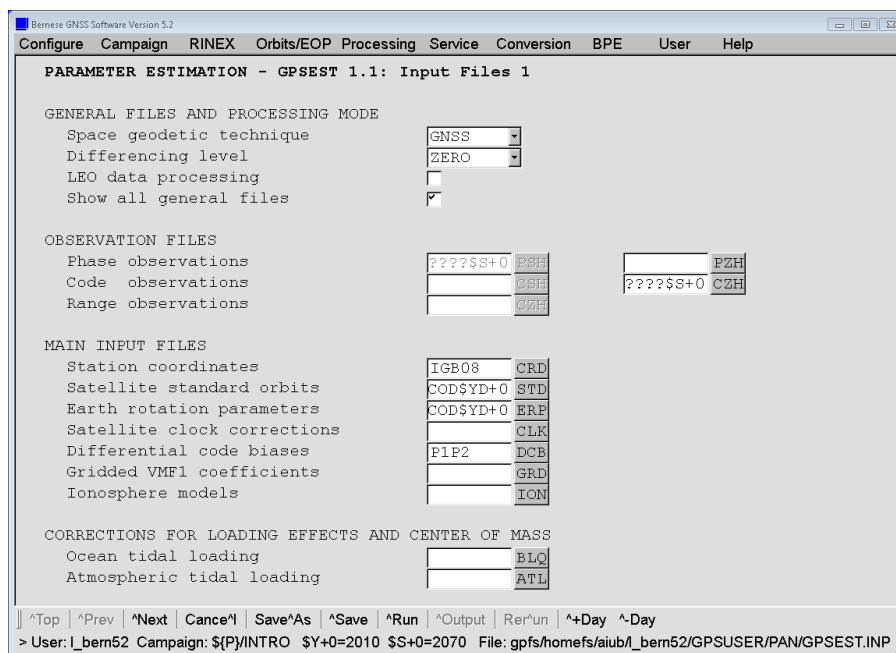


Figure 13.9.: Input files for GPSEST.

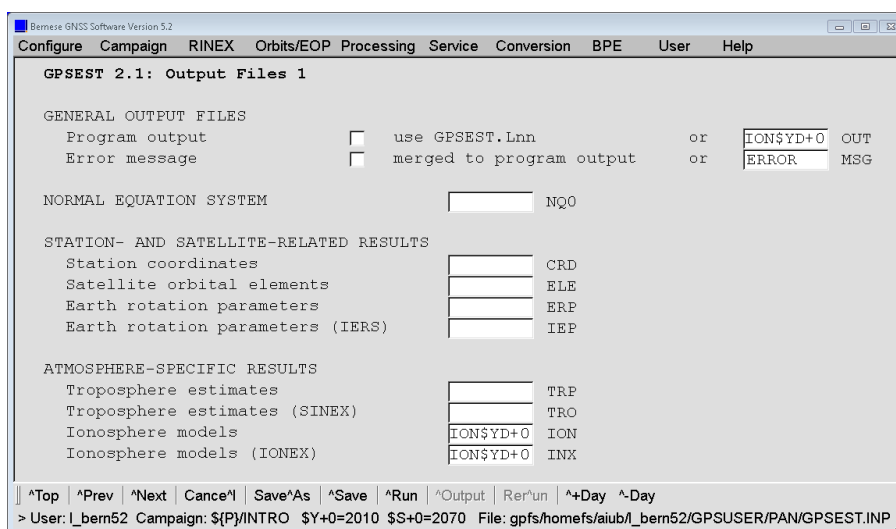


Figure 13.10.: Output files for GPSEST.

In panel “GPSEST 1.1: Input Files 1” (see Figure 13.9), you have to select zero–difference smoothed “Code observation files” (after setting “Differencing level” to ZERO), or in the double–difference case, single–difference “Phase observation files” (after setting “Differencing level” to DOUBLE). When processing code measurements (here in the zero–difference case), the specification of a “Differential code biases” input file containing DCB values for all satellites of the constellation is highly recommended. Corresponding files, like <http://www.aiub.unibe.ch/download/BSWUSER52/ORB/P1P2.DCB> (moving 30–day average), may be downloaded (see Section 4.13.1). A detailed description on the differential code biases is given in Chapter 14.

To save the estimated ionosphere models for further processing steps, you have to specify a filename for the ionosphere models at option “Ionosphere models” (panel “GPSEST 2.1: Output Files 1”, Figure 13.10). If you specify a filename for “IONEX”, you get a file that contains a set of ionosphere maps in the so–called Ionosphere model EXchange format (IONEX), a format internationally adopted. Note that for the creation of the header a “IONEX control file” has to be specified in panel “GPSEST 1.4: General Files”. This file must be adjusted and completed in advance according to the detailed description in Section 24.3.19. Both ionosphere–related files (default extensions are ION and INX) are stored in the campaign–specific ATM directory. In the double–difference case, do refrain from specifying a DCB output filename.

In panel “GPSEST 3.1: General Options 1” (see Figure 13.11), the option “Frequency/linear combination” is essential, L4 is recommended there. Furthermore, it is recommended to select BASELINE as “Correlation strategy” in the zero–difference case and CORRECT in the double–difference case.

In the double–difference case it is a good idea to set the ambiguity “Resolution strategy” to NONE. In an ambiguity–fixed scenario the option “Introduce L1 and L2 integers” should be chosen (see Figure 13.12). In both cases it makes sense to set option “Pre–elimination: Ambiguities” to AS_SOON_AS_POSSIBLE in panel “GPSEST 5.1: Setup of Parameters and Pre–Elimination 1”.

In panel “GPSEST 5.1: Setup of Parameters and Pre–Elimination 1” you have to set up “Parameter Setup: global ionosphere parameters”, and, exclusively in the zero–difference case, you

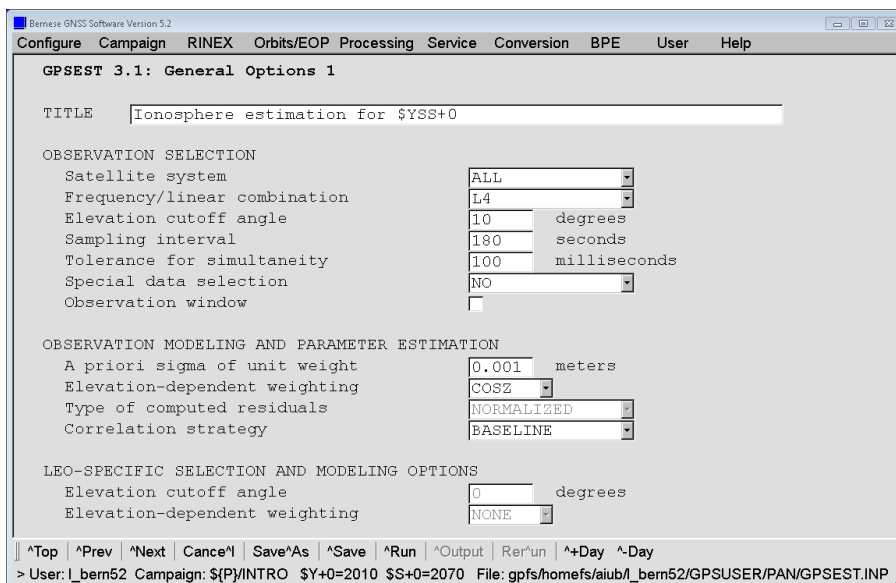


Figure 13.11.: General options for GPSEST (1).

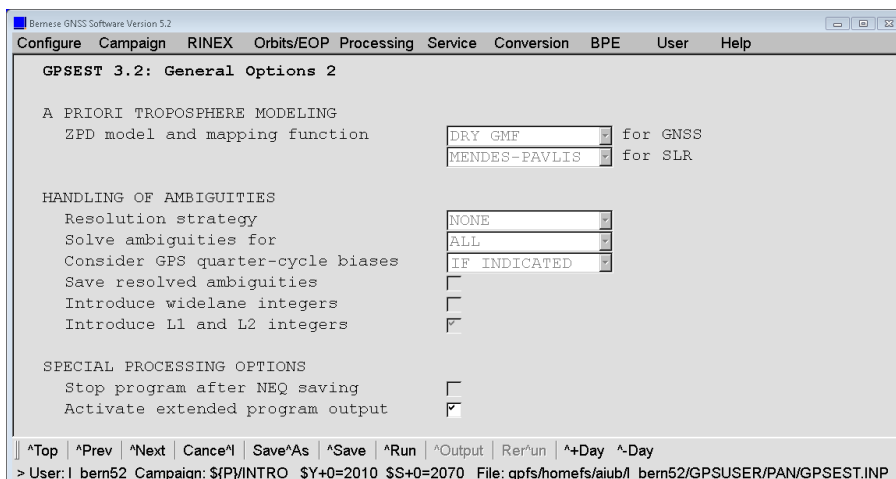


Figure 13.12.: General options for GPSEST (2).

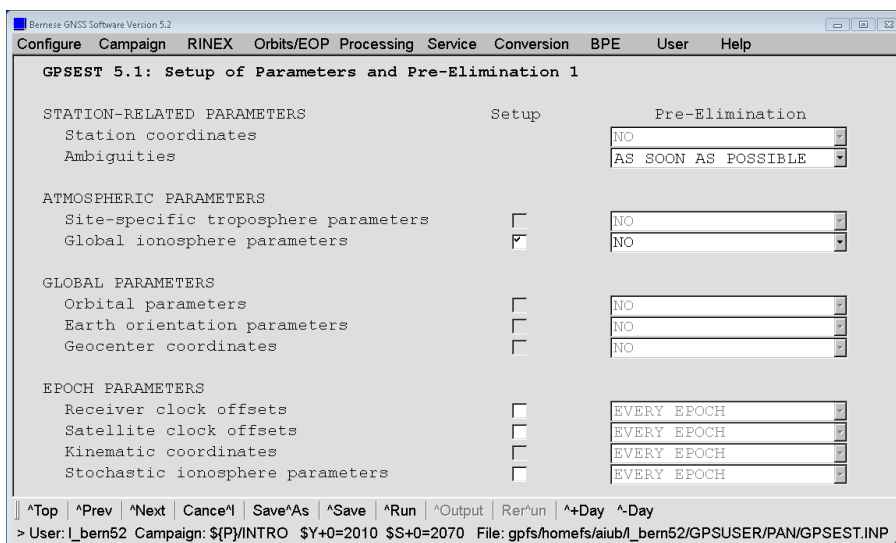


Figure 13.13.: Parameter setup and pre-elimination (1).

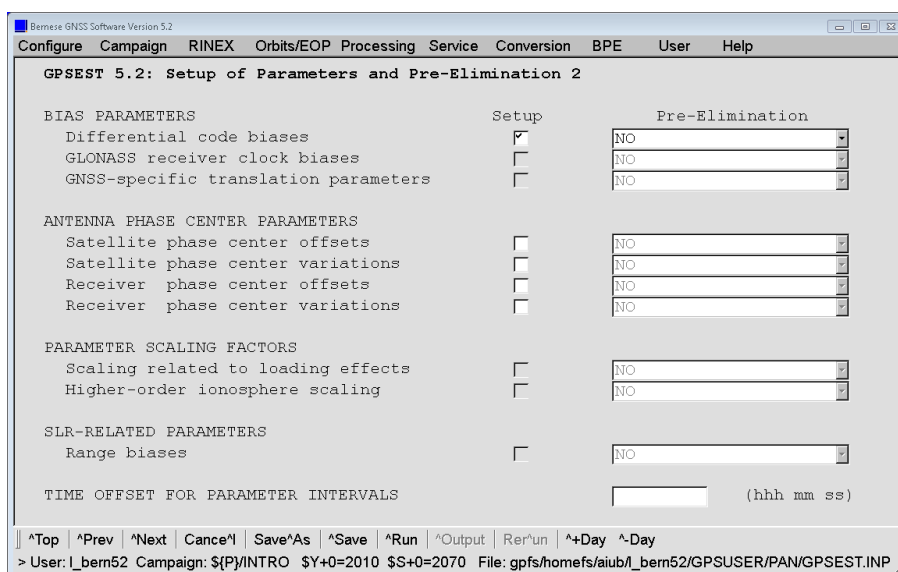


Figure 13.14.: Parameter setup and pre-elimination (2).

have to set up “Differential code biases” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”.

In panel “GPSEST 6.2.1: Global Ionosphere Parameters 1” (see Figure 13.15), you may enter the requests specific to the TEC modeling. The “GIM: Parameter spacing/interval” should be set to 24 00 00 for regional or station-specific models assuming a (maximum) session length of 24 hours. A larger number of coefficient sets (models) and, therefore, a shorter parameter spacing may be appropriate for the global application.

“GIM: maximum degree of spherical harmonics” and “GIM: maximum order of spherical harmonics” correspond to n_{max} and $m_{max} (\leq n_{max})$ of the TEC model, Eqn. (13.12). For regional models, a smaller maximum degree than given in the above panel should be specified (e.g., $n_{max} = 6$, $m_{max} = 6$), depending on the extent of the network processed. Assuming $m_{max} = n_{max}$, you have to reckon $(n_{max} + 1)^2$ GIM parameters per session.

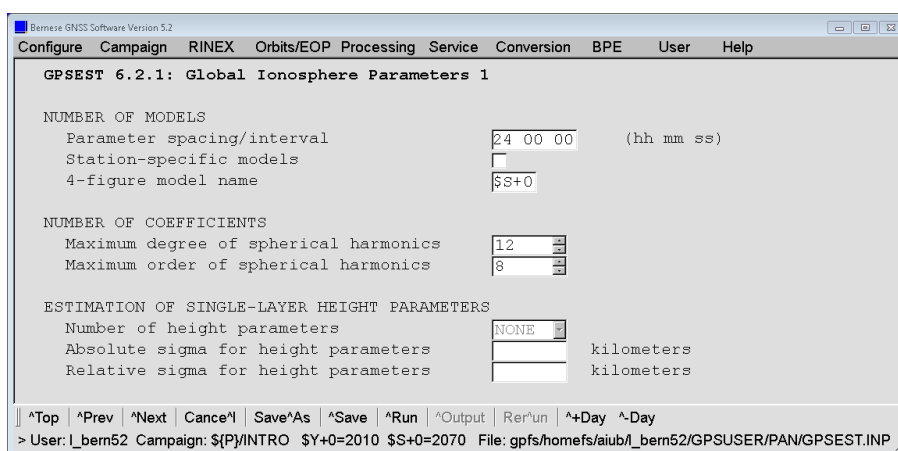


Figure 13.15.: Global ionosphere related options in GPSEST (1).

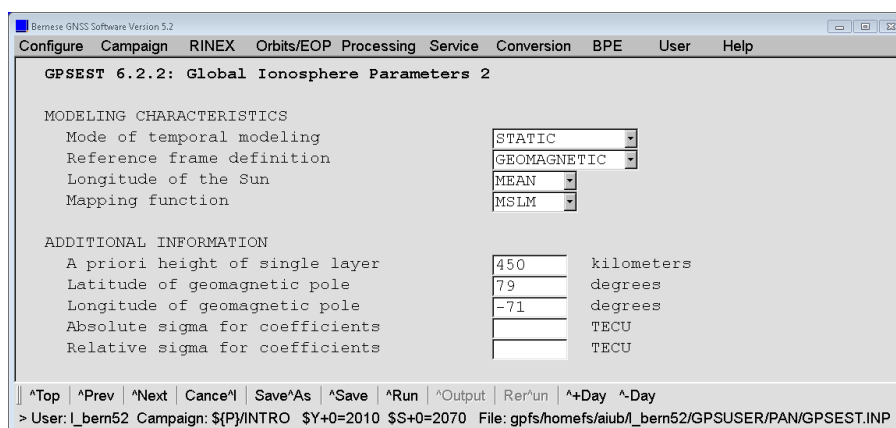


Figure 13.16.: Global ionosphere related options in GPSEST (2).

Modeling characteristics may be set in panel “GPSEST 6.2.2: Global Ionosphere Parameters 2” (see Figure 13.16). Select `STATIC` to create ionosphere models representing static (or “frozen”) TEC structures in the sun–fixed frame. They refer to specific time intervals. `DYNAMIC` models the TEC coefficients as piecewise linear functions $a_{nm}(t)$ and $b_{nm}(t)$ representing a (low–)dynamic ionosphere $E(\beta, s, t)$. If you select `DYNAMIC`, the TEC coefficients are always referred to particular reference epochs. With the option “GIM: reference frame definition”, you may decide in which reference frame the TEC should be modeled, a `GEOGRAPHIC` or a `GEOMAGNETIC` frame. With the setting `MEAN` or `TRUE` for the “GIM: longitude of the Sun”, the argument s is computed according to the right–hand or left–hand side of Eqn. (13.11). The “GIM: mapping function” should be `COSZ` to be in accordance with Eqn. (13.7).

It is recommended to set the “GIM: a priori height of single layer” to $H = 450$ km. The fields “GIM: latitude of geomagnetic pole” and “GIM: longitude of geomagnetic pole” expect the coordinates of the Earth–centered dipole axis, if you chose `GEOMAGNETIC` as reference frame. Finally, you have the possibility to define “GIM: absolute sigma for coefficients” as well as “GIM: relative sigma for coefficients”. An absolute sigma of, e.g, 10 TECU is recommended to produce regional or station–specific models.

You might set up in addition single–layer height parameters as unknowns in panel “GPSEST 6.2.1: Global Ionosphere Parameters 1”. In that case, GPSEST requires an a priori GIM file — stemming from an initial program run — to be specified in panel “GPSEST 1.1: Input Files 1”, option “Ionosphere models”, because the parameter estimation problem is no longer linear.

Deterministic ionosphere models in a piecewise linear representation may be stored just like other parameters in normal equation files in the program GPSEST. They may be combined later on in program `ADDNEQ2` (“Menu>Processing>Combine normal equation systems”). Absolute and relative constraints may be specified in panel “ADDNEQ2 9: Options for Atmospheric Parameters”. Just like GPSEST, `ADDNEQ2` offers the possibility to store `IONEX` as well as Bernese ionosphere result files. All parameter operations described in Section 9.3 may be applied to ionosphere parameters, too. Due to the piecewise linear representation, ionosphere models of consecutive days will automatically result in a continuous model. To reduce the number of parameters in, e.g., a three–day solution, the `EXCEPT_FOR_BOUNDARY` pre–elimination option for the first and third day may be applied. As demonstrated in the provided `PPP.PCF` example (description in Section 23.4.1), `ADDNEQ2` may also be used to compute a regional ionosphere model from a set of subnetworks or even from a set of individually analyzed stations.


```

CODE'S GLOBAL IONOSPHERE MAPS FOR DAY 139, 2003                24-MAY-03 12:43
-----
MODEL NUMBER / STATION NAME                : 1390-01
MODEL TYPE (1=LOCAL,2=GLOBAL,3=STATION)   : 2
MAXIMUM DEGREE OF SPHERICAL HARMONICS     : 15
MAXIMUM ORDER                             : 15
DEVELOPMENT WITH RESPECT TO
  GEOGRAPHICAL (=1) OR GEOMAGNETIC (=2) FRAME : 2
  MEAN (=1) OR TRUE (=2) POSITION OF THE SUN  : 1
MAPPING FUNCTION (0=NONE,1=COSZ,2=MSLM,3=ESM) : 2
HEIGHT OF SINGLE LAYER AND ITS RMS ERROR (KM) : 450.00    0.00
COORDINATES OF EARTH-CENTERED DIPOLE AXIS
  LATITUDE OF NORTH GEOMAGNETIC POLE (DEGREES) : 79.59
  EAST LONGITUDE (DEGREES)                     : -71.99
PERIOD OF VALIDITY
  FROM EPOCH / REFERENCE EPOCH (Y,M,D,H,M,S) : 2003 05 19 00 00 00
  TO EPOCH                                     :
LATITUDE BAND COVERED
  MINIMUM LATITUDE (DEGREES)                 : -88.62
  MAXIMUM LATITUDE (DEGREES)                 : 89.57
ADDITIONAL INFORMATION
  NUMBER OF CONTRIBUTING STATIONS            : 178
  NUMBER OF CONTRIBUTING SATELLITES          : 38
  ELEVATION CUT-OFF ANGLE (DEGREES)         : 10
  MAXIMUM TEC AND ITS RMS ERROR (TECU)       : 65.25    0.68
COMMENT / WARNING                            :
COEFFICIENTS
DEGREE ORDER    VALUE (TECU)    RMS (TECU)
  0      0      23.21633875    0.0333
  1      0      5.64451669    0.0303
  1      1      8.01834535    0.0334
...
 15     -14     0.01665035    0.0235
 15     15     0.00388322    0.0249
 15     -15     0.02498974    0.0248
...

```

Figure 13.17.: Example for an ionosphere file containing a series of global TEC models.

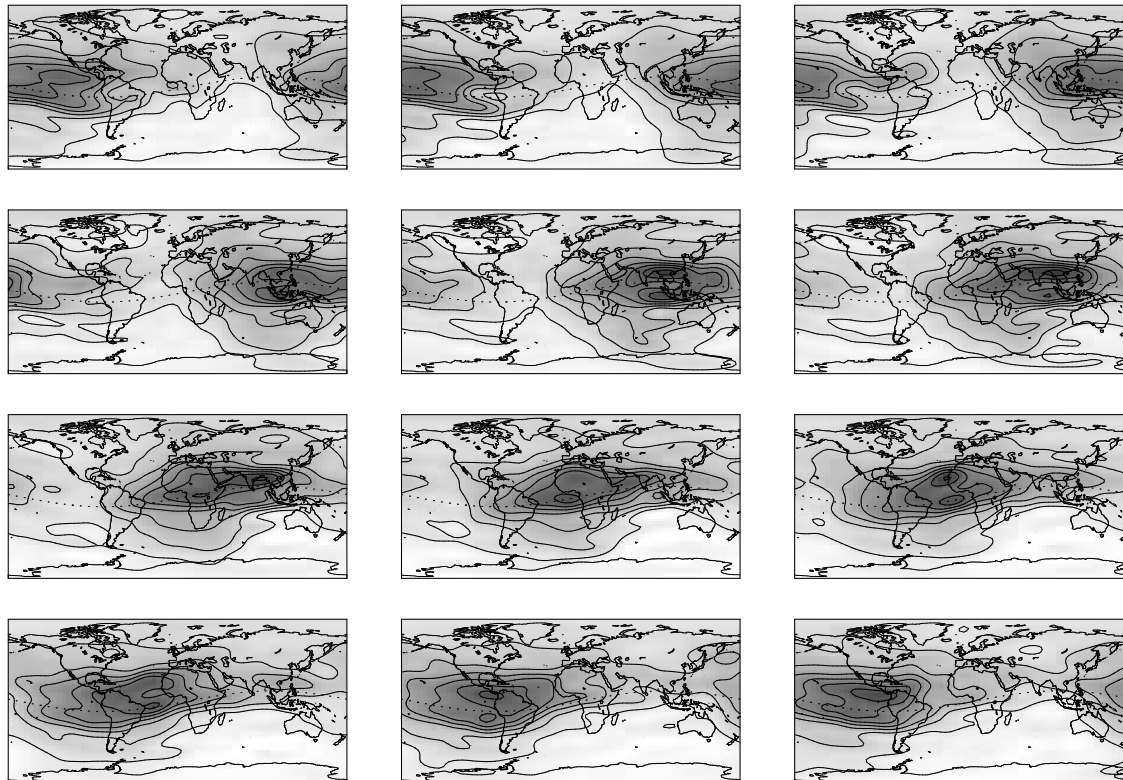


Figure 13.18.: Left to right, top to bottom: Two-hourly global TEC snapshots for May 19, 2003, as produced by CODE (with an hourly resolution since October 19, 2014).

GIM-related information may be extracted from the GPSEST output files with the program GPSXTR ("Menu>Processing>Program output extraction>Parameter estimation/stacking"). Just enter a filename in "GIM summary". Resulting summary files (default extension SUM) are stored in the OUT directory.

Figure 13.17 shows an example of an ionosphere file containing 12 2-hour global models. To join a series of global/regional models (type-2 models) stored in individual ionosphere files into a "multi-session" model, you may simply copy these files together in chronological order.

The GIMs (corresponding coefficients are listed in Figure 13.17), are visualized in Figure 13.18. TEC snapshots taken at 00:00, 02:00, 04:00, . . . , 22:00 UT are shown. Contour lines are given for every 10 TECU. The typical "bulge" (dark area), which may be bifurcated, is aligned to some extent with the Sun ($s \approx 0$). The dotted line indicates the geomagnetic equator.

Since January 1, 1996, the CODE Analysis Center is routinely producing Global Ionosphere Maps as an additional product. Apart from that, GIMs for the entire year 1995 have been computed in a reprocessing step (Schaer et al. 1996). The corresponding ION files starting with day 001 of 1995 are available via anonymous ftp (see also Chapter 4). Regional ionosphere models for Europe, routinely generated since December 1995, are available as well.

Figure 13.19 shows the mean TEC that has been extracted from the GIMs produced by CODE (Schaer 1998). This parameter roughly describes the ionospheric activity on a global scale (see also Figure 13.2).

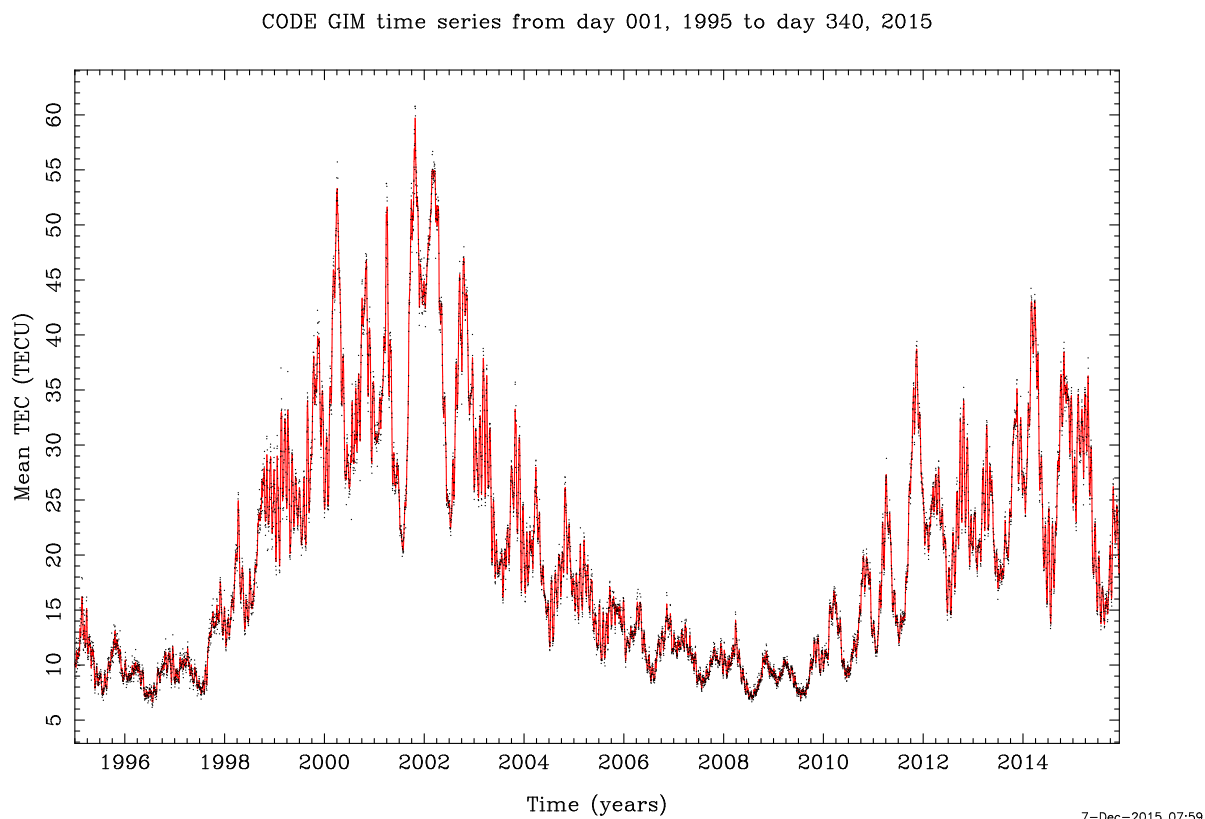


Figure 13.19.: Mean TEC from January 1, 1995, extracted from CODE GIMs.

13.4.3. Estimation of Differential Code Biases

Estimation of differential P1–P2 code biases (or simply DCBs) is an essential issue for ionosphere analysis when processing undifferenced code observations. Details on DCBs may be found in Chapter 14 and specifically in Section 14.3.2, where the estimation of P1–P2 DCB parameters is addressed.

13.4.4. Application of Deterministic TEC Models

Deterministic TEC models may be used by two processing programs, namely the preprocessing program MAUPRP and the parameter estimation program GPSEST. The requested ionosphere file has to be specified in the option “Ionosphere models” in panel “MAUPRP 1: Input Files” and panel “GPSEST 1.1: Input Files 1”, respectively. Both programs will automatically detect whether local (type-1), global/regional (type-2), or station-specific (type-3) ionosphere models are introduced. In this context, we may mention that the program CODSP only supports a very simple ionosphere model with “hard-wired” values for the day- and night-time electron content which is therefore not really representative for actual ionospheric conditions.

Where can deterministic ionosphere models help in GNSS data processing?

- In preprocessing, if large TEC gradients occur. Note, however, that short-term TEC variations are not reflected in the deterministic ionosphere models, i.e., strong scintillations will still harm preprocessing.
- For ambiguity resolution, to make the ambiguity fixing more reliable by reducing the fractional parts of (L_1 , L_2 , or especially L_5) ambiguities, if you do not use (precise) dual-band code measurements when analyzing the Melbourne–Wübbena linear combination, see Eqn. (2.28).
- In parameter estimation steps, to reduce the ionosphere-induced scale bias in GNSS network solutions (see Table 13.1), if you process L_1 and/or L_2 observations — and not the ionosphere-free (L_3) linear combination.
- In the processing steps to allow for higher order ionosphere corrections (see Section 13.6) what is relevant even for the ionosphere-free (L_3) linear combination.

13.5. Stochastic Ionosphere Modeling Technique

13.5.1. Estimation of Stochastic Ionosphere Parameters

Stochastic Ionosphere Parameters (SIPs), representing the term I_k^i in Eqn. (13.13), may be set up in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”. This parameter type is only active if both frequencies L1&L2 are selected in option “Frequency/linear combination” in panel “GPSEST 3.1: General Options 1”.

For the SIP parameters it is highly recommended to activate the pre-elimination algorithm working epoch by epoch (select EVERY_EPOCH as pre-elimination method again in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”; a description of the algorithm is given in Section 7.7.1). The reason for this is the huge number of SIPs usually involved. The drawback is that you will not get a solution for the SIP parameters in the GPSEST program output because the back-substitution step is not implemented for this particular parameter type (see Section 7.7.2).

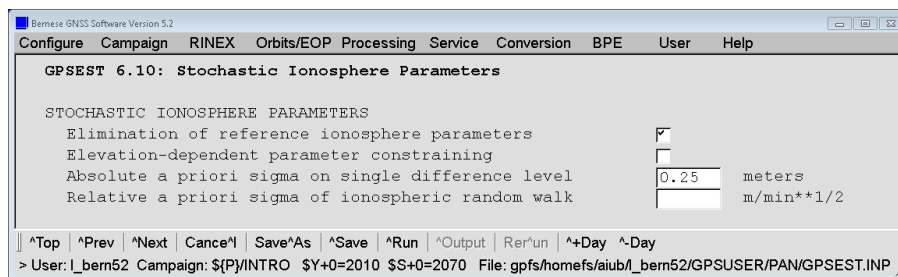


Figure 13.20.: Options for stochastic ionosphere parameters in GPSEST.

Panel “GPSEST 6.10: Stochastic Ionosphere Parameters ” offers several options concerning SIPs (see Figure 13.20).

“Stoch lono: elimination of reference ionosphere parameters” is the option where you decide whether to estimate SIPs on a double–difference or a quasi–single–difference level. The estimation on the quasi–single–difference level should be used when defining so–called relative a priori sigma at “Stoch lono: relative a priori sigma of ionospheric random walk”. If you eliminate reference ionosphere parameters, the resulting SIPs are estimated with respect to a reference satellite, actually the satellite closest to the zenith. The consideration of “Stoch lono: elevation-dependent parameter constraining” is recommended in particular when processing low–elevation data.

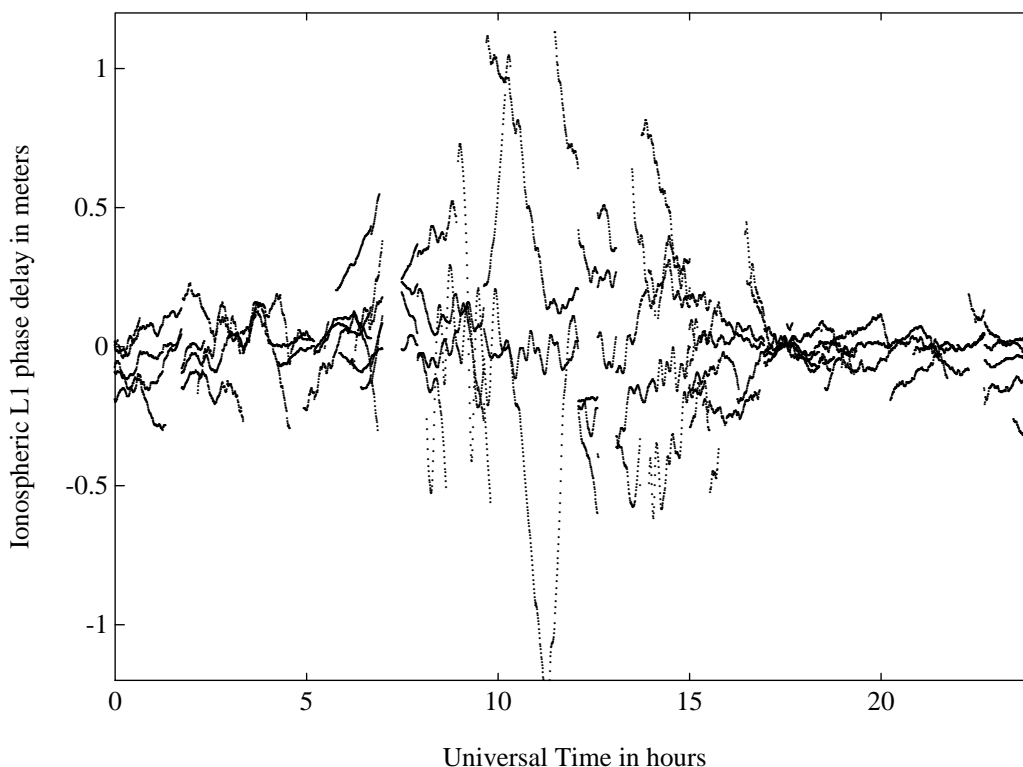


Figure 13.21.: Stochastic ionosphere parameters (SIPs) describing the double–difference ionospheric delay on L_1 .

An absolute a priori sigma must be specified in the field “Stoch Iono: absolute a priori sigma on single difference level” to get “hybrid” dual-band observations. By entering 0.00, no SIP constraints are introduced. When using the General-Search ambiguity resolution strategy in conjunction with the stochastic ionosphere modeling, we recommend to specify an absolute a priori sigma between, let us say, 0.01 and 0.1 meters, and between 0.1 and 1 meters when using the QIF strategy (see also Figure 13.4). Relative a priori constraints between consecutive SIPs of the same satellite may be defined to model the correlation in time of the ionospheric signal. This option may be used only if you do not eliminate reference ionosphere parameters (option “Stoch Iono: elimination of reference ionosphere parameters”). Such a “SIP smoothing” might be useful, e.g., for kinematic applications under moderate ionospheric conditions.

Figure 13.21 shows the resulting SIPs for a European 600-kilometer baseline of the IGS network. The approximately 12 000 parameters which describe the double-difference ionospheric delay on L_1 have been estimated in several program runs by defining shifted time windows. Short-term variations like the so-called Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) with their typical periods of 10 to 60 minutes may be recognized.

13.5.2. Using Stochastic Ionosphere Parameters

The main application for stochastic ionosphere modeling is ambiguity resolution using strategies like the General-Search and the QIF strategy, both directly solving for the L_1/L_2 ambiguities. There is another possible use as already demonstrated in Figure 13.4: by varying the a priori constraints imposed on the SIPs, you have the possibility to smoothly switch between a pure L_1/L_2 solution and an L_3 solution.

Last but not least, we have to emphasize that “hybrid” dual-band observations contain in principle the full information concerning geometry and ionosphere. Consequently, it is possible to set up GIM parameters in addition to SIPs to instantaneously separate — in a single processing run — the stochastic and the deterministic component of the ionosphere.

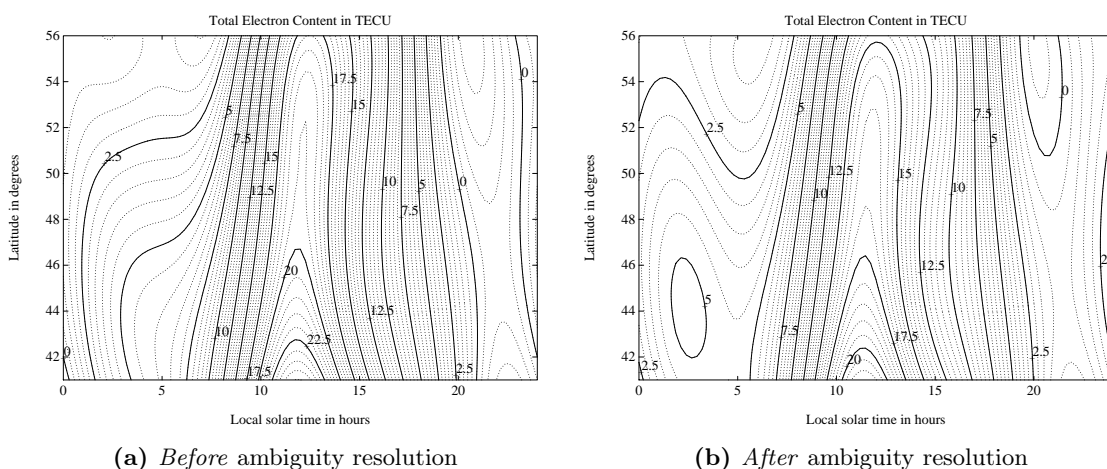


Figure 13.22.: Regional (or baseline-specific) ionosphere model.

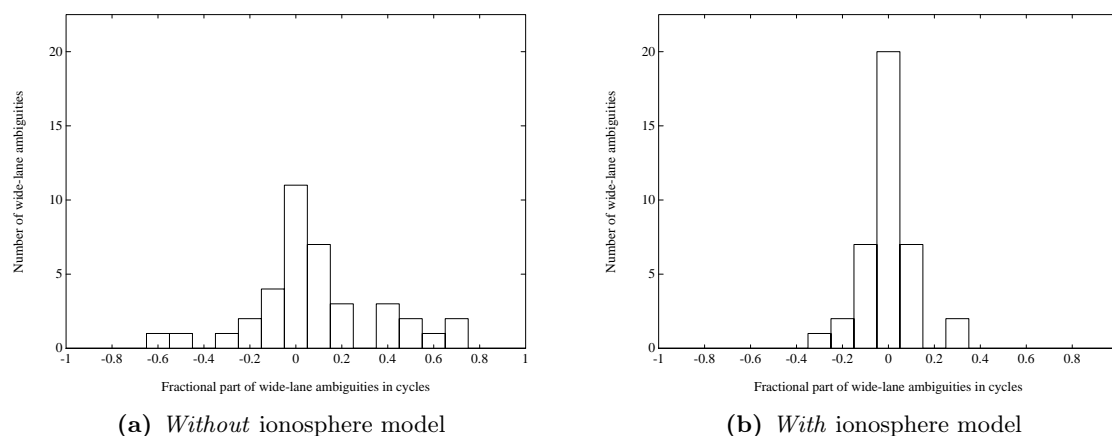


Figure 13.23.: Fractional parts of wide-lane ambiguities indicating the (remaining) deterministic part of the ionosphere.

Figure 13.22 shows a regional ionosphere model as derived from double-difference phase data of one baseline (a) before and (b) after the QIF ambiguity resolution. Large values and rms errors for regional TEC parameters often occur due to the limited latitude range covered. They may be ignored — as in this example — provided that the rms errors for the actual TEC representation $E(\beta, s)$, evaluated within the probed area, are reasonable. The resulting “fractional parts” of the wide-lane ambiguities are shown in Figure 13.23, if (a) no deterministic TEC parameters are set up and if (b) GIM parameters are estimated.

13.6. Higher-Order Ionosphere (HOI) Corrections

The *Bernese GNSS Software* Version 5.2 allows to take into account higher order ionosphere (HOI) and ray path bending correction terms. These are:

1. second-order term,
2. third-order term, and
3. ray path bending term.

In order to compute the second- and third-order ionosphere correction terms for L_1 , L_2 , and, in particular, for the L_3 (first-order ionosphere-free) phase observations, the frequency-dependent formulae from Fritsche et al. (2005) are considered in the GPSEST parameter estimation program. The algorithm is based on Bassiri and Hajj (1993), where the geomagnetic field is characterized by a co-centric tilted magnetic dipole. This model has been replaced finally by (the 12th generation of) the more realistic International Geomagnetic Reference Field (IGRF). Finally, it should be mentioned that the previously introduced GIM products are of fundamental importance for computation of these higher-order ionosphere correction terms.

Depending on station latitude, elevation angle and time of the day, the second-order correction term of one observation may reach 1 cm. The correction for the third-order term is negative (i.e., a positive effect or time delay) and even for very high elevation angles may exceed 1 mm in an absolute sense. During quiet ionosphere conditions, the only noticeable influence up to 2 mm comes from the second-order correction term at low elevation angles.

One may conclude that, in time periods with high ionosphere activity, HOI terms should be considered in the GNSS analysis when processing global or large-scale networks or in case of a PPP (as far as HOI corrections have been applied to the solution where the satellite clock corrections are taken from). In times with low TEC levels, these correction terms are not significant. Depending on station latitude, elevation angle (an elevation mask angle of 3 degrees is used at CODE), and observation epoch, the second-order HOI correction term of a single observation may reach few centimeters in extreme cases. Nevertheless, observation corrections due to HOI refraction effects are generally comparably small but the computation of the corresponding correction values is relatively CPU-time consuming. That is why the HOI correction is usually applied just for the final network processing step using GPSEST. As for instance Petrie et al. (2010) but also other authors confirm, the impact on station positions (and consequently on the reference frame relied on) is of systematic nature in global analysis and therefore has to be taken into account (for the final network analysis step).

13.6.1. HOI Correction and HOI Scaling Factors

Figure 13.24 shows the deciding switch to get the HOI correction applied (mainly) for L_3 (first-order ionosphere-free) observations. GPSEST and ADDNEQ2 were expanded with the ability to assign additional scaling parameters to each individual HOI term. This implementation concept allows *switching on and off* individually each HOI correction term at normal equation level. Corresponding scaling parameters may be set up globally or even specific to each ground station involved (in order to detect station anomalies and eventually refine HOI correction models). Moreover, the significance of each term may be verified at observation level for different ionosphere conditions.

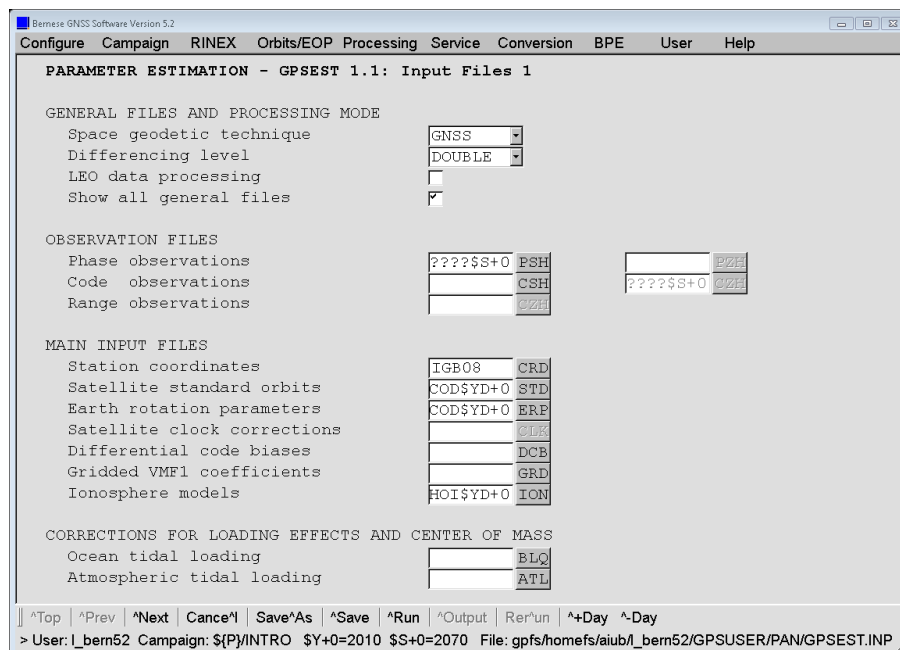


Figure 13.24.: GPSEST: Activation of HOI correction for L_3 (first-order ionosphere-free) observations by specifying an ionosphere input file (here: HOI\$YD+0; default extension ION).

How to set up such HOI scaling factors using GPSEST (for later manipulation on normal equation level) is shown in Figures 13.25 and 13.26.

With ONE_FOR_ALL in “GPSEST 6.18: Higher-order Ionosphere Scaling Factors”, HOI scaling parameters are set up globally; with ONE_PER_STATION they are set up for each individual station (and again each of the three HOI terms, see Lutz et al. 2009, 2010). The interested reader is referred to Section 13.2.1 and, moreover, to Chapter 9, specifically Section 9.5, for more information on scaling parameters (which are also available for other observation model components). Last but not least, it should be emphasized that consideration of HOI scaling factors is definitively not a must for standard analyses, where the HOI correction should be applied just following Figure 13.24.

13.6.2. HOI Correction Switch at NEQ Level

Figures 13.27 and 13.28 show how included HOI scaling parameters should be treated for computation of a solution with HOI corrections applied. If you would like to compute a solution without consideration of HOI corrections, ZERO would have to be chosen as a priori value(s) in panel “ADDNEQ2 19: Options for Higher-order Ionosphere Scaling Factors” (Figure 13.28).

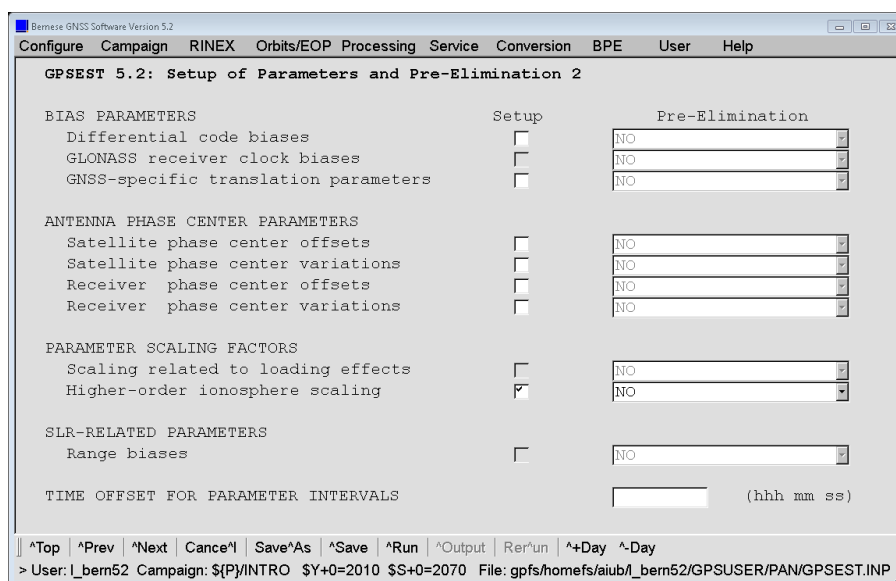


Figure 13.25.: GPSEST: Setup of HOI scaling factors (1).

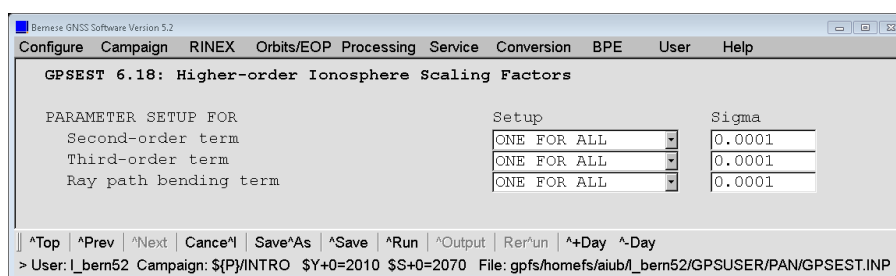


Figure 13.26.: GPSEST: Setup of HOI scaling factors (2).

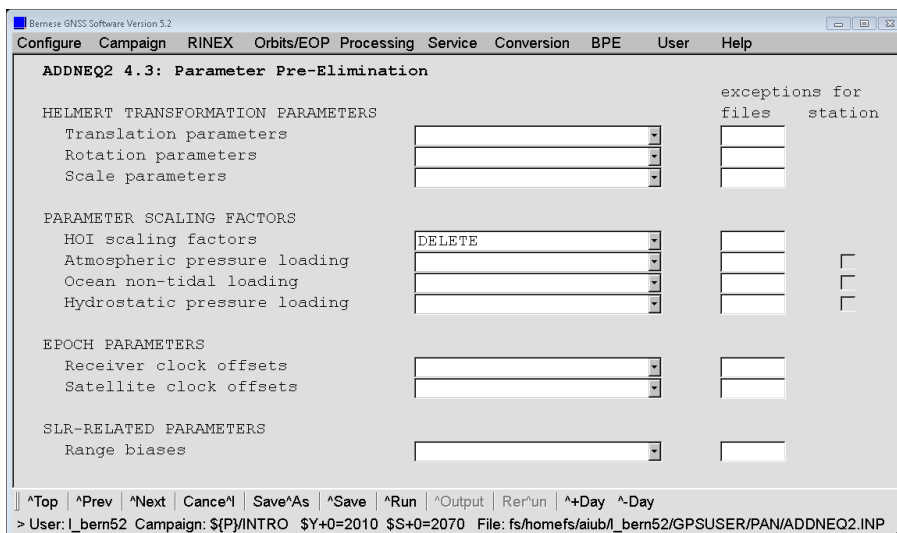


Figure 13.27.: ADDNEQ2: Parameter treatment mode for HOI scaling factors.

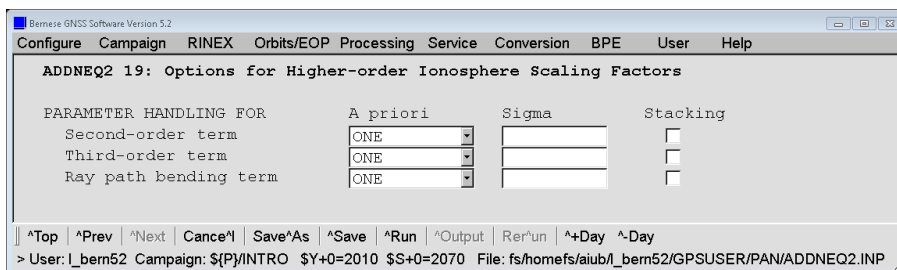


Figure 13.28.: ADDNEQ2: Specification of reference values for HOI scaling factors.

If you would like to generate and thus store a NEQ output file, NO should be chosen in panel “ADDNEQ2 4.3: Parameter Pre-Elimination” (Figure 13.27), otherwise the HOI scaling parameters get removed (or deleted) from the resulting NEQ information (while using DELETE).

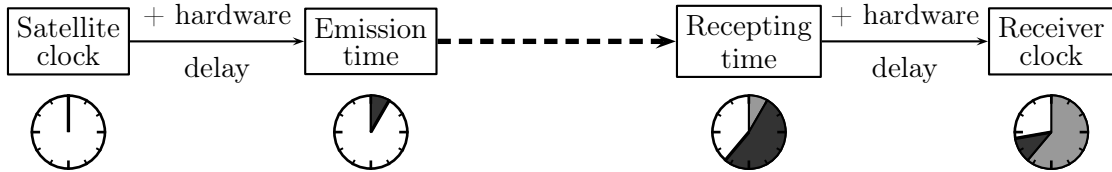
14. GNSS Related Biases

14.1. Introduction

Existing code (or pseudorange) biases represent a non-negligible error source for all precise GNSS applications using code observation data. They become relevant as soon as the code observations are used, for instance in case of GNSS satellite clock estimation as well as time transfer among GNSS tracking stations, but also code-based resolution of carrier phase ambiguities, or in the context of ionosphere analysis. They result from the hardware delay in the satellites and receivers. These biases dependent on frequencies, signal type, receiver tracking technologies, and last but not least on the GNSS tracked by the receiver. In Section 14.1.1 this will be explained in more detail.

14.1.1. Where Do Code Biases Come from?

The code biases are time delays within the satellite and receiver caused by their hardware. This means, that the given time from the satellite clock is not equal to the signal emission time. The same is valid for the receivers. The given reception time by the receiver is the time when the signal was demodulated and linked to the internal receiver clock. However, there is a time delay between the receiving time in the antenna and the time linking within the hardware.



The satellite and receiver clock terms in the basic GNSS observation equation (Eqn. 2.20) consequently contain both, the current clock correction with respect to a reference time scale (e.g., GPS system time) and the related hardware delay. When considering this fact, the observation equation have to be extended introducing the corresponding biases:

$$P_{1k}^i = \varrho_k^i + I_k^i + T_k^i + c (\Delta\delta_k + B_{1k}) - c (\Delta\delta^i + B_1^i) \quad (14.1a)$$

$$P_{2k}^i = \varrho_k^i + \frac{f_1^2}{f_2^2} I_k^i + T_k^i + c (\Delta\delta_k + B_{2k}) - c (\Delta\delta^i + B_2^i) , \quad (14.1b)$$

where B denotes the hardware delay and $\Delta\delta$ is the reading of the related clock. The differential observation equation (2.21) assumes that the clock terms completely cancel out. This is only true, if the satellite hardware delays B_1^i and B_2^i are equal for both tracking stations k and ℓ . In analogy, the receiver hardware delays B_{1k} and B_{2k} have to be identical for both satellites i and j .

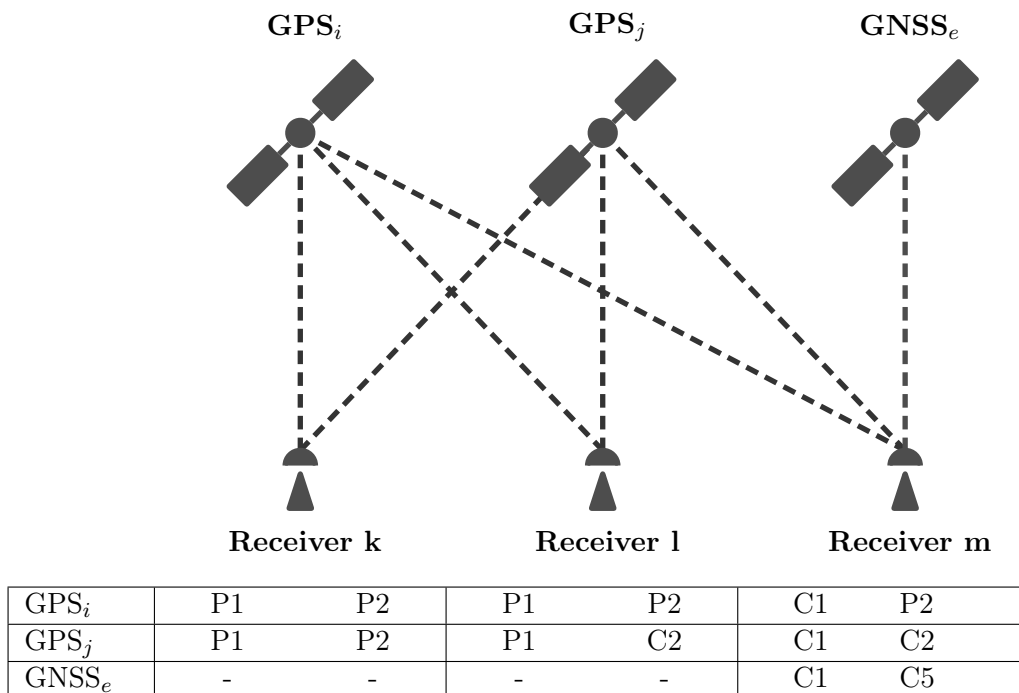


Figure 14.1.: Satellite–Receiver: diversity of observation codes tracked by receivers.

Because of the FDMA technology, this assumption is in general not true for GLONASS, if both satellites use different frequencies f_i and f_j . This results in inter–frequency bias (IFB) for GLONASS which will be discussed in Section 14.4.1 .

As Figure 14.1 illustrates, biases may also become relevant for differences between GPS satellites: receiver k is tracking the same signal from satellites i and j whereas the receiver l tracks the P2 signal from satellite i but from satellite j the C2 signal. The clock parameter for satellite j will refer to $(\Delta\delta^i + B_2^i(P2))$ for station k and $(\Delta\delta^i + B_2^i(C2))$ for station l . To allow the estimation of a common satellite clock parameter, the difference between the two hardware delays has to be considered. This consistency can be achieved in two ways

$$\begin{aligned}
 (\Delta\delta^i + B_2^i(P2)) &= (\Delta\delta^i + B_2^i(C2) + D_2^i(P2, C2)) \\
 (\Delta\delta^i + B_2^i(P2) + D_2^i(C2, P2)) &= (\Delta\delta^i + B_2^i(C2))
 \end{aligned}$$

that are fully equivalent because $D_2^i(P2, C2) = -D_2^i(C2, P2)$. The current convention by the IGS defines that the clock parameters have to refer to the ionosphere free linear combination of P1 and P2 signals. The resulting biases are in that case Differential Code Biases (DCBs) $D_1^i(P1, C1) = P1 - C1$ and $D_2^i(P2, C2) = P2 - C2$. A more complete overview of the resulting biases from the configuration in Figure 14.1 is given in Tables 14.1 and 14.2 for satellites and receivers, respectively.

The example in Figure 14.1 also includes a multi–GNSS receiver m . It tracks the C1 signal from GPS but also from another GNSS (e.g., Galileo). In that example, the first

Table 14.1.: Satellite code biases according to tracking scenario in Figure 14.1 to obtain ionosphere linear combination of P1 and P2 as the reference.

Satellite Reference		GPS i $B_3^i(\text{P1,P2})$	GPS j $B_3^j(\text{P1,P2})$	GNSS e $B_3^e(\text{C1,C5})$
Rec. k	OBS 1	$B_1^i(\text{P1})$	$B_1^j(\text{P1})$	
	OBS 2	$B_2^i(\text{P2})$	$B_2^j(\text{P2})$	
Rec. l	OBS 1	$B_1^i(\text{P1})$	$B_1^j(\text{P1})$	
	OBS 2	$B_2^i(\text{P2})$	$B_2^j(\text{C2}) + D_2^j(\text{P2, C2})$	
Rec. m	OBS 1	$B_1^i(\text{C1}) + D_1^i(\text{P1, C1})$	$B_1^j(\text{C1}) + D_1^j(\text{P1, C1})$	$B_1^e(\text{C1})$
	OBS 2	$B_2^i(\text{P2})$	$B_2^j(\text{C2}) + D_2^j(\text{P2, C2})$	$B_5^e(\text{C5})$

Table 14.2.: Receiver code biases according to tracking scenario in Figure 14.1 to obtain ionosphere linear combination of P1 and P2 as the reference.

Receiver Reference		Rec. k $B_{3k}(\text{P1,P2})$	Rec. l $B_{3l}(\text{P1,P2})$	Rec. m $B_{3m}(\text{P1}_G, \text{P2}_G)$
GPS i	OBS 1	$B_{1k}(\text{P1})$	$B_{1l}(\text{P1})$	$B_{1m}(\text{C1}) + D_{1m}(\text{P1, C1})$
	OBS 2	$B_{2k}(\text{P2})$	$B_{2l}(\text{P2})$	$B_{2m}(\text{P2})$
GPS j	OBS 1	$B_{1k}(\text{P1})$	$B_{1l}(\text{P1})$	$B_{1m}(\text{C1}) + D_{1m}(\text{P1, C1})$
	OBS 2	$B_{2k}(\text{P2})$	$B_{2l}(\text{C2}) + D_{2l}(\text{P2, C2})$	$B_{2m}(\text{C2}) + D_{2m}(\text{P2, C2})$
GNSS e	OBS 1			$B_{1m}(\text{C1}) + D_{1m}(\text{P1}_G, \text{C1}_E)$
	OBS 2			$B_{5m}(\text{C5}) + D_{2m}(\text{P2}_G, \text{C5}_E)$

signal frequency is the same for GPS and Galileo. Nevertheless, $B_{1m}(\text{C1})_{GPS}$ cannot be assumed to be the same as $B_{1m}(\text{C1})_{Galileo}$ because the receiver has to handle two completely different signals (from different GNSS). This will result again in different hardware delays. Using GPS as a reference, the inter-system bias (ISB) for the receiver m can be written as $B_{1m}(\text{C1})_{Galileo} - B_{1m}(\text{C1})_{GPS}$. If the case between GPS and GLONASS is considered, a part of the ISB can also be addressed for differences in the signal frequency.

14.1.2. Different Receiver Classes

We have to distinguish between three receiver classes:

1. **P1/P2** receivers providing C1, P1, P2
(it is common practice to disregard C1 code data)
2. **C1/X2** so-called cross-correlation (CC) receivers providing C1 and a particular linear combination of code observables (denoted here with X2),
3. **C1/P2** modern generations of receivers providing C1 and P2
(some receivers also provide C2 instead of P2 from the GPS Block IIR-M and Block IIF satellites).

The grouping of the receiver tracking technology can be found in the file $\${X}/\text{GEN}/\text{RECEIVER}$. (available for all receiver types used in CODE's processing at <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>). It has to be noted, that today, there are also GNSS receiver types that must be attributed to two classes: C1/P2 for GPS and P1/P2 for GLONASS. Because an ISB needs to be estimated for each receiver between GPS and GLONASS, the corresponding DCB will also be absorbed in this bias parameter. Conse-

quently, the entries in this receiver information file have to refer to the tracking technology for the GPS measurements.

14.1.3. Differences of Code Biases

Instrumental biases, B_{C1} , B_{P1} , B_{P2} , are present with respect to C1, P1, P2. As it was demonstrated in Section 14.1.1, these biases are not accessible by their absolute values. It is common to consider the following differences of code biases:

$$\begin{aligned} B_{P1} - B_{P2} &= B_{P1-P2} , \\ B_{P1} - B_{C1} &= B_{P1-C1} , \text{ and} \\ B_{P2} - B_{C2} &= B_{P2-C2} , \end{aligned}$$

where B_{P1-P2} , B_{P1-C1} , and B_{P2-C2} are called *Differential Code Bias (DCB)*. B_{P1-P2} is addressed in GPS-ICD (1993) as *group delay*, τ_{GD} (see also Wilson et al. 1999). The relation between τ_{GD} and B_{P1-P2} may be given as:

$$\tau_{GD} = -1.55 \cdot B_{P1-P2} + B_0, \quad (14.2)$$

where B_0 is an arbitrary offset (irrelevant to our applications).

The two bottom plots in Figure 14.2 show the order of magnitude of B_{P1-P2} DCB values for the current GPS and GLONASS satellite constellation. These values are a by-product from the global ionosphere analysis performed at CODE. One can see that the order of magnitude for GPS and GLONASS satellites is comparable. It is remarkable that for GPS the P1–P2 DCB values are clearly dependent on the satellite type: the latest generation of Block IIF satellites have negative values whereas the all older satellites have positive values. The values for the Block IIR–B satellites are significantly bigger than those for the remaining three types for GPS. The variation within each group is below 5 ns (corresponding to about 8 TECU).

The B_{P1-C1} (middle row in Figure 14.2) and B_{P2-C2} (top row of Figure 14.2) DCB values are shown as well. Compared with B_{P1-P2} values, the order of magnitude of these values is approximately 3 times smaller: the minimum–to–maximum value is about 4 nanoseconds. Nevertheless, expressed in units of wide–lane cycles, this corresponds to a maximum inter–satellite B_{P1-C1} DCB of 1.4 cycles.

For GPS a satellite type dependent behaviour is again observable (but less clear because of the smaller order of magnitude). The P1–C1 DCB for the Block IIR–M and Block IIF satellites have bigger values than the older satellite types. Because the C2 signal in case of GPS is only provided by the most recent two satellite types, the P2–C2 biases cannot be computed for all satellites. The bigger variation of the P1–C1 and P2–C2 for GLONASS satellites may be a result from the frequency dependence of the satellite and receiver hardware.

The day–to–day reproducibility has a RMS of around 0.05 nanoseconds (for satellite bias retrievals responding to B_{P1-C1}). Finally, it should be stated that it is common practice to impose a zero–mean condition on the set of DCB estimates (with respect to each GNSS) for datum definition because the receivers are not calibrated regarding the DCB–related hardware delays (or at least this information is not publicly available). This implies that DCB results may be shifted by a common offset value, B_0 (cf. Eqn. (14.2)).

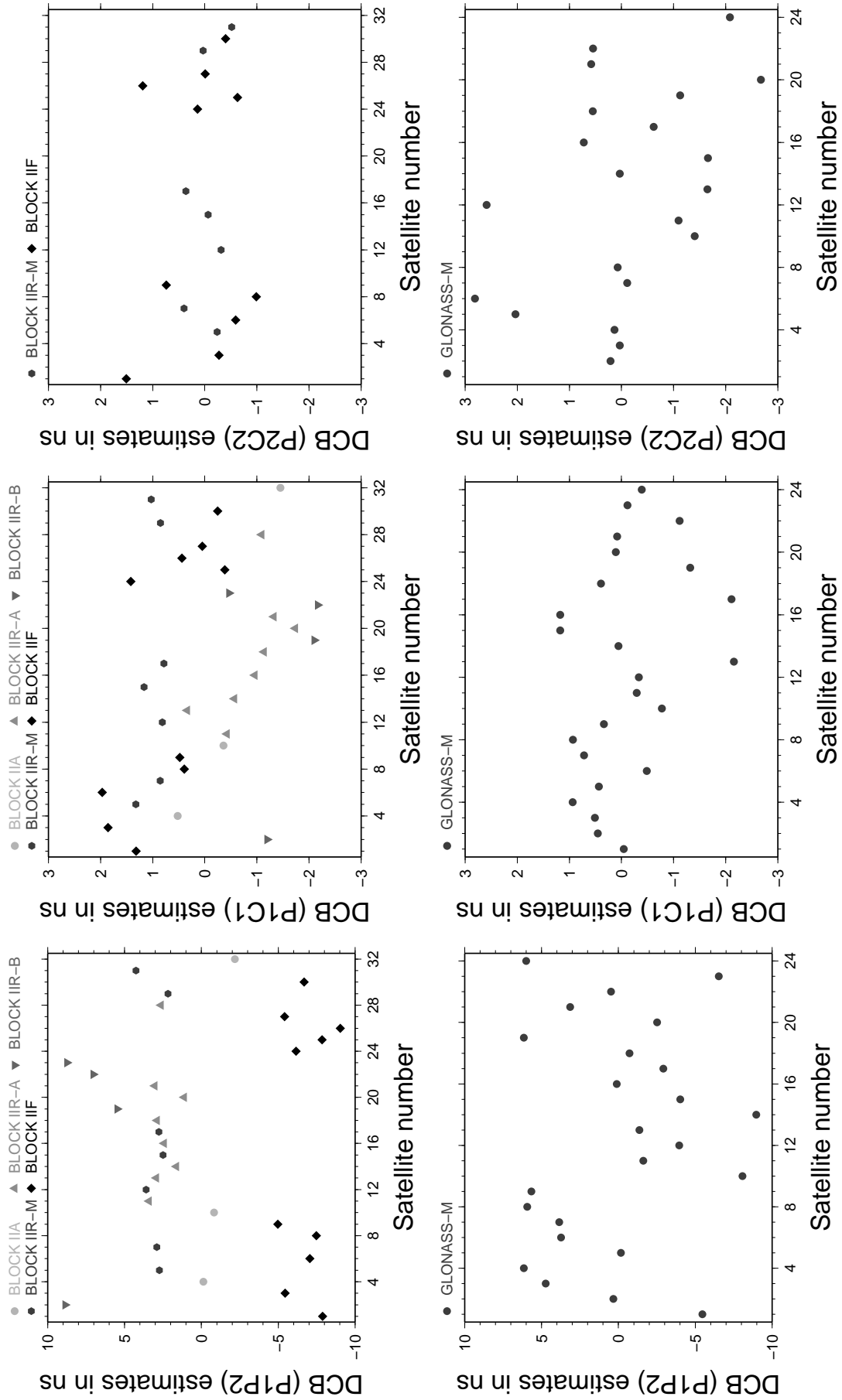


Figure 14.2.: Different types of DCBs from CODE processing (October 2015) for GPS (top plots) and GLONASS (bottom plots) satellites.

14.2. Correcting for Differential Code Biases

14.2.1. Differential Code Biases and Linear Combinations

By convention, IGS precise satellite clock corrections have to be consistent with respect to the P1 and P2 observables. This implies that each clock correction contains the ionosphere-free linear combination of (unknown) B_{P1} and B_{P2} biases, i.e., $2.55 \cdot B_{P1} - 1.55 \cdot B_{P2}$. The same is also true regarding the GPS broadcast satellite clock information.

It is obvious that code tracking data from both the C1/X2 and the C1/P2 receiver class must be corrected in order to achieve full consistency with P1/P2 data, or precise satellite clock information. On the basis of B_{P1-P2} and B_{P1-C1} DCB values for the GPS/GLONASS satellite constellation, corrections may be derived for the three receiver classes initially introduced.

Table 14.3 summarizes the necessary DCB corrections for six different linear combinations derived from the available code observables. As expected, no DCB correction is needed for the ionosphere-free (L3) linear combination of P1/P2 code data. To correct the (commonly used) L3 linear combination of C1/X2, or C1/P2, just a correction specific to the B_{P1-C1} (not B_{P1-P2}) DCB is necessary.

Table 14.3 includes also the single-frequency (C1) case (see L1 for C1/X2 or C1/P2). The DCB correction in that case is not only $-\tau_{GD} = +1.55 \cdot B_{P1-P2}$ as suggested by GPS-ICD (1993) (cf. Eqn. (14.2)) but it may also include an additional correction term responding to $+B_{P1-C1}$ for some of the receiver groups.

For the geometry-free (L4) linear combination, the B_{P1-P2} DCB (a synonym for τ_{GD}) plays an important role, specifically with respect to the satellites observed as well as the involved receivers. In case of GPS/GLONASS-combined receivers, two receiver-specific bias values must be considered, one related to GPS and one related to GLONASS. From our experience, GPS or GLONASS receiver bias values for B_{P1-P2} should not exceed the level of few tens of nanoseconds. Corresponding estimates for all IGS stations processed at CODE can be found at <http://www.aiub.unibe.ch/ionosphere> (Schaer 1998).

The so-called Melbourne-Wübbena linear combination is essential for ambiguity resolution (particularly on long baselines). Even when analyzing double-differenced data, the effect

Table 14.3.: Corrections due to the satellite-specific P1-P2 and P1-C1 code bias values for the most important linear combination (LC) derived from various combinations of code observable types.

LC	P1/P2	C1/X2=C1+(P2-P1)		C1/P2	
L_1	$+1.546 \cdot B_{P1-P2}$	$+1.546 \cdot B_{P1-P2}$	$+B_{P1-C1}$	$+1.546 \cdot B_{P1-P2}$	$+B_{P1-C1}$
L_2	$+2.546 \cdot B_{P1-P2}$	$+2.546 \cdot B_{P1-P2}$	$+B_{P1-C1}$	$+2.546 \cdot B_{P1-P2}$	
L_3	0		$+B_{P1-C1}$		$+2.546 \cdot B_{P1-C1}$
L_4	$-B_{P1-P2}$	$-B_{P1-P2}$		$-B_{P1-P2}$	$+B_{P1-C1}$
L_5	$-1.984 \cdot B_{P1-P2}$	$-1.984 \cdot B_{P1-P2}$	$+B_{P1-C1}$	$-1.984 \cdot B_{P1-P2}$	$+4.529 \cdot B_{P1-C1}$
L_6 (MW)	$-1.984 \cdot B_{P1-P2}$	$-1.984 \cdot B_{P1-P2}$	$-B_{P1-C1}$	$-1.984 \cdot B_{P1-P2}$	$-0.562 \cdot B_{P1-C1}$

$$f_2^2/(f_1^2 - f_2^2) = 1.546$$

$$f_1^2/(f_1^2 - f_2^2) = 2.546$$

$$f_1 f_2/(f_1^2 - f_2^2) = 1.984$$

$$f_1/(f_1 - f_2) = 4.529$$

$$f_1/(f_1 + f_2) = 0.562$$

of B_{P1-C1} does *not* cancel out in case of a receiver network consisting of more than one receiver class! In consideration of this fact, it is actually possible to produce “ambiguity-fixed” B_{P1-C1} results. Such a refined DCB product is generated at CODE as part of the MW ambiguity resolution process.

14.2.2. Relevance of Differential Code Biases

From the previous section and the Table 14.3 it can be derived which of the DCBs are relevant for which standard application:

- Positioning based on C/A-code measurements only.
- Precise clock estimation (or time transfer) as soon as P1/X2 or C1/P2 receiver models are involved.
- Ionosphere analysis relying on (raw or smoothed) GNSS code measurements.
- Ambiguity resolution using the Melbourne–Wübbena linear combination, if you have baselines involving two different receiver models.

The necessary corrections due to DCBs are automatically computed and applied to the observations in all relevant processing programs in the *Bernese GNSS Software*, provided that a DCB input file is specified in the corresponding input panel.

Monthly mean values of all relevant DCBs are available at <http://www.aiub.unibe.ch/download/CODE/>. They can be introduced for different applications according to Table 14.3. It is even possible to combine the different files into one file containing all potential DCBs (P1–P2 and P1–C1, see Section 24.6.12). The software is computing the correction for the receiver type automatically. As mentioned above, the receiver tracking technology is reported in the receiver information file $\${X}/GEN/RECEIVER$. (description in Section 24.3.6).

14.2.3. Correcting P1–C1 Code Biases on RINEX Level

Within IGS, it is common to use `cc2noncc` to convert “CC” data (obtained from C1/X2 or C1/P2 receivers) into “non-CC” data (conform to P1/P2 data). `cc2noncc` is an easy-to-use tool (developed by Jim Ray) that applies corrections due to GPS P1–C1 code biases directly to RINEX observation files. The interested reader is referred to <https://goby.nrl.navy.mil/IGStime/index.php#P1-C1/> and Ray (2000, 2001). For users of the *Bernese GNSS Software* consideration of the RINEX utility program `cc2noncc` is not necessary since P1–C1 corrections are comfortably handled by `GPSEST`.

14.3. Determination of GNSS Code Biases

14.3.1. Direct Estimation from RINEX Observation Files

If P1 and C1 or P2 and C2 observations are both available in parallel, the related P1–C1 and P2–C2 DCBs can directly be estimated (as, e.g., described and applied by Gao et al. 2001; Jefferson et al. 2001). In that case it must be considered that both, the receiver and the satellite, contribute to each difference of the P1 minus C1 or P2 minus C2 observation. In case of the receiver DCB, an independent value for each GNSS needs to be established as concluded in Section 14.1.1.

The results are reported in diverse Bernese formatted DCB files in the `ORB` directory of the campaign.

Please note that this implementation was distributed with Version 5.2 of *Bernese GNSS Software* on an experimental status. The extension to other DCBs (e.g., P1–P2 when introducing the influence of the ionosphere) is under development.

14.3.2. Estimating P1–P2 Code Biases

Based on Table 14.3, one may draw the conclusion that the geometry-free (L4) linear combination is the most appropriate linear combination for accurate P1–P2 code bias retrieval. P1–P2 DCB values are computed while solving for ionosphere parameters (see also Chapter 13). Remark: it should be clear that B_{C1-P2} (not B_{P1-P2}) will result as receiver bias in case of C1/P2 receiver models.

Note: Extraction of GPS τ_{GD} values is possible using `RXNBV3`. τ_{GD} values are exported as B_{P1-P2} values in form of a DCB file.

14.3.3. Estimating P1–C1 Code Biases

The estimation of P1–C1 DCBs with *Bernese GNSS Software* Version 5.2 is based on the ionosphere-free (L3) linear combination in the course of a global GNSS clock analysis. We solve for (satellite-specific) B_{P1-C1} parameters together with the epoch parameters corresponding to satellite and receiver clock offsets (Schaer 2000). The partial derivatives with respect to these satellite DCB parameters are exactly the factors as gathered from the L3 row of Table 14.3: 0, or undefined for P1/P2, -1 for C1/X2, and -2.55 for C1/P2. Obviously, a “mixed” receiver network is indispensable for our method.

The main advantage of this approach (with respect to the direct estimation described in Section 14.3.1) is that the resulting P1–C1 DCB estimates directly reflect the code bias differences between the three receiver classes as seen by an analysis center in its clock estimation procedure. In other words, the bias values are estimated directly from the data sets for which they will be applied. We do not make use of C1 code measurements from P1/P2 receivers (providing C1/P1/P2).

14.3.4. Verification of the Receiver Tracking Technology

A special application of the P1–C1 bias parameter estimation is the possibility to verify which of the three receiver classes a particular receiver model may be attributed to. The principle is relatively simple: instead of solving for B_{P1-C1} parameters, these parameters are assumed to be known and one common factor is set up as unknown parameter (called “P1–C1 DCB multiplier”) for each single receiver.

Figure 14.3 shows an excerpt of a corresponding `GPSEST` output file. The line starts with the station name and the indicator for the GNSS. The estimated factor and its formal uncertainty can be found in the third and fourth column. A factor close to 0 indicates a P1/P2 receiver, a factor around 1 a C1/X2 receiver, and, with an expected factor of 2.55, identification of C1/P2 is utmost reliable (Schaer 2002). This conclusion is reported in the fifth column of the output. If the estimate for the factor is not reliable enough, it is indicated by `?1/?2`, like in the example of `WTZZ 14201M014` in the Figure 14.3. At the end

```

=====
PART 6: VERIFICATION OF RECEIVER TRACKING TECHNOLOGY
=====
GANP 11515M001  -G   2.824   0.021   C1/P2  13.001  85.134   TRIMBLE NETR8      C1/P2  OK
HERT 13212M010  -G   2.502   0.019   C1/P2   2.334  79.790   LEICA GRX1200GGPRO C1/P2  OK
JOZ2 12204M002  -G   2.487   0.024   C1/P2   2.426  61.770   LEICA GRX1200GGPRO C1/P2  OK
LAMA 12209M001  -G   2.545   0.020   C1/P2   0.060  75.743   LEICA GRX1200GGPRO C1/P2  OK
MATE 12734M008  -G   2.453   0.025   C1/P2   3.743  58.406   LEICA GRX1200GGPRO C1/P2  OK
ONSA 10402M004  -G   0.316   0.023   P1/P2  14.007  30.259   JPS E_GGD          P1/P2  OK
PTBB 14234M001  -G  -0.097   0.027   P1/P2   3.606  40.710   ASHTECH Z-XII3T    P1/P2  OK
TLSE 10003M009  -G   2.850   0.023   C1/P2  13.315  80.905   TRIMBLE NETR5      C1/P2  OK
WSRT 13506M005  -G  -0.092   0.022   P1/P2   4.102  48.655   AOA SNR-12 ACT     P1/P2  OK
WTZR 14201M010  -G   2.502   0.030   C1/P2   1.491  50.903   LEICA GRX1200GGPRO C1/P2  OK
WTZZ 14201M014  -G   0.335   0.023   ?1/?2  14.627  29.097   TPS E_GGD          P1/P2  OK
ZIM2 14001M008  -G   2.891   0.025   C1/P2  13.938  76.353   TRIMBLE NETR5      C1/P2  OK
ZIMM 14001M004  -G   2.607   0.021   C1/P2   2.895  76.470   TRIMBLE NETRS      C1/P2  OK

```

Figure 14.3.: Verification of the receiver tracking technology: excerpt of a PPP BPE processing summary file (PPP102070.PRC; output was shrunk for printing).

of the line you can find the receiver type and the corresponding receiver group as found in the receiver information file.

If you have a new receiver where you are not sure about the tracking technology, i.e., to which group it belongs, you may start with any assumption in the receiver information file. Run the PPP_DEMO.PCF example BPE (description in Section 23.4.1) on an observation file from a station using this receiver and check this part of the protocol. Now you are able to check and occasionally correct the entry in the receiver information file.

14.3.5. Estimating DCBs in GPSEST and ADDNEQ2

To activate the estimation of DCBs in the program GPSEST, you have to enable the option “Differential code biases” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”. This will activate the panel “GPSEST 6.11: Differential Code Biases” (displayed in Figure 14.4), where you can select one particular DCB parameter type (P1–P2, P1–C1, or P1–C1_MULTIPLIER) to be set up.

All types of DCB parameters (apart from the P1–C1_MULTIPLIER) can be stored in NEQ files for combination, using the program ADDNEQ2. In panel “ADDNEQ2 1.2: Input Files 2” you may specify in “Differential code biases” to adjust the a priori values of the DCB param-

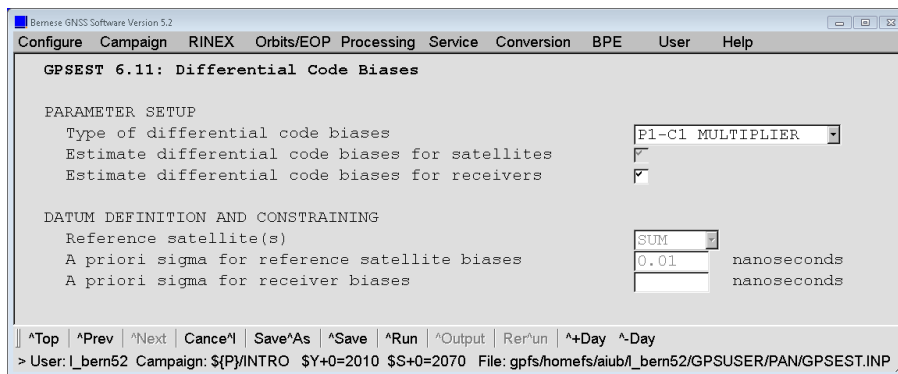


Figure 14.4.: Estimation of P1–C1 DCB multipliers in GPSEST.

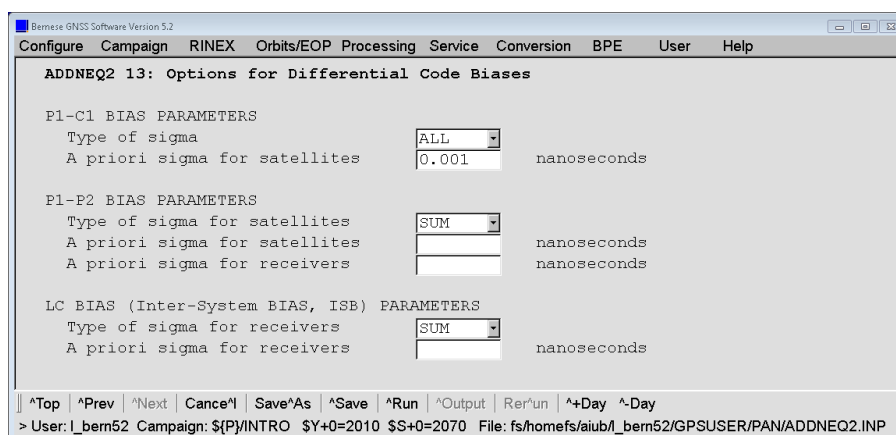


Figure 14.5.: Estimation of DCB parameters in ADDNEQ2.

eters. If you do not introduce a file there, the a priori values for the DCB parameters are transformed to zero.

This behavior is exceptional if you look at the general philosophy of handling a priori parameters in ADDNEQ2 (described in Section 9.3.4.1). On the other hand, it easily allows to establish a zero-mean condition choosing SUM for a specific type of DCB parameters in panel “ADDNEQ2 13: Options for Differential Code Biases” (see for instance option “P1-P2: Reference satellite(s)” in Figure 14.5). When introducing an a priori DCB file, the values can be considered with an absolute constraint as well (choose ALL as for example for option “P1-C1: Reference satellite(s)” in Figure 14.5).

14.4. GPS–GLONASS Inter–System Biases

14.4.1. GPS–GLONASS Code Biases

As introduced in Section 14.1.1 an ISB is introduced by the receiver — even if it is tracking signals on the same frequency but provided from different GNSS. Such a bias can be estimated by choosing LC in option “Type of differential code biases” (panel “GPSEST 6.11: Differential Code Biases”, displayed in Figure 14.4). This bias is considering one bias (typically referring to the ionosphere-free linear combination) per receiver. Whether a DCB should be applied as well, because a receiver is not using the defined reference signal, does not matter because the parameter absorbs only the sum of all biases. It might only become relevant if a receiver is providing two signals from one and the same satellite and different solutions are compared that have used a different set of these signals (see, e.g., Dach 2012).

In case of GLONASS the situation is even more complicated because of the FDMA. As Figure 15.4 in Section 15.2.2 demonstrates, each frequency channel is asking for an individual bias. That means that in the end one individual inter-system bias has to be estimated per frequency (to make it more reliable, a bias per satellite is recommended). This bias sums up the ISB related to the receiver hardware installation (antenna, cable, receiver), the bias caused by the different frequencies used by the individual GLONASS satellites, and a potential DCB.

To enable this, the checkbox for option “GLONASS receiver clock biases” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” needs to be selected. This enables the parameter setup in the input field “Rclk.off: Parameter setup” in panel “GPSEST 6.8.1: Clock Estimation 1”. Section 15.2.2 provides more details.

14.4.2. Geometric GPS–GLONASS Inter–System Biases

In Chapter 18 it is discussed that the antenna characteristics depends on the GNSS — as well as the code biases. Typically, the receiver antenna calibrations for GPS are more reliable than those for GLONASS or any other system. If the calibration of the antenna phase center offset contains any deficiency for one out of two GNSS and only one common set of coordinates is estimated, the discrepancy remains in the system and may distribute into different parameters according to the least squares principle. For instance, in Dach et al. (2011b) it has been shown that the old antenna calibration model `IGS05.atx` had systematic differences between the GPS and GLONASS antenna phase center corrections.

To monitor and eventually compensate for such effects, the *Bernese GNSS Software* provides so called GNSS–specific translation parameters. The principle is to estimate a translation vector per station between the GPS and GLONASS coordinates. If the geodetic datum definition is performed according to the standard procedure (described in Section 10.2.2) only the GPS related coordinates are effected.

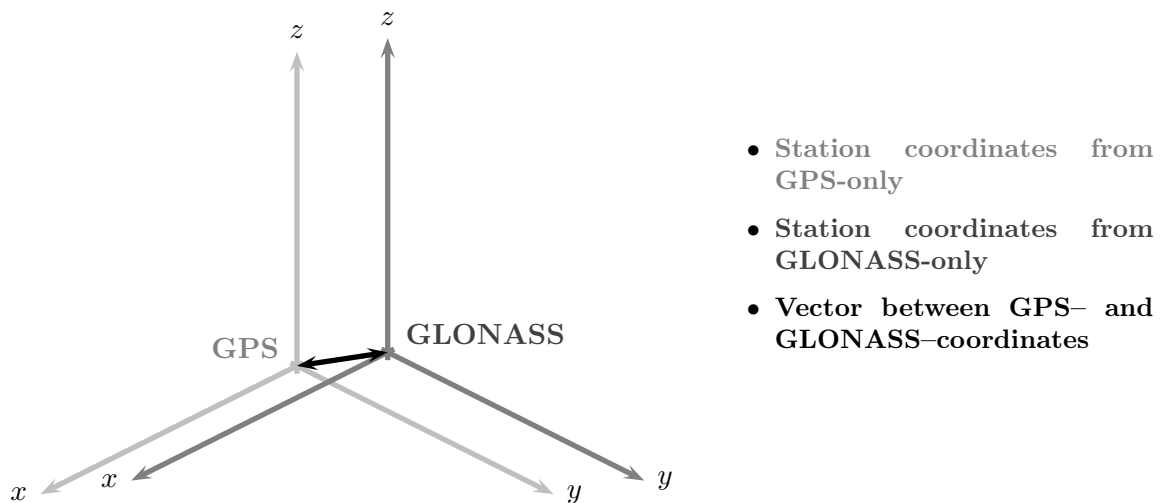


Figure 14.6.: Principle of GNSS–specific translation parameters in *Bernese GNSS Software*.

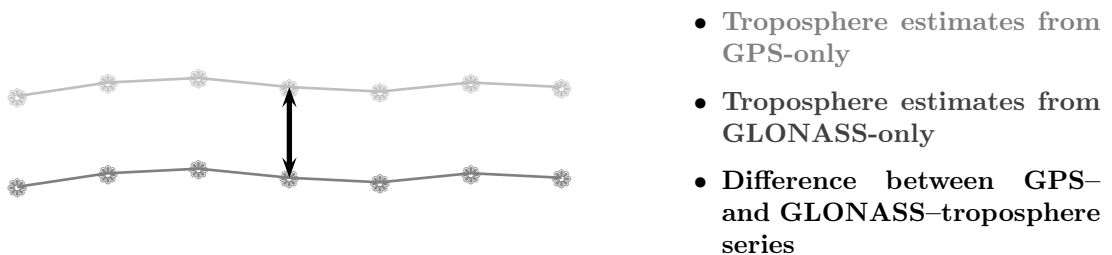


Figure 14.7.: Principle of GNSS–specific troposphere parameters in *Bernese GNSS Software*.

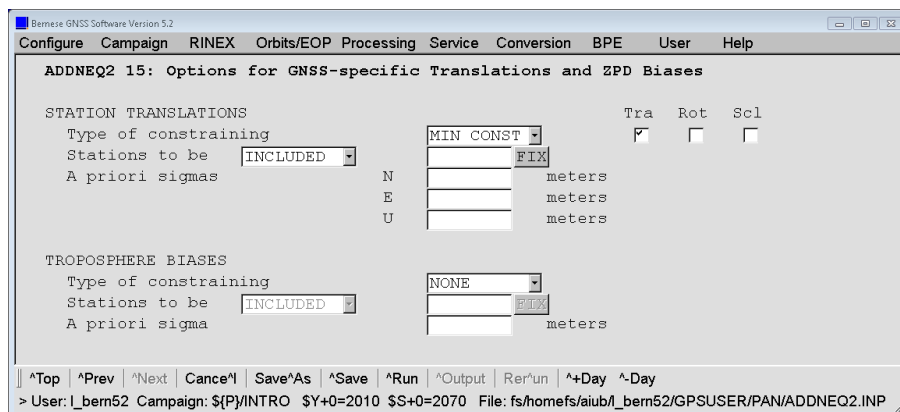


Figure 14.8.: Estimation of GNSS-specific translation and troposphere Biases in ADDNEQ2.

The datum definition for the differential vectors between GLONASS and GPS needs to be done separately using the features in option “GNSS-specific station translation: Datum definition” (panel “ADDNEQ2 15: Options for GNSS-specific Translations and ZPD Biases” displayed in Figure 14.8). Typically the MIN_CONST is a proper choice, where the degrees of freedom apply on the similar way as for the geodetic datum definition. This condition is applied to all stations supporting both systems unless a different specification in option “GNSS-specific station translation: In-/Exclusion” is used. In this way this parameter definition is independent from the availability and distribution of reference frame stations supporting both GNSS.

GNSS-specific parameters:							

Station name	Sys	Typ	A priori value	Estimated value	Correction	RMS error	

ABMF 97103M001	GLO	X	0.00000	-0.00480	-0.00480	0.00122	
		Y	0.00000	-0.00051	-0.00051	0.00208	
		Z	0.00000	-0.00070	-0.00070	0.00089	
	U	U	0.00000	-0.00197	-0.00197	0.00243	
		N	0.00000	-0.00015	-0.00015	0.00052	
		E	0.00000	-0.00446	-0.00446	0.00065	
		T	0.00000	0.00083	0.00083	0.00068	
ALBH 40129M003	GLO	X	0.00000	0.00510	0.00510	0.00081	
		Y	0.00000	0.00287	0.00287	0.00107	
		Z	0.00000	-0.00455	-0.00455	0.00132	
	U	U	0.00000	-0.00686	-0.00686	0.00172	
		N	0.00000	0.00087	0.00087	0.00055	
		E	0.00000	0.00267	0.00267	0.00055	
		T	0.00000	0.00070	0.00070	0.00047	

Figure 14.9.: GNSS-specific bias parameters in the ADDNEQ2 program output.

Whereas a GNSS-specific deficiency in the receiver antenna calibration is degrading the coordinate estimation, a deficiency in the receiver antenna pattern may mainly be absorbed by troposphere delay estimates (discussed in Chapter 12). For that reason also one bias parameter per station may be set up between a GPS and a GLONASS derived set of troposphere parameters. The principle is illustrated in Figure 14.7.

The reporting of the parameter estimates in the GPSEST or ADDNEQ2 program output is quite self-explaining. An example is given in Figure 14.9. The magnitude of a few

millimeters is a typical value and can repeated from week to week very well — even below the millimeter level.

Even if these parameters are mainly motivated by monitoring the quality of receiver antenna calibration, also system–specific multipath or even system–specific receiver characteristic contribute. In this way these parameters are a useful tool to identify or exclude potential system–specific problems with the GNSS equipment.

15. Clock Estimation

15.1. Introduction

According to the observation equations (2.20) the terms $c\delta_k$ and $c\delta^i$ are defined as the corrections of the receiver and satellite clocks with respect to GPS time. For most applications these parameters are a huge number of uninteresting unknowns. By forming double-differences of the observations (see Eqns. (2.21)) the clock parameters are eliminated.

Other applications such as time transfer using GNSS measurements require that these clock parameters are estimated instead of being pre-eliminated by forming double-differences. If, e.g., some of the receivers (k and ℓ) in the network are connected to “well defined” clocks (e.g., at time laboratories) the estimated clock parameters may be compared ($\delta_k - \delta_\ell$). If the internal receiver clock, for which the clock parameters δ_k are estimated, can be measured with respect to another clock or to UTC(k) of the time laboratory the difference UTC(k)–UTC(ℓ) can be obtained for each epoch where clock parameters are estimated. In a network solution all contributing clocks can be compared in this way epoch by epoch. If the internal receiver clock is driven by an external clock but the difference is unknown (but constant) then the estimates for the receiver clock δ_k can be used for frequency transfer.

Together with the receiver clocks the satellite clock parameters are estimated, as well. In this way you get a consistent set of receiver and satellite clocks for each epoch. The satellite clock corrections are interesting, e.g., for a PPP (see Section 10.6). Introducing the satellite clocks together with the consistent orbit and ERP-information, the position (or epoch-wise kinematic positions) as well as the epoch-wise receiver clock parameters of a single station may be computed. The results are consistent with the solution that produced the satellite orbit, the ERP information, and the satellite clocks.

Only differences between receiver and satellite clock parameters ($c\delta_k - c\delta^i$) appear in the observation equations (2.20). It is, therefore, only possible to solve for the clock parameters in a relative sense. Parameters for all but one clock may be estimated, i.e., either a receiver or a satellite clock has to be kept fixed. Alternatively an ensemble of clocks may be selected as a reference. Their sum of estimated clock corrections may be constrained using a zero-mean condition. The selected reference clock needs to be synchronized with respect to GPS system time (see Section 2.3.5). If you fix more than one reference clock (e.g., all satellite clocks in the case of a PPP) you must ensure that all these clocks are strictly consistent — they have to originate from one solution.

Precise Time and Frequency Transfer Using Phase Measurements

The phase observations are much more accurate than the code data and it is therefore preferable to use them for the estimation of clock parameters. The problem of using

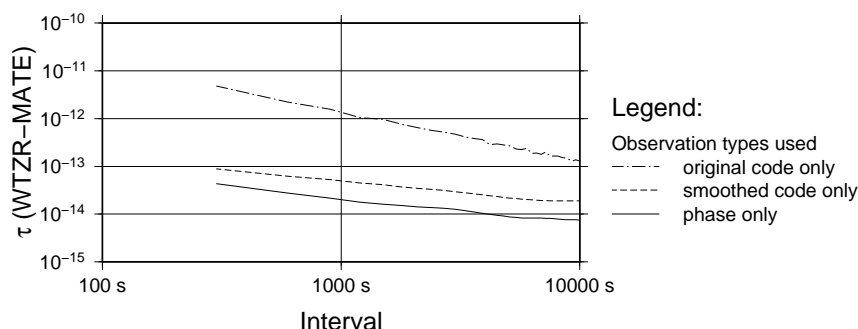


Figure 15.1.: Allan variance for the time transfer between WTZR and MATE for day 10–2070 using original code, smoothed code, and phase observations for the clock estimation.

the phase data for time transfer is the one-to-one correlation between the clock parameters ($c\delta_k$ and $c\delta^i$) and the initial phase ambiguity λn_k^i , which is evident from the observation equations (2.20). This correlation prevents direct access to the clock parameters when only carrier phase measurements are used. As a consequence, the initial phase ambiguity parameter n_k^i absorbs the mean reading of the clock averaged over the measurement resp. analysis time interval. Only the change of clock values with respect to a reference epoch can be estimated from using exclusively carrier phase observations because the initial phase ambiguity cancels out by differencing measurements from successive epochs. This means that carrier phase alone can only be used for frequency transfer as long as phase ambiguities are connecting the epochs.

On the other hand, the pseudorange measurements have direct access to the clock parameters. It is, therefore, possible to use both observation types in a combined data analysis. The different accuracy levels of the two measurement types are taken into account by weighting the data in the parameter estimation procedure.

The same fact may also be explained in another way: In the observation equations the correction of the receiver (and satellite) clocks with respect to GPS system time δ_i (δ^k) not only contains the difference between the clock and GPS time but also the hardware delays¹. These delays may be different for pseudorange and phase observations. In the case of time transfer — i.e., when comparing two receiver clocks — the hardware delays for a satellite cancel out if it was observed from both stations at the same epoch.

In a time transfer solution using only the carrier phase observations the hardware delays will be absorbed by the initial phase ambiguities. For a pure pseudorange solution, on the other hand, the hardware delays remain in the clock parameters. A combined solution using phase and pseudorange observations is necessary (a) to compute the receiver clock parameters and (b) to take advantage of the high accuracy of the carrier phase observations.

To illustrate the benefit from using phase observations for time transfer, the final solution of the clock determination example from Version 5.2 is repeated four times: using only original code observations (dotted line in Figure 15.1), using only smoothed code observations (dashed line in same figure), and using only phase observations (solid line). The solution

¹“Hardware delay” is used in the sense of the constant part of the clock parameters in the GPS observation equations. It contains not only the real hardware delay — e.g., cable delays — but also a constant reading of the receiver (satellite) clock. The two cannot be distinguished by analyzing GPS data without changing the hardware configuration and introducing additional measurements.

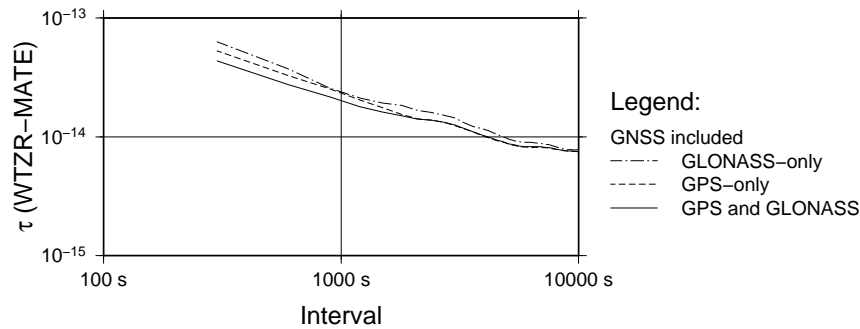


Figure 15.2.: Allan variance for the time transfer between WTZR and MATE for day 10–2070 using GPS-only, GLONASS-only, and observations from both systems together for the clock estimation.

using smoothed code and phase observations together is exactly underneath the solid line of the phase-only solution and is, therefore, not drawn. From all four solutions the clock differences between the station clock parameters for WTZR and MATE are extracted and their Allan variance is displayed in Figure 15.1. The improvement in the noise of the clock differences achieved by adding the phase observations is obvious.

At the same time, the benefit of additional satellites for the time transfer is demonstrated in Figure 15.2. For short intervals the additional observations from a combined GPS and GLONASS solution (solid line) help to improve the time transfer results compared to a single system solution, whereas for longer intervals other effects dominate.

15.2. Precise Clock Estimation

The clock estimation may be done in a GPS-only analysis. When processing GLONASS data by including the code measurements the receiver hardware delay is frequency dependent which results in the so called inter-frequency bias (IFB) (Dach et al. 2006a). In case of a combined processing of GPS and GLONASS observations the inter-system bias (ISB) is also relevant. All these possibilities are supported by the *Bernese GNSS Software*, Version 5.2. Specific aspects of processing GLONASS measurements are discussed in Section 15.2.2.

15.2.1. Epoch-Wise Clock Estimation in GPSEST

Clock corrections have to be estimated from zero-difference data. In GPSEST the clock parameters may be handled in two different ways:

- All clock parameters are estimated together with other parameters (e.g., station coordinates, troposphere parameters) in the main normal equation.
- The clock parameters are set up resp. pre-eliminated epoch by epoch. After solving the main normal equation (containing all non-epoch parameters) the resulting parameters are introduced and kept fixed when the epoch-parameters are estimated epoch by epoch in a back-substitution step. We refer to Section 7.6.2 for more details on the handling of epoch parameters.

The estimated clock corrections are identical in both cases. To obtain the correct covariance information for the resulting epoch parameters the back-substitution algorithm requires significantly more computing resources. Therefore, a simplified computation giving too optimistic formal accuracies is usually recommended (see Section 7.7.2).

The first strategy is preferable if only a small number of epoch parameters is requested (e.g., PPP with a sampling of 5 minutes for one day). The overhead generated by the epoch-wise pre-elimination and the back-substitution can be avoided in this case. The limitation is the number of parameters to be estimated in one normal equation system: With 15 stations observing on average 12 satellites, 27 parameters have to be estimated per epoch. Applying a 5 minutes sampling rate (i.e., 288 epochs per day) this yields 7776 clock parameters to be estimated. Even if the corresponding arrays are limited by default to `MAXPAR= 1000` in program `GPSEST`, an inversion of such a NEQ will take a considerable amount of computing time.

For the second strategy the number of parameters in the main normal equation is dramatically reduced and many more clock parameters may be estimated in one run of `GPSEST`. Here, the limitation results from the number of parameters to be estimated in the main normal equation (e.g., phase ambiguity parameters limit the processing to about 70 stations per day). This limitation is independent of the sampling rate.

A mixture of both algorithms for station and satellite clocks (e.g., `EVERY_EPOCH` for “Pre-elimination: Receiver clock offsets” and `NO` resp. `PRIOR_TO_NEQ_SAVING` for “Satellite clock offsets” in panel “`GPSEST 5.1: Setup of Parameters and Pre-Elimination 1`”) is possible, if necessary, for specific applications.

When processing code observations only (original or smoothed code, see Section 6.2.5) for the clock parameter estimation, no ambiguity parameters need to be introduced and the number of parameters in the main normal equation is reduced. In the extreme case all parameters apart from the clock corrections (e.g., station coordinates, troposphere parameters, orbits, ERPs, ...) are introduced from another program run (e.g., from a double-difference solution). In this case all epochs are completely independent and the solution thus becomes independent from the observation window used for the processing. In this case not only the estimates, but also their error values, are identical for all computation strategies because introducing all non-epoch parameters as known into `GPSEST` is equivalent to the simplified algorithm for computing the covariances based on the neglect of all non-epoch parameters.

For precise estimation of the clock parameters the use of the phase observations is indispensable (see Figure 15.1). They greatly improve the epoch-to-epoch accuracy of the solution for the clock parameters. As stated in the introductory section the correlation between the clock parameters and the phase ambiguities makes it necessary to analyze both observation types together (unless the goal is precise frequency transfer, only). Therefore, it is important that you select the corresponding “Phase observation files” and “Code observation files” in the input panel “`GPSEST 1.1: Input Files 1`”.

It is important that both code and phase binary observation files contain the same receiver clock corrections. The receiver clock corrections have to be stored by selecting `BOTH` in option “Save clock estimates” in panel “`CODSPP 2: Input Options`” of the program `CODSPP`. The program `GPSEST` uses the results from the receiver clock synchronization as a priori values for the station clock estimation but it does not check the consistency of the values in the two corresponding observation files. You may, however, provide an “Input clock RINEX

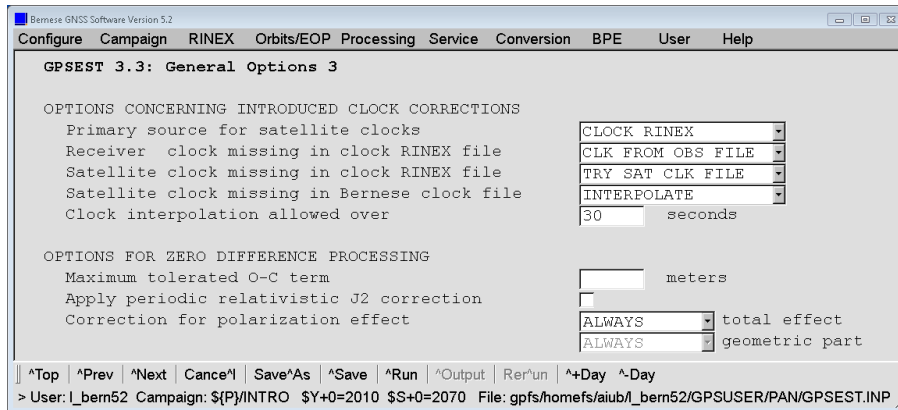


Figure 15.3.: Priority settings concerning introduced clock corrections in GPSEST.

file” with receiver clock information in panel “GPSEST 1.2: Input Files 2” and select the corresponding action in option “Receiver clock missing in clock RINEX file” in panel “GPSEST 3.3: General Options 3” (see Fig. 15.3).

It is recommended to introduce clock corrections as a priori even if clocks are estimated. This is meant for satellite as well as for receiver clock corrections. The satellite clock corrections may get values of up to 1 ms. If you do not introduce a priori information the estimates may become very big and the numerical reliability of the parameter estimation may no longer be guaranteed. The “Input clock RINEX file” may be used as an add-on to the “Satellite clock corrections” file here. The section “OPTIONS CONCERNING INTRODUCED CLOCK CORRECTIONS” in panel “GPSEST 3.3: General Options 3” (Figure 15.3) gives the opportunity to decide which of the files should be used as “Primary source for satellite clocks” and what should be done if “Satellite clock missing in clock RINEX file” and/or “Satellite clock missing in Bernese clock file”. If INTERPOLATE is selected for one of the options concerning missing input clocks, the option “Clock interpolation allowed over” becomes active and the clocks may be linearly interpolated up to the given value.

Specifying an “Input clock RINEX file” allows to introduce a clock solution from a previous program run. In that case, it is possible to omit the estimation of clock parameters. Of course, this limits the applicable options displayed in Figure 15.3. In such a setup, observations without sufficient clock information are typically not processed.

It is possible to perform the back-substitution of the pre-eliminated epoch parameters from phase data, only. Option “Epoch parameters only from phase” in panel “GPSEST 6.7: General Options for Epoch Parameters” has to be activated for this. This ensures that no “code-only” clocks are generated but also no residuals for the code measurements will be available.

The option “Periodic relativistic J2 correction” (Kouba 2004) in panel “GPSEST 3.3: General Options 3” (Figure 15.3) should only be activated if a clock model shall be applied for a satellite clock. Otherwise it is not needed, because according to IGS standard these corrections are *not* applied.

The input file “Differential code biases” in panel “GPSEST 1.1: Input Files 1” needs additional comments in the context of clock parameter estimation. As soon as you process data from receivers that do not provide P1 and P2 measurements, differential code biases need to be considered when estimating clock parameters. Specify the P1–C1 DCB corrections (provided at <http://www.aiub.unibe.ch/download/CODE/yyyy/P1C1yyymm.DCB>,

where $yyyy$ is the 4-digit year and $yymm$ the 2-digit year and month for the session you are processing). We refer to Chapter 14 for more details about the Differential Code Bias.

15.2.2. GLONASS Clock Estimation

The GLONASS clock estimation is possible in the *Bernese GNSS Software*. Special attention has to be given to the biases in and between the different GNSS. Figure 15.4 illustrates the connection between all the bias types:

Differential Code Bias (DCB): the difference in the hardware delays between P1–C1 and P2–C2, respectively (see Chapter 14 for a detailed discussion of this topic). They are present for GPS and GLONASS.

inter-frequency bias (IFB): is specific for GLONASS because each satellite emits the signal on an individual frequency. It reflects the frequency-dependency of the receiver hardware.

inter-system bias (ISB): responds to the difference in the GPS and GLONASS system time as well as system-specific hardware delays of the receivers.

In GNSS data processing, only the sum of these three biases can be assessed, e.g., by estimating one bias per GLONASS satellite with respect to all GPS satellites for each GPS/GLONASS tracking station.

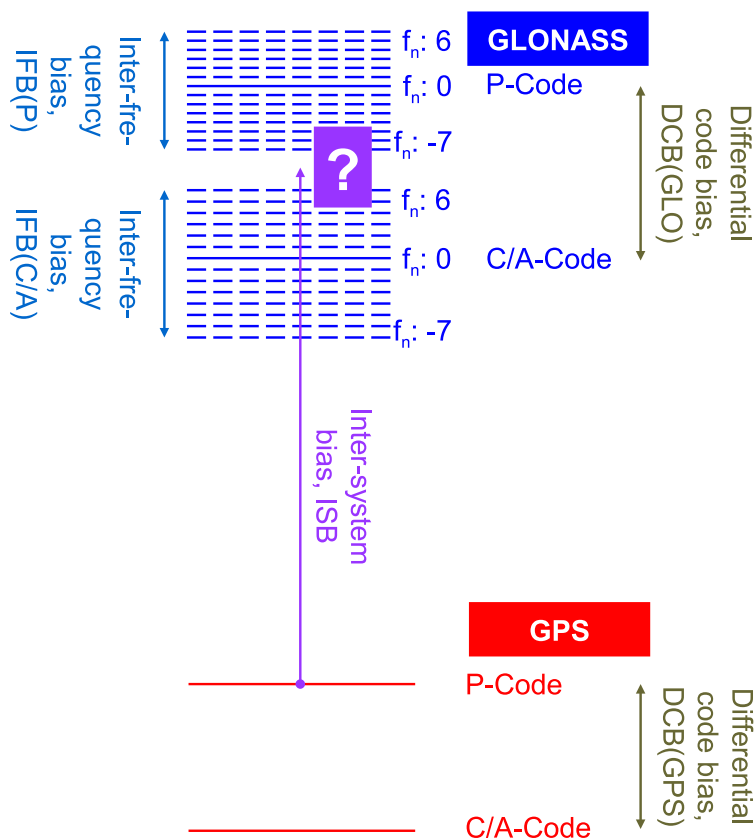


Figure 15.4.: Biases in a combined GPS/GLONASS analysis.

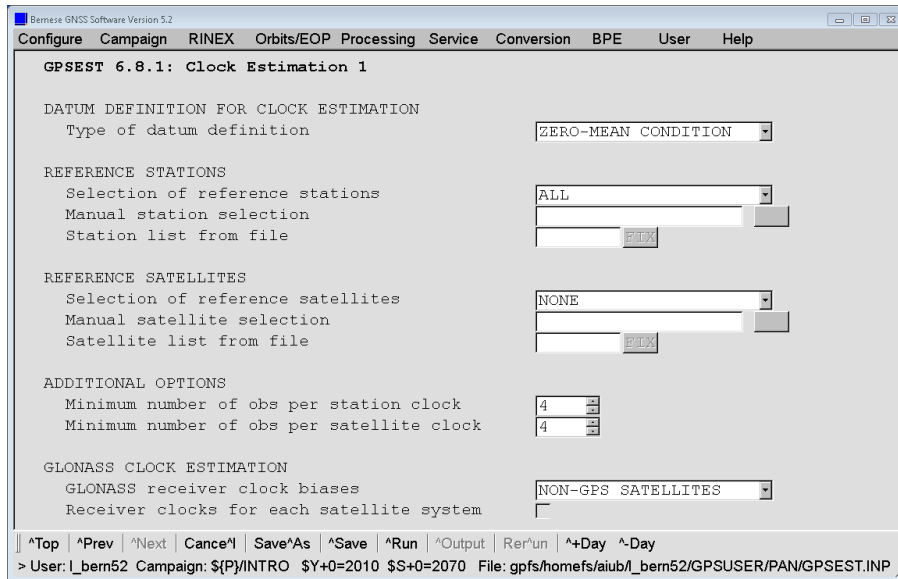


Figure 15.5.: Options for GLONASS clock estimation and an example for selecting the reference clock in the GPSEST program panel.

The co-estimation of GLONASS clock corrections has to be initiated in three different panels from GPSEST.

1. “GPSEST 3.1: General Options 1”: The “Satellite system” has to be set either to ALL or at least to GPS/GLO.
2. “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”: The “GLONASS receiver clock biases” have to be set up if they are not introduced from an input file.
3. “GPSEST 6.8.1: Clock Estimation 1” (Figure 15.5): The specification for the “Rclk.off: Parameter setup” has to be made with this option whereas the following possibilities are given:
 - NONE: No bias parameter is setup.
 - NON-GPS_SATELLITES: Individual bias parameters for each of the GLONASS satellite; no parameters for GPS satellites.
 - FREQUENCY_SPECIFIC: Common bias parameters for GLONASS satellites with the same frequency; no parameters for GPS satellites.
 - FREQ_SPEC_POLYNOM: Frequency-specific biases for GLONASS are represented by a polynomial (degree 4); this might be useful if the GLONASS constellation/network is weak; no parameters for GPS satellites.
 - SATELLITE_SPECIFIC: Bias parameters for each satellite (GPS and GLONASS).

The last case is the most general one. It is mainly intended for research purposes, because for GPS satellites no significant biases between the different satellites have been found so far. When processing GLONASS code measurements it is recommended to introduce biases for all NON-GPS_SATELLITES. This selection also allows for differences in the biases between the two GLONASS satellites using the same frequency number. The necessary zero-mean condition for the improvements of all relevant parameters is automatically applied.

The ISB/IFB may be stored and re-introduced in DCB-files. They can be estimated together with the usual DCB-parameters for GPS (e.g., P1-C1).

If the GLONASS clock estimation is done in clusters, one has to make sure that the IFB and ISB refer to the same satellite (and receiver) clock values. A re-sampled set of clock parameters (using, e.g., the option “Sampling rate for preelimination” in panel “GPSEST 6.7: General Options for Epoch Parameters”) may be stored from each cluster together with the bias parameters in a NEQ file. Program ADDNEQ2 is able to combine these parameters to obtain a unified set. The option “Inter-frequency bias, alarming limit” (panel “ADDNEQ2 14: Options for GLONASS Receiver Clock Biases”) provides a threshold to report potential inconsistencies in the IFB parameters between stations. The CLKDET.PCF example includes all necessary steps for a combined GPS/GLONASS clock estimation with clustering.

Instead of estimating ISB/IFB you may also estimate independent series of receiver clock corrections for GPS and GLONASS (option “Receiver clocks for each satellite system”). If you have selected a “Clock RINEX” file in panel “GPSEST 2.2: Output Files 2” in fact two files are generated: one containing the GPS clock solution and the other one with the GLONASS clock solution. The filename from the output file is extended by `_g` and `_r`, respectively.

15.2.3. Selection of the Reference Clock

The options for the reference clock selection in GPSEST may also be found in Figure 15.5. You have the possibility to select one or more stations or satellite clocks as reference for the clock estimation in options “Selection of reference stations” and “Selection of reference satellites”, respectively. There are two ways to realize the reference clock in GPSEST:

- No clock corrections are estimated for the selected reference clock(s). The a priori values are kept fixed. Select `REFERENCE_FIXED` in option “Type of datum definition”. If either “Receiver clock offsets” or “Satellite clock offsets” are selected for estimation in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” all clocks of the other type (satellite or receiver) are not setup for estimation and are kept fixed as reference.
- Clock corrections are estimated for all clocks including the reference clock(s). Instead of fixing the reference clock the sum of the estimates for all selected reference clocks is set to zero by selecting `ZERO-MEAN_CONDITION` in option “Type of datum definition”.

Fixing a reference clock makes sense, e.g., if you want to get the clock corrections with respect to a specific receiver clock. If the receiver clock for this particular station is not synchronized with CODSP the resulting clock corrections for this reference clock are set to zero. All computed clock corrections are differences to this reference clock which may be convenient in some cases. The pre-requirements for this approach are that the reference clock values are close enough to the GPS time (so that the receiver clock synchronization with program CODSP is not required) and the observation file contains measurements for all epochs because the estimation of clock corrections becomes singular for epochs without a reference clock.

In general it is preferable to choose a zero-mean condition for the clock correction estimates of an ensemble of reference station clocks. If an epoch is missing for a station the clock corrections for all other receivers can be computed. If, e.g., all receiver clocks are synchronized to GPS time scale with program CODSP then you may select all receiver clocks as reference independently from the performance of the receiver clocks. An alignment of the resulting clock corrections to an optionally selected reference clock can be carried out

later using program CCRNXC (see Section 15.3.4). The advantage of this is that no station fulfilling special requirements needs to be selected for the processing.

Instead of an ensemble of receiver clocks you may choose also the satellite clocks as reference. Be careful in this case when a satellite clock maintenance event takes place. You may use the program CODXTR to remove such satellites from the Bernese satellite clock files (see Section 6.3.4).

If parts in your network are not connected to the reference clock by observations to common satellites, the clock parameters in these parts are singular and no solution is available for these clocks. To apply the zero-mean condition in program GPSEST it is additionally required that no isolated parts exist in the network.

15.2.4. Program Output and Result Files

The program output of GPSEST has two sections for reporting the results of the estimation of clock corrections: A first section is dedicated to receiver clocks, a second section to satellite clocks. If the clocks are computed using the epoch-wise pre-elimination/backsubstitution algorithm then the clock values are ordered by time, otherwise the list is sorted by the clock names. Figure 15.6 shows the results in the program output for the processing example described in Section 23.4.4 for session 2050 in year 2011. Because this part of the program output may get very large you can enable the option “Printing: Suppression of output concerning epoch parameters” in panel “GPSEST 3.2.1.1: Extended Program Output Options” to skip this part of the program output.

The first part reports the receiver clock corrections. For each parameter one line is printed containing the following information:

TYPE and STAT	Internal numbering in GPSEST.
EPOCH (MJD)	Epoch of the clock parameter in modified Julian date.
STATION CLOCK VALUES (USEC)	
A PRIORI	A priori value of the clock from the observation file in microseconds.
CORRECTION	Estimated correction of the clock value in microseconds.
TOTAL	Total estimated clock correction in microseconds.
RMS (NSEC)	Formal error for the estimated parameter in nanoseconds.
#OBS	Number of observations contributing to the epoch parameter (code and phase observations are counted separately).
STATION	Name of the station following a #-character.

The second part lists the epoch-wise estimated satellite clock corrections. The program output is similar to the output for the station clocks (see Figure 15.6). Instead of the station name at the end of the line the satellite number is reported in the second column labeled by SAT. The a priori information for the satellite clock corrections is taken from the “Satellite clock corrections” file specified in panel “GPSEST 1.1: Input Files 1” or from the “Input clock RINEX file” file specified in panel “GPSEST 1.2: Input Files 2”. If you have specified both files this depends on your selection in section “OPTIONS CONCERNING INTRODUCED CLOCK CORRECTIONS” in panel “GPSEST 3.3: General Options 3”.

If the clock parameter is estimated in the main normal equation then the formal error (reported in column RMS(NSEC) of the program output) is computed, as usual, from the a posteriori covariance matrix. If the epoch-wise pre-elimination/back-substitution algorithm is activated and the option “Var-covar wrt epoch parameters” in panel “GPSEST 6.7: General Options for Epoch Parameters” is set to SIMPLIFIED, then the non-epoch parameters

```

EPOCH WISE STATION CLOCKS:
-----
TYPE STAT EPOCH(MJD) A PRIORI STATION CLOCK VALUES (USEC) TOTAL RMS(NSEC) #OBS STATION
-----
23 1 55766.000000 -0.032792 -0.000000 -0.032792 0.003 16 R # GAMP 11515M001
23 2 55766.000000 0.004650 0.000000 0.004650 0.003 16 R # HERT 13212M010
23 3 55766.000000 0.002998 0.000000 0.002997 0.003 16 R # J022 12204M002
23 4 55766.000000 0.010105 -0.000001 0.010104 0.003 15 R # LAMA 12209M001
23 5 55766.000000 -0.011506 -0.000001 -0.011507 0.003 14 R # MATE 12734M008
23 6 55766.000000 -19.813574 -0.000000 -19.813574 0.003 13 R # ONSA 10402M004
23 7 55766.000000 0.509855 -0.000004 0.509851 0.004 5 R # PTBB 14234M001
23 8 55766.000000 -0.019659 -0.000002 -0.019657 0.003 17 R # TLSE 10003M009
23 9 55766.000000 1.144958 -0.000000 1.144958 0.004 10 R # WSRT 13506M005
23 10 55766.000000 9.047588 0.000011 9.047598 0.003 17 R # WTRZ 14201M010
23 12 55766.000000 -0.026246 -0.000005 -0.026251 0.003 17 R # ZIM2 14001M008
23 13 55766.000000 0.029136 -0.000000 0.029135 0.004 8 R # ZIMM 14001M004
23 1 55766.003472 -0.026989 -0.000000 -0.026989 0.003 16 R # GAMP 11515M001
23 2 55766.003472 0.003833 0.000000 0.003833 0.003 17 R # HERT 13212M010
...

EPOCH WISE SATELLITE CLOCKS:
-----
TYPE SAT EPOCH(MJD) A PRIORI SATELLITE CLOCK VALUES (USEC) TOTAL RMS(NSEC) #OBS
-----
24 11 55766.000000 -170.672801 -0.000000 -170.672801 0.003 12
24 14 55766.000000 163.235452 -0.000000 163.235452 0.006 9
24 17 55766.000000 181.504814 -0.000001 181.504814 0.006 11
24 19 55766.000000 -165.272666 -0.000000 -165.272666 0.010 9
24 20 55766.000000 50.990877 -0.000000 50.990877 0.003 11
24 23 55766.000000 289.593500 -0.000001 289.593500 0.008 11
24 24 55766.000000 409.172729 -0.000001 409.172728 0.002 12
24 28 55766.000000 54.133642 0.000000 54.133642 0.016 5
24 31 55766.000000 115.555063 -0.000001 115.555063 0.010 11
24 32 55766.000000 -297.265706 -0.000001 -297.265706 0.002 12
24 101 55766.000000 -180.897837 -0.000000 -180.897837 0.005 9
24 110 55766.000000 -243.278762 -0.000000 -243.278762 0.003 8
24 112 55766.000000 -91.877803 -0.000000 -91.877804 0.011 9
24 111 55766.000000 -75.220384 -0.000000 -75.220384 0.009 9
24 117 55766.000000 -263.732482 -0.000000 -263.732482 0.003 9
24 118 55766.000000 -33.333893 -0.000000 -33.333893 0.004 9
24 124 55766.000000 88.568858 -0.000000 88.568857 0.010 8
24 11 55766.003472 -170.673870 0.000000 -170.673870 0.003 13
...
    
```

Figure 15.6.: GPSEST program output from the processing example for the estimation of clock corrections (session 2050 in year 2011).

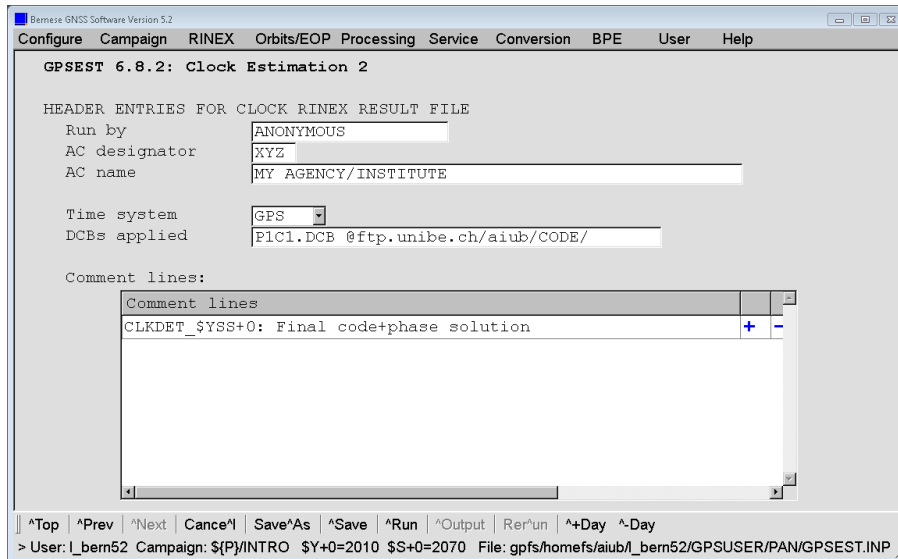


Figure 15.7.: Example of header entries for the resulting clock RINEX file.

are assumed to be free of errors when introduced from the solution of the main normal equation into the epoch solution. The RMS reported here is computed from the a posteriori covariance matrix of the epoch solution only. When the option “Var-covar wrt epoch parameters” is set to CORRECT the error propagation for the parameters introduced from the main normal equation into the epoch solution is included. The formal errors for the epoch parameters are then correct but the procedure is very time and memory consuming.

In the part EPOCH WISE STATION CLOCKS of the program output listed in Figure 15.6 the character R just after the number of observations indicates that the clocks are used as reference clocks. In this case the reference clock was realized by a zero-mean condition for all station clocks.

If either all station clocks or all satellite clocks are fixed (e.g., for a PPP) the corresponding part is not printed to the program output.

In the case of a local network (e.g., like in the processing example) not all satellites can be observed for each epoch. A minimum number of observations contributing to a clock parameter can be defined in the input panel separately for station and satellite clock parameters (see Figure 15.5). If fewer observations contribute to the clock parameter then the corresponding value is not written to the external clock file and is marked by an asterisk in the column containing the number of observations in the program output.

The program GPSEST is able to write the results of the clock parameter estimation to a clock RINEX formatted output file. The header information is taken from the input panel “GPSEST 6.8.2: Clock Estimation 2” (see Figure 15.7). Enter the correct name and identification of your institution here. The entries for “Time system” and “DCB line” are necessary in accordance with the clock RINEX format description and IGS standards.

Although the clock RINEX format is an international format for exchanging precise clock values, it is also used as an internal file format in the *Bernese GNSS Software Version 5.2*.

It is, e.g., officially not allowed to store clock values in the clock RINEX file when a zero-mean condition is used to realize the reference clock. In addition, clock corrections for satellites in eclipse are flagged with **E** for internal purposes. Clock RINEX files containing such internal features should, therefore, only be used within the *Bernese GNSS Software* and should not be distributed.

Using the program `GPSXTR` clock differences may be extracted for pairs of receiver and/or satellite clocks from a `GPSEST` program output containing clock correction estimates. More than one pair of clocks can be extracted at the same time if more than one pair of stations is specified in the “Pairs of clocks for clock summary” file specified in panel “`GPSXTR 2: Output Files`”. This file defines the pairs of clocks to be reported in “Clock summary: clock differences” and “Clock summary: Allan deviation”. More than one pair can be specified but both clocks must be provided in the same `GPSEST` program output because in the general case each individual `GPSEST` run may be based on an individual reference clock. The “Clock summary: Allan deviation”’s are computed from a series of clock corrections, which are extracted from the clock correction estimates in the `GPSEST` program output.

15.2.5. Precise Receiver Clock Synchronization

If you have a consistent set of satellite orbits, EOPs, and satellite clocks, e.g., as a result from a clock estimation following the processing example in Section 23.4.4, you can synchronize more station clocks to this set of clocks. This works in the same way as the Precise Point Positioning (PPP) described in the Section 10.6 and provided by the processing example (see Section 23.4.1).

Figure 15.8 demonstrates the consistency between the clock results for the station PTBB for session 2070 in year 2010 from a network solution (result from the example campaign in Section 23.4.4, file `{P}/DOCU_CLK/OUT/TP_102070.CLK`) and a precise receiver clock synchronization. All input options are taken from the last `GPSEST` run in the clock determination example. The only difference is that the resulting satellite clock corrections `{P}/DOCU_CLK/ORB/TP_102070.CLK` are introduced as fixed when performing the receiver clock synchronization for station PTBB (of course, only the observation files for PTBB are used instead of the entire network). Coordinates and troposphere parameters are introduced as known from a network solution (left) or recomputed together with the receiver clock corrections (right).

The left hand plot shows that the differences to the network solution are below one picosecond if the station coordinates and the troposphere parameters are fixed on the network

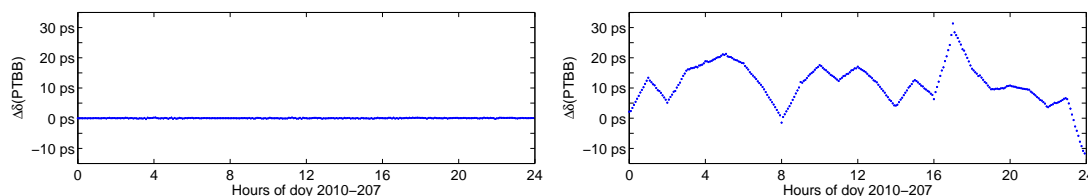


Figure 15.8.: Comparison of the precise receiver clock synchronization with the clock estimation from the corresponding network solution for the station PTBB, session 2070 in year 2010 from the example in Section 23.4.4.

In the left figure the coordinates and troposphere parameters are identical for the receiver clock synchronization and the network solution whereas in the right hand figure those parameters are recomputed independently for the receiver clock synchronization.

results. In general, however, the station coordinates and the site troposphere parameters need to be estimated as in the usual PPP approach. The results of this PPP and the coordinate results from the corresponding network solution (file $\${P}\}/\text{DOCU_CLK/STA/TP_102070.CRD}$) differ by $(-2.5, 0.4, +0.8)$ mm in the up, north, and east components. This corresponds to an offset in the estimated receiver clock of close to 10 ps which is reflected by the right hand diagram in Figure 15.8. An extended study of error propagation for time transfer using GPS can be found in Dach et al. (2003).

This procedure allows you to estimate precise receiver clocks, but it is not possible to include the results into the Bernese observation file. Therefore, this precise receiver clock synchronization cannot replace the synchronization based on the program CODSPP in the preprocessing step (see Section 6.3).

15.3. Clock RINEX Utilities in *Bernese GNSS Software* (RNXCLK and CCRNXC)

Four programs in the *Bernese GNSS Software* Version 5.2 write clock RINEX files:

CODSPP may store the used satellite clock corrections together with the estimated station clocks into a clock RINEX file (see Section 6.3).

GPSEST may save the results of the epoch-wise satellite/station clock estimation into a clock RINEX file (see Section 15.2).

CLKEST may be used for efficiently computing high-rate clocks (see Section 15.5).

CCRNXC manipulates clock RINEX files and may write the results into a clock RINEX file again.

In Version 5.2 the clock RINEX format is also used as the internal clock format of the *Bernese GNSS Software* if satellite and station clocks have to be stored together.

The program RNXCLK is a very simple program reading clock RINEX files and copying the values into corresponding Bernese satellite clock files (see Section 15.3.1). The program CCRNXC is the main clock RINEX utility of the *Bernese GNSS Software* and may be used to

- cut/concatenate clock RINEX files as well as to extract selected clocks from input files,
- merge or combine clock RINEX files,
- compare clock RINEX files,
- select a reference clock and align the clock values to this reference,
- detect jumps in the clock time series, and
- extrapolate clock time series.

This program has many options that are explained for some standard applications in the following sections.

15.3.1. Extracting Satellite Clocks from Clock RINEX Files

The extraction of satellite clock corrections from an input clock RINEX file and writing of a corresponding Bernese satellite clock file is very simple. It is done with the program

RNXCLK. Specify your clock RINEX files in option “Clock RINEX files” in panel “RNXCLK 1: Filenames”. The satellite clock values from each input clock RINEX file are copied without any modifications into a Bernese satellite clock file with the same name as the input file but in a different directory. By default clock RINEX files are located in the campaign’s OUT–directory while Bernese clock files are located in the ORB–directory.

15.3.2. Basic Processing of Clock RINEX Files

The basic function of the program CCRNXC is to read clock RINEX files generated by other Bernese programs or obtained from external sources. After manipulating the files the results are written again to a clock RINEX file. The satellite clocks may be stored in a Bernese satellite clock file as well.

Only the clock records for the user specified time interval (option “Use time window” in panel “CCRNXC 2: Clock/Epoch Selection for Processing”, see Figure 15.9) are read. If no time window is specified all records from the input files are imported. The output clock records are either initialized for the user specified time window or the total time interval covered by all selected clock RINEX input files.

An equidistant sampling of the epochs in the output clock file is imposed. It is either computed from the sampling of the input clock RINEX files or the user value from option “Sampling rate for clocks” in panel “CCRNXC 2: Clock/Epoch Selection for Processing” (see Figure 15.9) is used. If you specify a sampling in this input field it has to be compatible with the sampling in the input files. Only those records from the input files are processed for which an epoch in the output array is defined.

In the section “DEFINE A LIST OF CLOCKS TO BE PROCESSED” in panel “CCRNXC 2: Clock-/Epoch Selection for Processing” (see Figure 15.9) you may specify a subset of clocks to be processed. All other clocks are skipped when reading the input clock RINEX files. The only exception is that the reference clocks from all input clock RINEX files are processed if CCRNXC retains the reference clock from one of the input files for the output file (option “Retain the reference clock from an input file” in panel “CCRNXC 4: Select Program Functions, Program Output”, see Section 15.3.4 for more details).

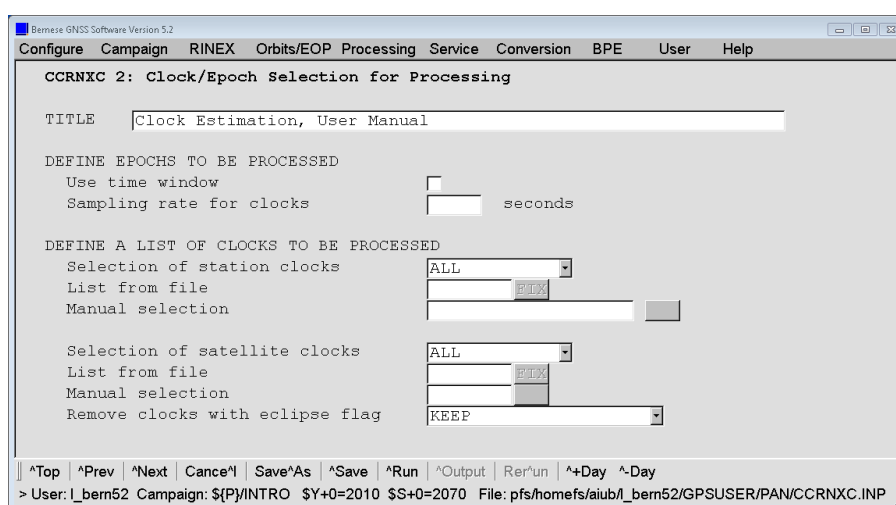


Figure 15.9.: Program input panel for selecting the clocks to be processed in program CCRNXC.

If the option “Statistic about the resulting clocks” in panel “CCRNXC 4: Select Program Functions, Program Output” is enabled, a summary table for the clocks is included in the program outputfile :

STATISTICS ON THE CLOCKS IN THE OUTPUT FILE						
Clock name	# per file		rms of poly. fit (ns)			
	out	001	n = 0	n = 1	n = 2	
WTZR 14201M010	288	288	2.177	0.000	0.000	
WTZZ 14201M014	286	286	2.168	0.016	0.016	
WSRT 13506M005	288	288	4.902	0.026	0.026	
ONSA 10402M004	288	288	11.568	0.038	0.027	
...						
G25	85	85	18.673	0.127	0.124	
G05	110	110	99.414	0.140	0.130	
G31	114	114	159.804	0.170	0.120	
G17	114	114	30.456	0.171	0.166	
...						

The table contains an entry for each station and satellite clock included in the output file. The number of epochs in the output file (column `out`) as well as in each of the input clock RINEX files (in this example only one input file 001 is available) is listed (Remember: If a time window was specified for the processing, the epochs outside the time window are ignored in the input clock RINEX files). The third part of this summary table reports the RMS of a low-order polynomial fitted to the clock values in the output file: For `n=0` only an offset is modeled, for `n=1` a linear clock model is applied, and for `n=2` a quadratic model is used to fit the clocks. The clocks may be sorted within the table (separately for station and satellite clocks) by the name (ALPHA) or by the RMS of the linear clock model listed in column `n = 1` (SIGMA), see option “Sort order for clock statistic” in panel “CCRNXC 4: Select Program Functions, Program Output”.

The option “Remove satellite clocks with eclipse flag” is needed to handle satellites with the eclipse flag “E”. This flag is set from the processing programs GPSEST, CLKEST, and CODSP for the corresponding satellites. The clock values for eclipsing satellites should be taken with care, because there is an uncertainty of the attitude behavior for the eclipsing phase. This flag is, however, not in conformance with the official clock RINEX format and one has to select either `REMOVE_FLAG_ONLY` or `REMOVE_ALL_RECORDS` before writing an output clock RINEX file for exchange with other institutions. `KEEP` may only be selected if you do not want to send the resulting clock RINEX files to an external source.

15.3.3. Combining Clock RINEX Files

The input clock RINEX files at equal epochs may refer to different reference clocks. To transform all files to the same reference, offsets between the individual files have to be estimated. This is done epoch-wise by a least-squares adjustment. You may select in the input panel “CCRNXC 3: Options for Clock RINEX File Combination” whether station and/or satellite clocks shall be used for the offset computation. In addition, a threshold for the maximum allowed residual of a clock contributing to the offset estimation may be specified (see Figure 15.10). It is obvious that this algorithm only works if the same IFB/ISB values have been used for each input clock RINEX file when they are derived from GLONASS observations.

The RMS of the estimation and the covariance information for each offset can be interpreted as a measure for the consistency of the clock RINEX files for the particular epoch. This information is written to the program output for each epoch if the “Detailed

report on clock combination” in panel “CCRNXC 4: Select Program Functions, Program Output” is enabled:

```

RESULTS FOR THE INTERVAL from 2004-01-14 00:20:00 to 2004-01-14 00:20:00
-----
Rms:                0.002 ns
Number of stations: 6
Number of satellites: 80
Number of removed outliers: 0
Number of parameters: 3
Degree of freedom: 84

Num  File name                Offset      Rms      (ns)
-----
  1  ${K}/TIMTRANS/OUT/TP014001.CLK  0.000    0.002
  2  ${K}/TIMTRANS/OUT/TP014002.CLK  0.003    0.002
  3  ${K}/TIMTRANS/OUT/TP014003.CLK -0.003    0.002
-----

```

In this way CCRNXC may be used to compare the consistency of clock RINEX files (e.g., from different solutions) and to detect epochs with analysis problems.

After applying the offsets to all clocks in each clock RINEX file, all clocks refer to the same reference and can be combined. If a clock is available in more than one input file an arithmetic mean can be computed to get the combined clock value. The weighting strategy for computing the mean, an outlier threshold, and a minimum redundancy for each clock may be defined in options “OPTIONS FOR CLOCK COMBINATION”, see Figure 15.10.

If an epoch is available in one input clock RINEX file only, the values are copied as such into the output clock array. If for one epoch no common clocks are available in the input clock RINEX files the offset cannot be computed. All clock values of the epoch are then copied into the output clock array without alignment to a common reference. If only a subset of the input clock RINEX files has common clocks to compute the offset only the clock values from those files are considered for the output clock array.

After combining the clock values from the input files and inserting the results into the output clock array, the reference clock selection, the clock jump detection, and/or the

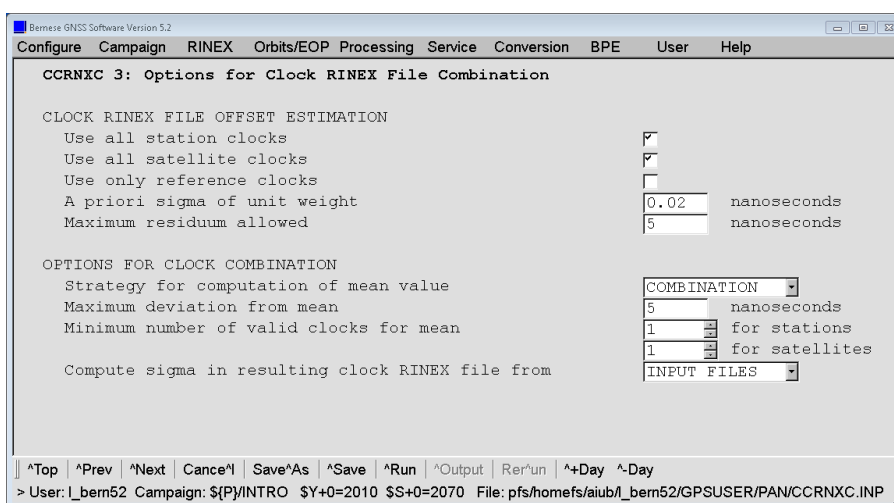


Figure 15.10.: Program input panel for combining clock RINEX files in program CCRNXC.

clock extrapolation are carried out according to the selected program functions in panel “CCRNXC 4: Select Program Functions, Program Output”.

15.3.4. Selection and Alignment of the Reference Clock

Because GNSS is only able to determine the differences between clocks, one degree of freedom remains: For each epoch one of the clocks can be set to an arbitrary (reasonable) value. Therefore the selection or the change of the reference clock does not affect the estimated clock solution. The only requirement is that the reference clock must be available for each epoch for which clock values are computed.

Nevertheless, it is preferable (e.g., for the extrapolation, see Section 15.3.6) if the time series of the clock values can be easily modeled (e.g., by an offset and a drift as it is expected for a perfect clock). A reference clock is selected and modeled as a perfect clock. A polynomial is fitted to the combined values for the clock. In this way the time scale represented by the reference clock (and therefore for the entire solution) does not change. If the clock was synchronized, e.g., to the GPS broadcast time during the processing, the aligned reference clock will refer to the same time scale.

The behaviour of the selected reference clock has to correspond to the model used for the alignment. All deviations of the real behaviour of the reference clock from the assumed model (e.g., noise or jumps) are reflected in all other clocks of the solution. Therefore, the reference clock must be selected carefully. A receiver clock driven by an H-Maser is preferable.

The program CCRNXC supports two cases:

- The reference clock is retained from one of the input clock RINEX files (option “Retain the reference clock from an input file” in panel “CCRNXC 4: Select Program Functions, Program Output”). This requires that the reference clock in this input file covers all epochs of the output file. This option is preferable, e.g., when merging clock RINEX files. Using this option the reference clocks from all input clock RINEX files cannot be deleted with the option “DEFINE A LIST OF CLOCKS TO BE PROCESSED” (see Figure 15.9).
- The program selects a new reference clock if you choose the option “Select a new reference clock for the output file”. This becomes necessary
 - if the input clock RINEX files contain clocks from different time intervals,
 - if the reference clocks in the input clock RINEX files are not aligned (e.g., when the zero-mean condition for the reference clock realization was used in GPSEST), or
 - if one of the input clock RINEX files does not contain a reference clock, because CCRNXC writes output clock files only if a reference clock is defined².

If the reference clock is chosen in the CCRNXC program run (e.g., from one of the station clocks — the recommended procedure) all reference clock candidates have to remain in the processing, see options “DEFINE A LIST OF CLOCKS TO BE PROCESSED” in panel “CCRNXC 2: Clock/Epoch Selection for Processing”.

Reference Clock Selection in CCRNXC

A list of potential reference clocks has to be selected in option “Selection of potential reference clocks” in panel “CCRNXC 5: Select a New Reference Clock for Output File”. Successively each

²The reference clock records are mandatory according to the clock RINEX format description.

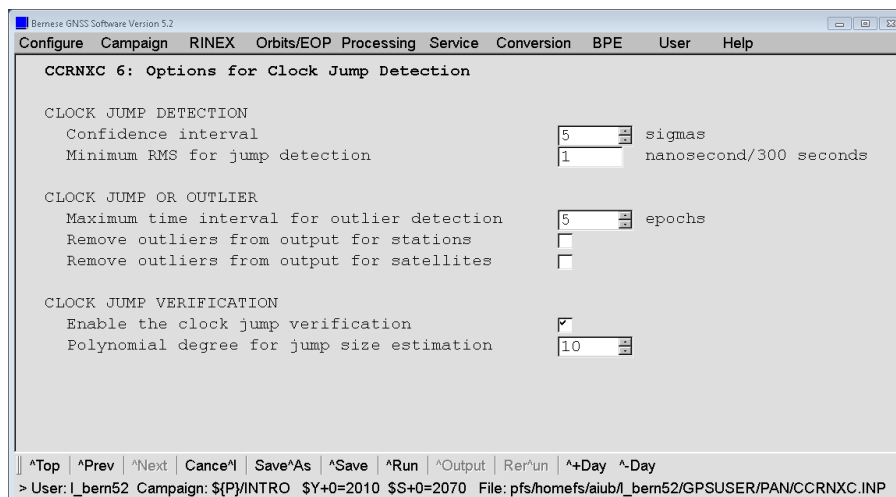


Figure 15.11.: Program input panel for clock jump detection in program CCRNXC.

of these clocks is used as reference clock and the complete clock solution is aligned to this reference clock candidate. The polynomial degree for the alignment is specified in option “Polynomial degree for alignment” in panel “CCRNXC 5: Select a New Reference Clock for Output File”. All clocks are then fitted by a polynomial of the same degree and the mean RMS is computed. The reference clock candidate which leads to the smallest mean fit RMS and at the same time is available for a maximum number of epochs (optimally for all epochs) is then selected as a reference.

15.3.5. Clock Jump Detection

A jump in a clock is a discontinuity in the clock value time series which may not be modeled by a continuous function. In order to distinguish between the noise behavior of a clock and a clock jump, the size of the jump must be significantly bigger than the mean change of the clock values between two epochs. The purpose of the clock jump detection is to obtain a reasonable model for the clock behavior for the clock extrapolation and to update the statistic summary in the program output.

The procedure is composed of four steps:

1. In a first step the mean change (absolute value only) of the clock value per second is computed for all epoch differences:

$$\overline{\Delta\delta} = \frac{1}{n-1} \sum_{i=2}^n \left| \frac{\delta(t_i) - \delta(t_{i-1})}{t_i - t_{i-1}} \right|.$$

The mean noise level of the clock $\sigma(\overline{\Delta\delta})$ is the standard deviation of the mean change $\overline{\Delta\delta}$.

A jump hypothesis is setup if the change between two epochs exceeds a specified threshold which depends on the mean value $\overline{\Delta\delta}$, the noise of the clock $\sigma(\overline{\Delta\delta})$, and a user-specified confidence interval n (option “Confidence interval”, see Figure 15.11):

$$\left| \frac{\delta(t_i) - \delta(t_{i-1})}{t_i - t_{i-1}} \right| > \overline{\Delta\delta} + n \cdot \sigma(\overline{\Delta\delta}).$$

The mean change of the clock per second is computed iteratively without using the epochs flagged with a jump hypothesis until no further jumps are found.

If the clock is very noisy no jump detection is carried out because a distinction between noise and jumps is no longer possible. The limit is hardwired to $\sigma(\overline{\Delta\delta}) > 100 \mu\text{s}$ in subroutine `LG/CCJUMP.f90`. On the other hand the computed noise level of excellent clocks can be very small. Because it makes no sense to detect “jumps” on the few picosecond level in a GNSS derived solution, the noise $\sigma(\overline{\Delta\delta})$ needs to have a lower limit which is available as a user input option (“Minimum RMS for jump detection”, see Figure 15.11).

2. The next step is to check the list of possible clock jumps for outliers in the clock time series. If two clock jumps are found for the same clock within a few epochs and with the same size (but the opposite sign), the clock values between these two events are marked as outliers:

$$\left| \left(\frac{\delta(t_{j+1}) - \delta(t_j)}{t_{j+1} - t_j} \right) - \left(\frac{\delta(t_i) - \delta(t_{i-1})}{t_i - t_{i-1}} \right) \right| \leq n \cdot \sigma(\overline{\Delta\delta})$$

where $|t_i - t_j|$ is smaller than the user-specified limit for “few epochs” in option “Maximum time interval for outlier detection”, see Figure 15.11. The two jumps are deleted from the list of clock jumps as long as no jump is found just before the first or after the second jump.

3. To distinguish a real clock jump from noise the uncertainty of the mean clock rate has to decrease significantly if the clock change at the jump epoch is not taken into consideration for its computation. For this test only a few clock values around the event are used. If no significant improvement can be found when introducing the jump, the clock event is removed from the list of clock jumps. The value n from option “Confidence interval” is used here to define the significance level.
4. In the last step the size of the clock jump is estimated using a polynomial. The assumption is that the clock can be modeled as a polynomial with the degree specified in the option “Polynomial degree for jump size estimation” over the entire time interval. This is only a verification of the detected clock jump. The results are printed on request into the program output.

These four steps are executed for each clock in the combined output array. The assumption is that the alignment to a reasonable reference clock has been done before. Therefore the clock jump detection is performed after the reference clock selection.

15.3.6. Clock Extrapolation

If the time window specified in panel “CCRNXC 2.1: Time Window” is not completely covered by clock values from the input clock RINEX files then the program CCRNXC may extrapolate the clock values. The combined clocks are aligned to a reference clock

and clock jumps are identified. The clock values are then modeled in the following way:

$$\begin{aligned} \delta(t) &= \sum_{i=0}^m a_i(t - t_0)^i && \text{polynomial part} \\ &+ \sum_{j=1}^n (b_{sj} \sin(\omega_j t) + b_{cj} \cos(\omega_j t)) && \text{periodic part} \\ &+ c_k && \text{clock jump .} \end{aligned}$$

The parameters of this function (a_i , b_{sj} , b_{cj} , and c_k) are computed for each clock using a least-squares adjustment. The polynomial degree m and the frequencies for the periodic functions ω_j are specified by the user in panel “CCRNXC 7: Options for Clock Extrapolation”. The clock jump term is setup for each epoch for which a clock jump was detected.

Two parameters trigger the extrapolation of a particular clock: The RMS of the least-squares adjustment for the parameters must be lower than a specified threshold (option “Maximum allowed RMS for fit” in panel “CCRNXC 7: Options for Clock Extrapolation”) and a minimum number of clock values used to determine the model parameters may be requested (option “Minimum number of clock values for fit” in the same panel).

15.4. Satellite Clock Validation

If satellite clocks are estimated together with receiver clocks in program GPSEST (see Section 15.2) the resulting satellite clock corrections are expected to be consistent with the used satellite orbits and the EOPs. If the clock corrections are aligned to a linearly behaving reference clock in program CCRNXC (see Section 15.3.4), it is expected that all linearly behaving receiver clocks can be represented by a linear clock model. This is expressed in the statistics part of the program output from CCRNXC (`rms of poly. fit: n = 1`) that is displayed on page 367.

As an alternative, a linear model for receiver clocks introducing satellite clock corrections can be estimated with the program CODSP (“Menu>Processing>Code-based clock synchronization”, description in Section 6.3). The linear clock model for the receiver clocks is activated if the option “Clock polynomial degree” in panel “CODSP 2: Input Options” is set to 1. Figure 15.12 shows an example for the CODSP summary file. You can see that the receiver clocks for most of the stations can be nicely modeled assuming a linear behavior of the receiver clock (RMS is below 0.15...0.20 m). This confirms the alignment as well as the consistency between the satellite clock corrections, satellite orbits, and ERPs. It does not matter if the RMS “explodes” for some stations. The receiver clocks in Frankfurt am Main (FFMJ) can obviously not be represented by a linear model.

If program CODSP is used for satellite clock validation purposes only, it makes sense to disable the option “Save clock estimates” in panel “CODSP 2: Input Options”.

SINGLE POINT POSITIONING SOLUTIONS: ELLIPSOIDAL COORDINATES IN WGS-84													
STATION NAME	SESS	F	FR	C	TR	I	EL	NS	DT	#OBS	RMS(M)	...	
ALGO	40104M002	1110	0	L3	2	G	N	15	1	300	2155	0.17	...
AMC2	40472S004	1110	0	L3	2	G	N	15	1	300	4325	0.18	...
BJNM	21616M001	1110	0	L3	2	G	N	15	1	300	6470	0.13	...
BRMU	42501S004	1110	0	L3	2	G	N	15	1	300	8685	1.80	...
BRUX	13101M010	1110	0	L3	2	G	N	15	1	300	10854	0.25	...
CHTI	50242M001	1110	0	L3	2	G	N	15	1	300	12991	2.39	...
CRO1	43201M001	1110	0	L3	2	G	N	15	1	300	15024	0.14	...
FFMJ	14279M001	1110	0	L3	2	G	N	15	1	300	152288518	4.43	...
GODE	40451M123	1110	0	L3	2	G	N	15	1	300	17150	0.15	...
GOPE	11502M002	1110	0	L3	2	G	N	15	1	300	19180	0.24	...
GUAT	40901S001	1110	0	L3	2	G	N	15	1	300	21366	0.92	...
MDVJ	12309M005	1110	0	L3	2	G	N	15	1	300	2173	0.23	...
...													...

Figure 15.12.: Example for a summary for satellite clock validation from program CODSP.

Validation of External Satellite Clocks

Another task may be the validation of the consistency of satellite positions, satellite clock corrections from an external precise orbit file, and the external ERPs. A precise point positioning using the program GPSEST can be used for this purpose.

As a first step you have to generate a standard orbit from the precise orbit file and to convert the ERPs into the Bernese format following the instructions in Chapter 5. When you extract the satellite clock corrections with program PRETAB you have to write the unmodified values (no polynomial fit) into the Bernese satellite clock file (set both of the options “Interval for polynomials” and “Polynomial degree” in panel “PRETAB 3: Options for Clocks” to zero). Specify the “Sampling interval” in panel “GPSEST 3.1: General Options 1” according to the sampling of the satellite clocks (e.g., 900 seconds). The a posteriori sigma of unit weight in the GPSEST run with the observations from any station is expected to be about 1 or 2 mm when introducing the satellite orbits, EOPs, and the satellite clocks, if all information is consistent (see Section 7.9.1 for more information).

15.5. Generation of High Rate Clocks Using Program CLKEST

Program CLKEST allows to generate high rate clocks in an efficient way. It is based on known orbit, station coordinate, and station troposphere information obtained, e.g., from a global network double-difference solution (troposphere delays may also be obtained from a model). Only clock parameters remain as unknowns in the observation equations of the ionosphere free linear combination with this information introduced as known. The program uses pseudorange and carrier phase observations from a (preferentially global) network of tracking stations.

In a first step pseudorange observations are screened and receiver clocks synchronized. Clock parameters are then computed from the pseudorange observations for each satellite clock and each involved station clock for each observation epoch. In a second step, carrier phase epoch-differences are formed (for each clock and each observation epoch-difference), screened, and used to compute clock epoch differences for each clock and each observation epoch-difference. This second step allows to get rid of phase ambiguities. Cycle slips are

identified as outliers in the phase epoch differences. In the third and last step, pseudorange derived clock values and carrier phase derived clock epoch-differences are combined independently for each clock using an efficient algorithm (option “Combination algorithm”, TRIDIAG). The singularity in the system is avoided by either fixing the values of one reference clock or the mean of an ensemble of clocks.

The procedure is very fast and allows the processing of data at high rate for a large network of stations. Drawbacks are, on one hand, missing covariance information (not provided by the efficient algorithm), while on the other hand, and more importantly, neglected correlations between successive clock epoch-differences. These missing correlations are equivalent to the estimation of individual ambiguities for each epoch difference and are the cause for a variation of the estimated clocks in a band of about ± 1 ns around the true values. This pseudo-random walk may be reduced by lowering the relative weight of the pseudorange observation with respect to the carrier phase observations. Alternatively, a time-averaged pseudorange clock value obtained by integrating the clock epoch-differences may be used to define the datum of the carrier phase clock time series (option “Combination algorithm”, SUM_CONDITION). Finally, it is also possible to constrain the carrier phase clock time series at specific epochs to precise clocks that are available (e.g., every 5 minutes) from another source (option “Fix on a-priori clocks”). This latter procedure is used at CODE to densify the 5 minute precise clocks to 30 second high rate clocks and then to 5 second high rate clocks (see Bock et al. 2009, where one can also find more details on the algorithm used).

16. Estimation of Satellite Orbits and Earth Orientation Parameters

16.1. Introduction

The improvement of satellite orbits is one of the core functionality of the *Bernese GNSS Software*. At CODE as well as at a few other IGS ACs the *Bernese GNSS Software* is used to compute precise GNSS orbits for every day. In fact, it is close to impossible to come up with better orbits than those produced by the IGS. Therefore, we recommend to use either the CODE orbit products or the products resulting from the IGS combination. See Sections 2.2.1 and 4.13 for more information on IGS orbits and their download servers.

The orbit models implemented in ORBGEN are optimized for GNSS satellites (e.g., GPS, GLONASS, and Galileo). Nevertheless, *Bernese GNSS Software* allows also orbit determination based on microwave observations for LEOs equipped with a GNSS receiver (see Chapter 17). Even SLR observations may be used for estimation of satellite orbits. The combination of SLR and GNSS measurements for orbit improvement is possible by superpositioning of the technique specific normal equations with ADDNEQ2.

This chapter provides information on the sequence of steps needed for orbit improvement focusing on GNSS satellites based on microwave tracking data. The procedure is, however, more general and can be applied equally well for precise orbit determination for LEOs or orbit estimation based on SLR observations. For more details on these special cases we refer to Chapters 17 and 19, respectively.

For the reliable estimation of GNSS orbit parameters data from a globally distributed network should be used. Only a subset of orbit parameters may be improved with a regional network. Usually, double differenced observations are processed for orbit determination with the *Bernese GNSS Software* since ambiguity resolution positively impacts the quality of the estimated orbits. A relatively dense global network is, however, required in this case.

GNSS tracking data acquired from receivers on the Earth's crust allows to estimate a subset of EOPs because the GNSS satellite constellations form a realization of an inertial system (or quasi-inertial system considering the Earth orbiting around the Sun). The motion of the GNSS satellites is to a certain extent sensitive to the Earth's gravity field. Therefore, the Earth's center of mass, with respect to the crust-fixed terrestrial reference, can be obtained by analysing the satellites motions. Information on the estimation of EOPs and geocenter coordinates is given in Section 16.4.

16.2. Orbit Prediction

Section 5.4 describes the procedure to prepare precise orbit information for use within the *Bernese GNSS Software*. The same procedure may be employed to fit a series of precise orbit files as well as to predict the adjusted orbit into the future (or the past). Sections 16.2.1 and 16.2.2 show how to obtain predicted orbits and predicted Earth orientation information, respectively. Section 16.2.3 describes the procedure for converting standard orbits into precise orbit files, a procedure that is not only used for orbit prediction but also for orbit estimation (see Section 16.3).

16.2.1. Preparation and Extrapolation of Earth Orientation Information

The UT1–UTC corrections provided with the Earth orientation information, generated based on GNSS tracking data, are referenced to an external value independently for each pole file by fixing, e.g., the first value to Bulletin A. The reason is that GNSS is insensitive to this correction (see Section 16.4). As a consequence, precise orbit files converted to the inertial frame exhibit jumps at pole file boundaries that may reach more than 10 cm. If a series of precise orbit files shall be fitted, a common procedure for orbit prediction, the UT1–UTC values from different pole files first have to be aligned to a common reference. Two programs are available in the *Bernese GNSS Software* to perform this task: POLXTR and POLINT.

The first of the two programs, available at "Menu>Orbits/EOP>Handle EOP files>Concatenate IERS pole files", allows for a sophisticated selection of the records from different input IEP files (pole files in IERS format, see Section 4.4) to be extracted and concatenated to a single Bernese pole file. To use the output pole file with ORBGEN select the corresponding option in the field "Handling of UT1-UTC". The program may also be used to extrapolate pole information into the future using the a priori file or a polynomial fit. In the latter case we recommend to use a linear extrapolation, only. Be aware that UT1R–UTC is fitted and extrapolated (i.e., the Earth rotation angle reduced by tidal variations) and not UT1–UTC. For additional information on the use of program POLXTR and the appropriate setting of the options, we refer to the online help.

Program POLINT is only available using the RUNGPS command (see Section 21.9). It allows to concatenate input pole files (in IERS format) in a straightforward way. Activate option "Continuity" in order to get a continuous time series in UT1–UTC. Do not activate option "Restitute subdaily" which is only for test purposes.

16.2.2. Fitting Precise Orbit Files and Predicting Orbits

For fitting n precise orbit files, each of them is first converted to tabular format as described in Section 5.4.2. In order to get the tabular orbits in consistent representations of the inertial frame, special attention has to be paid to the Earth rotation information used because UT1–UTC information from successive pole files may not be continuous (see Section 16.2.1). Depending on the application you may use Earth orientation information from IERS, e.g., Bulletin A or C04 covering the time period for which you want to get the orbit fit and prediction (see Section 5.2.2).

To fit the n tabular files, select them all in the field "Start with tabular orbits" in program ORBGEN. For predicting the orbit into the future (or into the past) simply shift the

right (resp. left) boundary of the time window accordingly (panel “ORBGEN 5: Orbital Arc Definition”). It is not recommended to include any stochastic pulses when fitting the tabular files for prediction purposes (option “Satellite number for stochastic pulses” in panel “ORBGEN 4: Parameter Selection” is set to NONE). It is preferable to “translate” these velocity changes of the satellites by once-per-revolution terms in all three components: “System DYX” in panel “ORBGEN 3.1: Options”. The complete radiation pressure model (nine parameters) is well suited to obtain a good fit over several days. You get the standard orbit file adjusting the selected tabular files and covering the specified time window as output. You may also generate a so-called LST file (see Figure 24.67) that contains a table of the fit RMS values for each satellite and each input orbit file. This file may be used to compute accuracy information for a precise orbit file header (see Section 16.2.3).

Note that instead of tabular files precise orbit files may directly be used as input for ORBGEN. For each input precise orbit file the corresponding pole file has to be available with the same name as the precise orbit file (but different extension).

16.2.3. Conversion of Standard Orbit Files to Precise Orbit Files

A standard orbit file can be converted to a precise orbit file format using the program STDPRE (“Menu>Orbits/EOP>Convert standard to precise orbits”). The program performs the transformation from the inertial to the Earth-fixed reference frame. For this transformation the same nutation and Earth rotation information must be used as for the generation of the standard orbit file in the previous steps. You may include satellite clock corrections in the precise orbit file by specifying a Bernese clock file in the field “Satellite clocks”. Missing clock values are substituted with 999999.999999.

If a satellite problem file (see Section 24.3.5) is specified in the corresponding field in panel “STDPRE 1.1: General Files”, satellites marked as bad for the specific time period are not written to the output precise orbit file. The satellite problem file also provides the maneuver epoch for repositioned satellites. The orbit positions corresponding to the correct arc before and after the maneuver are then written to the output file.

There are two possibilities to include accuracy information in the precise orbit file header. Accuracy codes reflecting the formal orbit accuracy as estimated by GPSEST or ADDNEQ2 may be derived from an input orbital element file (see Section 16.3.1.2). Program STDPRE reads the formal error du of the argument of latitude (in radians) for each satellite and converts it to an accuracy code using the formula $acc = \text{NINT}(\log(a \cdot du) / \log(2))$ where $a = 2.65 \cdot 10^7$ m is the semimajor axis.

Alternatively, program PREWEI (“Menu>Orbits/EOP>Set accuracy codes in precise orbits”) may be used to include accuracy information derived from the fit RMS values gathered from a LST file written by ORBGEN. Such a file is generated when specifying a filename in the field “Summary file” in panel “ORBGEN 2: Result and Output Files” and fitting precise orbit files covering several days with ORBGEN. The accuracy information then represents the “modelability” of the orbits that is in general more realistic than the information obtained from the formal errors in the orbital elements file.

16.3. Orbit Improvement

Orbit improvement (sometimes also called orbit determination) is the process of improving orbital parameters using observations. In the *Bernese GNSS Software*, three programs are involved in the orbit improvement: ORBGEN as well as the processing programs GPSEST and ADDNEQ2. Orbital parameters which may be improved are the six Keplerian osculating elements (initial conditions at the beginning of the arc), up to nine parameters of the CODE empirical radiation pressure model as described in Section 2.2.2.3 (see also Beutler et al. 1994), and stochastic pulses (velocity changes) at predefined epochs. However, the new orbit parametrization proposed in Arnold et al. (2015b) are not available for orbit improvement in Version 5.2 of *Bernese GNSS Software*. The alternatively available piecewise constant accelerations for predefined intervals are mainly intended to be used in the case of LEO orbit determination (see Section 17.5).

Within the *Bernese GNSS Software* estimated orbits always refer to the satellite's center of mass. Information on the satellite antenna phase center offset is obtained from the satellite information file (e.g., `$/X}/GEN/SATELLIT.I08`, see Section 24.3.4) plus the nadir-dependent satellite antenna phase center pattern (e.g., `$/X}/GEN/PCV.I08`, see Section 24.3.3) in conjunction with nominal satellite attitude or, for LEOs, alternatively from an attitude file (see Section 17.4).

16.3.1. The Procedure for Orbit Improvement in the *Bernese GNSS Software*

Orbit improvement in the *Bernese GNSS Software* involves the following steps:

1. **Preparation of orbit improvement:**

A priori orbit as well as the partial derivatives of the orbit positions with respect to the parameters to be estimated are generated with program ORBGEN by numerical integration of the equations of motion and of the variational equations. The information is written to a standard orbit (default extension STD) and a so-called radiation pressure file (default extension RPR).

2. **Estimation of improvements for orbit parameters:**

Program GPSEST reads the a priori orbit and the derivatives from these two files, builds up the normal equations in a loop over all observations, and solves the equation system to obtain the parameter improvements. The improved orbital parameters are written to a so-called element file (default extension ELE) referring to the start epoch of the a priori orbit (osculation epoch).

Alternatively, the program ADDNEQ2 may be used to generate a solution based on normal equations containing orbit parameters. As in the case of GPSEST, the estimates are also provided in one or, in case of long-arc solutions, more element files.

3. **Update of orbit:**

ORBGEN reads the element file written by GPSEST or ADDNEQ2 and integrates the orbit numerically based on the improved orbit parameters. The output is a standard orbit for a specified time interval.

The last two steps may be iterated if the a priori orbit deviates too much from the “true” orbit. Subsequent steps may include a combination of a sequence of orbital arcs generated by GPSEST to longer arcs using program ADDNEQ2 and the conversion of the improved

standard orbit into a precise orbit file. The individual steps are described in more details in the following sections.

16.3.1.1. Prepare the Orbit Improvement

Let us first state that if you improve orbits it is in principle not important whether you start from broadcast, orbit predictions (e.g., from the previous day) or precise orbit information to create an a priori standard orbit. It has to contain all satellites which will be processed. If your a priori orbit is, however, only good to about 20 m you should definitely go through a second iteration step, i.e., repeat the orbit improvement steps described in Section 16.3.1.2 and 16.3.1.3 with the orbit generated during the first iteration step, which is now certainly within 0.1 m of the final results.

You may thus generate the a priori orbit starting from broadcast information as described in Section 5.3 or from precise orbit files as described in Section 16.2 (e.g., obtained by prediction from previous days). You may follow exactly the procedure described in Section 5.4.3 with the standard ORBGEN parameter settings to generate the necessary files. The output orbit information has to cover the complete time interval for which you want to perform orbit improvement with a single arc. It is recommended to restrict to daily arcs.

Which of the nine available radiation pressure parameters are setup in this preparing ORBGEN step depend on the further processing. You should keep in mind when making the related selection that constraints in the subsequent parameter estimation step act on the estimate with respect to the a priori value. If an orbit parameter is selected here its value from this ORBGEN (but not the value zero) is the basis for the constraining. For that reasons we recommend to choose here only those orbit parameters that will be estimated later on without constraints.

Please be aware of two restrictions in this context:

- It is not possible to perform an orbit improvement with Version 5.2 of *Bernese GNSS Software* if you set up “Satellite number for stochastic pulses” in panel “ORBGEN 4: Parameter Selection” when fitting the a priori information in the first ORBGEN run.
- The extended empirical CODE orbit model (see Arnold et al. 2015b) (“System D2X” in panel “ORBGEN 3.1: Options”) is not supported for orbit improvement with Version 5.2 of *Bernese GNSS Software* (even after the release “2015-02-05”). Only the traditional parametrization (“System DYX”) is supported.

Not only the equations of motion but also the so-called variational equations (derivatives of satellite positions with respect to orbit parameters, see Section 2.2.2.5) have to be integrated numerically for orbit improvement. Specify a filename in the field “Radiation pressure coeff.” in panel “ORBGEN 2: Result and Output Files” in order to invoke the integration of the variational equations.

The integration process writes the polynomial coefficients for each satellite, each component, and each integration subinterval into the standard orbit file specified in the field “Standard orbits” and those for all the partials into the “Radiation pressure coeff.” file (default extension RPR). However, if the coefficients for the partial derivatives were saved in the same way as those for the satellite positions, the file length of the radiation pressure files would be 15 times the size of the standard orbit files — which is a waste of disk space. This is true particularly if one takes into account that the accuracy requirements for the partials are by no means as stringent as those for the orbits.

The procedure used in Version 5.2 seems to be an optimum: whereas the variational equations are solved using exactly the same interval subdivision and the same polynomial degree as for the integration of the primary equations, it is possible and advisable to change the polynomial degree and the subinterval length for storing the coefficients associated with the variational equations. In practice we use for GNSS satellites a subinterval length of six hours and a polynomial degree of 12 for storing the coefficients for the partials (options “VARIATIONAL EQUATIONS: Length of interval” and “VARIATIONAL EQUATIONS: Polynomial degree” related to the section “VARIATIONAL EQUATION” in panel “ORBGEN 3.2: Options”, see Figure 5.6). By using this procedure, we have the partials available in the files with sufficient precision (6 to 8 significant digits) without wasting too much disk space.

16.3.1.2. Improve Orbit Parameters

The actual orbit improvement has to be set up in program GPSEST. We recommend to use program GPSEST with data spans of at maximum one day. If you want to produce longer arcs, use program ADDNEQ2 to combine the one-day arcs, see Section 16.3.2.

To allow for orbit parameter estimation, specify the names of the a priori standard orbit file in field “Satellite standard orbits” in panel “GPSEST 1.1: Input Files 1” and of the radiation pressure file in field “Satellite orbit partials” in panel “GPSEST 1.2: Input Files 2”.

Orbit parameter estimation is enabled by marking the checkbox “Parameter setup: GNSS or LEO orbit determination” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” (the option gets active if a radiation pressure input file is specified). A subsequent panel is then activated that is specific for the setting up of orbit parameters.

In the case of GNSS orbit improvement, the first panel is “GPSEST 6.3.1: Satellite Orbit Determination 1” (see Figure 16.1). You may specify whether you want to estimate GNSS orbit parameters for GPS only, for GLONASS only, or for all satellite systems (“Orb.est: satellite system selection”). The selection of MANUAL allows to specify one single satellite or a list of specific satellites. In the same panel you can set up each individual osculating element (section “SETUP OF ORBITAL ELEMENTS”) and dynamical parameter (radiation pressure parameters, section “SETUP OF DYNAMICAL PARAMETERS”) and a corresponding a priori constraint.

In order to preserve all options for future runs with program ADDNEQ2 we recommend that you set up all (osculating and dynamical) orbit parameters but that you tightly constrain parameters that you want to fix for a particular experiment. You are then able to change the constraining in runs based on normal equations. In our analysis at CODE we freely estimate all parameters but constrain the periodic dynamic parameters in the directions D and Y for GNSS satellites because correlations with EOPs would otherwise degrade the estimates of length of day (LOD) (see settings in Figure 16.1).

The option “Estimation of stochastic pulses” activates the panel “GPSEST 6.3.2: Satellite Orbit Determination 2” (see Figure 16.2) that allows for a detailed setting up of pseudo-stochastic parameters (velocity changes at pre-defined epochs in three orthogonal directions).

The number of equally spaced epochs per satellite and per day for which stochastic parameters shall be set up may be specified in option “Stoch. forces: Number of parameter sets

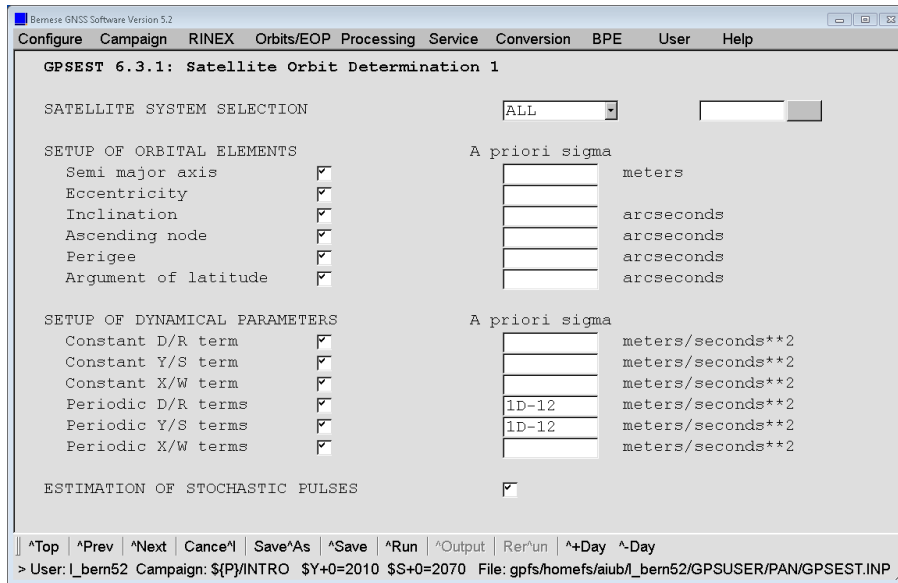


Figure 16.1.: Options for defining the setup of GNSS orbital parameters in GPSEST.

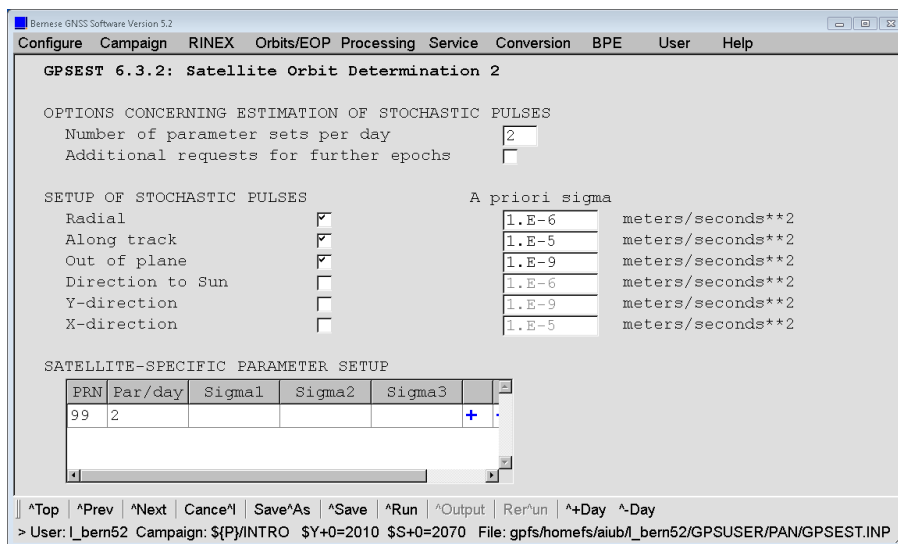


Figure 16.2.: Options for defining the setup of stochastic orbit parameters in GPSEST.

per day”. If you enter 2, e.g., parameter sets would be set up at 00 UT, 12 UT, 24 UT, etc. The parameters at the beginning and end of the arc are, however, not set up. For a one-day arc, therefore, only the pulses at noon are estimated. Pulses at the day boundaries may later be set up in ADDNEQ2 if you want to combine one-day arcs into n -day arcs (Section 16.3.2). For GNSS satellites we recommend to set up two sets of stochastic parameters per day.

Section “SETUP OF STOCHASTIC PULSES” in the panel allows to specify the direction for which pseudo-stochastic pulses shall be set up as well as their default a priori constraint (with respect to zero). In the example displayed in Figure 16.2, pulses are set up in radial, along-track, and in out-of-plane directions. To cope with correlations with ERPs the out-of-plane direction is actually constrained to (almost) zero.

The section “SATELLITE-SPECIFIC PARAMETER SETUP” in the same panel can be used to specifically define satellite-specific requests concerning the setup of pseudo-stochastic pulses. You may include lines with individual satellite PRN number, 99 for all satellites, or 98 for eclipsing satellites. If 97 is specified, stochastic pulses are set up for eclipsing satellites only for the epochs about 45 minutes after the satellites leaving the Earth’s shadow. For fields left blank the values defined in the above options are used. Entering a value overwrites the default values. In order to setup pulses for all satellites you need to specify a 99-line.

Enabling the checkbox “Stoch. pulses: Additional requests for further epochs” activates yet another panel where you get the possibility to specify in detail also the pulse epochs individually for each satellite. These stochastic pulses are set up in addition to the pulses defined in panel “GPSEST 6.3.2: Satellite Orbit Determination 2”. Bear in mind that pulse epochs are shifted to the nearest integration subinterval boundary.

After having executed program GPSEST with observations covering one day, you have (among many other result files) an orbital element file, a normal equation file, and an ERP file at your disposal. Keep in mind that in general you should also estimate ERPs when you determine the GNSS satellite orbits. More information on this topic may be found in Section 16.4. A refinement of the solution, e.g., by an improved datum definition using the program ADDNEQ2, is recommended before using the element file for the subsequent step.

16.3.1.3. Update Improved Orbit

Updating of a standard orbit using program ORBGEN according to an orbital element file is the last step of an orbit improvement. Insert the orbital element file as well as the ERP file generated in the previous step with program GPSEST (or alternatively with program ADDNEQ2, see Section 16.3.2) to obtain an updated standard orbit file. You may select two element files which will then be merged into a single standard orbit file (e.g., separate element files for GPS and GLONASS).

You may define the length of the arc interval (starting at the osculation epoch, i.e., the start epoch of the a priori orbit) in the program panel. You may also specify whether you actually want to use the updated orbits or reconstruct the a priori orbit which was used for the orbit improvement (option OLD resp NEW in the field “SELECTION OF ORBITAL ELEMENTS” in panel “ORBGEN 6: Selection of Orbital Elements”).

It is essential that the orbit models used for the generation of the a priori orbit and for updating of the orbit are identical. Program ORBGEN makes sure that, e.g., the same gravity field or satellite information file is used. In case of any discrepancy ORBGEN will stop with a corresponding message. The update process also takes the estimated stochastic pulses into account which are stored in the orbital element files as well. The updated standard orbit may be converted to a precise orbit file using program STDPRE as described in Section 16.2.3.

In order to perform an additional orbit improvement iteration, write also the radiation pressure file and repeat the step described in Section 16.3.1.2 using the updated orbit information as well as the update step described in this section. Please note that the element file may not contain any stochastic pulses for this direct preparation of the a priori orbit for the next iteration. Alternatively, you may extract a precise orbit file first that is fitted again according to Section 16.3.1.1.

For such an iteration it is important to note that a resulting element file contains only entries for satellites for which an orbit improvement was enabled in GPSEST (e.g., if you have selected only GLONASS in option “Orb.est: satellite system selection” in panel “GPSEST 6.3.1: Satellite Orbit Determination 1”, the resulting element file contains only the values for the GLONASS satellites). After the update step, the resulting standard orbit (and eventually also the radiation pressure) file will only contain orbits for GLONASS satellites). To get the possibility for a GNSS analysis with the updated standard orbit another file containing the elements for the GPS satellites needs to be specified (obtained, e.g., from an “orbit improvement” with heavily constrained elements for the GPS satellites).

16.3.2. Orbit Combination with ADDNEQ2

Orbital parameters, if saved in normal equation files, can be manipulated by program ADDNEQ2. It is in particular possible to change the constraining of orbit parameters, revise the geodetic datum definition (see Section 10.2.3), combine the NEQs from subnetworks, or to combine subsequent NEQs from one-day arcs to longer arcs. The theory for this long-arc combination may be found in Beutler et al. (1996).

Manipulation of orbital elements in ADDNEQ2 is initiated by supplying one or several normal equation files that contain orbital parameters and to enable option “Orbital elements” in panel “ADDNEQ2 4.1: Parameter Pre-Elimination”. Additional panels are then activated that allow for the definition of orbit-specific options. Figures 16.3 and 16.4 show the panels designed for specifying the constraints for osculating elements as well as of dynamical and pseudo-stochastic parameters.

Option “Long-arc computation” in the first panel enables long-arc combination of arcs if a sequence of consecutive normal equation files containing orbital parameters is provided as input. The output is then a series of orbital element files. In addition, new pseudo-stochastic parameters may be set up at the boundaries of the normal equation files with option “Stochastic pulses at NEQ boundaries”. Combination of arcs at particular boundaries of the normal equation files for specific satellites (e.g., for badly modelable orbits) may be suppressed by supplying a satellite problem file containing corresponding splitting information (see Section 24.3.5) as input file to ADDNEQ2. If the tracking network for a specific set of

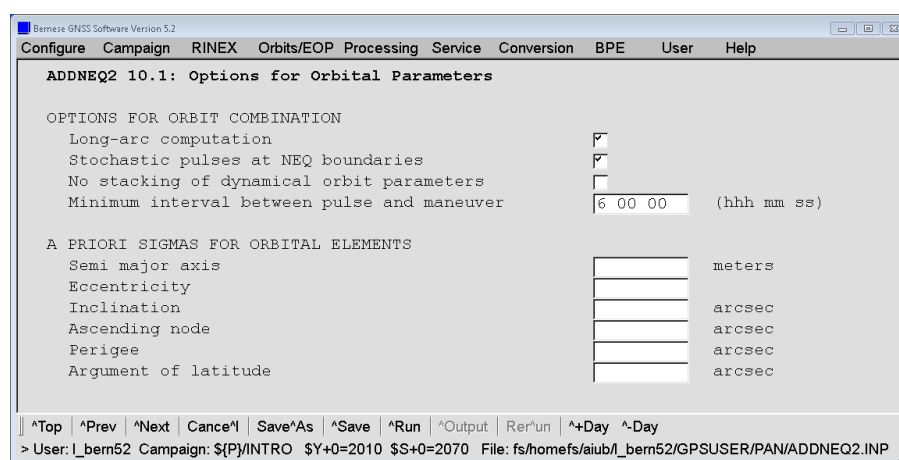


Figure 16.3.: Panel for defining orbit estimation options in ADDNEQ2.

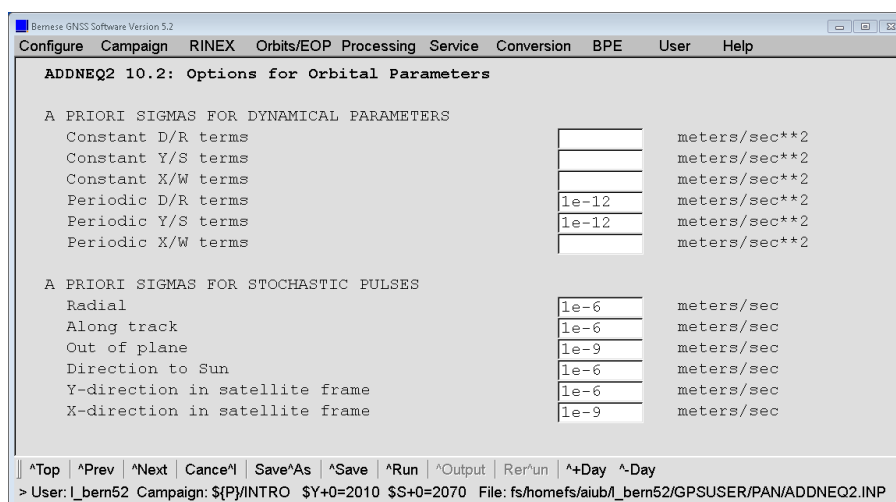


Figure 16.4.: Options for defining constraints for dynamic and stochastic parameters in ADDNEQ2.

satellites is only available to a limited extent stochastic pulses for those satellites may also be removed during a given interval using the satellite problem file.

The long-arc computation in ADDNEQ2 requires information from the standard orbit and radiation pressure files (STD and RPR). As a consequence, each normal equation file (NQE) containing orbit parameters, needs to be complemented with the related a priori orbit files when archiving these files or when copying them from one into another campaign area.

If normal equation files of different sessions are combined (e.g., to compute long arcs), the output of program ADDNEQ2 is a sequence of orbital element files, one for each input normal equation file. In this case you have to use wildcard characters (either % or ?) in the output file name in the field “Orbital elements”. The wildcard characters are then replaced by the corresponding characters of the a priori standard orbit file name used to create the normal equation files. To give an example, let us assume that the a priori standard orbit files used to generate three one-day normal equation files were named G1_06061.STD, G1_06062.STD, and G1_06063.STD and that you would like to create a three-day arc with program ADDNEQ2. If you specify G3_????? for the orbital element output file name, ADDNEQ2 will save the estimated orbital parameter for each day in the files G3_06061.ELE, G3_06062.ELE, and G3_06063.ELE. Be in particular careful when processing several sessions with the BPE in order not to overwrite element files from older sessions by files from newer sessions.

The orbital element files obtained as output from ADDNEQ2 may be updated using program ORBGEN as described in Section 16.3.1.3. The resulting standard orbits may finally be converted to precise orbit files (see Section 16.2.3).

16.3.3. Production of Three-Day Orbital Arcs at the CODE Analysis Center

The routines at an orbit determination center consist of various time consuming steps. One of them is collecting, screening, and validating the data which is then used for the

orbit determination. A brief overview of the actual procedure to generate a three-day arc at the CODE AC is:

- The a priori orbit is taken over from the generation of the CODE Rapid Orbit.
- All single-difference files of the day are processed in GPSEST by modeling the correlations correctly on the baseline level only. Orbits are improved with stochastic parameters tightly constrained.
- The residuals with respect to this “first” one-day arc are screened for outliers, bad phase observations are marked.
- With these screened observation files, GPSEST is invoked again, still in the single baseline mode, but this time stochastic orbit parameters are estimated at noon.
- The new one-day arc is used to resolve ambiguities on the single baseline level.
- After ambiguity resolution, a new (already very precise) a priori orbit without stochastic parameters is defined and used for the remaining one-day solutions. This orbit is then also the basis for all three-day solutions.
- Again, we use GPSEST and set up all 15 orbit parameters, but we tightly constrain all of them. Moreover, we do not process the entire one-day data set in one program run, but we produce four regional cluster solutions, where within each cluster (corresponding to one run of program GPSEST) the correlations are modeled correctly, and the ambiguities resolved previously are introduced as known.
- The four cluster solutions are superposed using program ADDNEQ2 to give the final one-day solution (after the verification of the geodetic datum according to Section 10.2.3).
- Three consecutive normal equation files corresponding to the final one-day solutions are combined to yield the final three-day solution.
- Any number of alternative solution series may now be produced using ADDNEQ2, only.

16.4. Estimation of Earth Orientation and Geocenter Parameters

16.4.1. Motivation

By the term Earth orientation parameters (EOPs) we understand a set of five parameters describing the orientation of the ITRF in the Inertial Celestial Reference Frame (ICRF) in conjunction with the conventional Precession–Nutation model. The parameters x_p , y_p locate the Celestial Intermediate Pole (CIP) (formerly called Celestial Ephemeris Pole, CEP) in the terrestrial reference frame, whereas the position of the CIP in inertial space is defined by the IAU 2006 Theory of Nutation. The parameters $d\psi$ and $d\varepsilon$ reflect the difference between the actual position of the celestial pole and the position given by the conventional IAU model. Finally, the difference $UT1-UTC$ (respectively $UT1-TAI$, TAI =International Atomic Time) gives access to the direction of the IERS reference meridian in the celestial reference frame (for details we refer to Castrique 1996).

Station positions are conveniently represented in an Earth-fixed reference frame rotating in a well-defined way with the Earth. This reference frame is realized today by a catalogue of adopted geocentric coordinates and a velocity field of tracking stations derived from the analysis of data from various space techniques (VLBI, SLR, GNSS, DORIS). The frame is designated as the ITRF maintained by the IERS.

The motion of the GNSS satellites is best described in the ICRF, realized by a list of adopted equatorial coordinates (epoch J2000.0) of extra-galactic radio sources uniformly distributed over the sky.

In order to compute the difference vector between the observing station and the satellite, both positions must be given in the same reference frame. Therefore, we need to know the current set of transformation parameters (EOPs) between the two frames when analyzing GNSS data. Moreover, when processing data from a global GNSS tracking network, it is possible to estimate a subset of EOPs if the positions of some tracking sites are known in the ITRF.

The satellite's equations of motion are formulated in a reference frame with a particular origin that may be identified with the center of mass of the Earth. The origin of the ITRF is defined to coincide on average with this center of mass. Variations of the geocenter coordinates (position of the Earth's center of mass with respect to the ITRF origin), e.g., due to changing mass distribution in the oceans and the atmosphere, may be measured with satellite geodetic methods.

16.4.2. Earth Orientation Parameters

16.4.2.1. Theory

The transformation between the celestial and the Earth-fixed coordinate system may be performed by means of equation

$$\mathbf{r}_E = \mathbf{X}^T \mathbf{Y}^T \mathbf{S} \mathbf{N} \mathbf{P} \mathbf{r}_I \quad (16.1)$$

where \mathbf{r}_E and \mathbf{r}_I denote the position vectors of a station in the terrestrial and inertial system, respectively. The sequence of rotation matrices $\mathbf{N} \mathbf{P}$ referring to nutation and precession describes the transformation between the mean celestial system at epoch J2000.0 and a system defined by the true equator and equinox of date. The *Bernese GNSS Software* Version 5.2, supports IAU 80, IAU 2000, and IAU 2006 nutation theories. The matrix $\mathbf{S} = \mathbf{R}_3(\Theta_{GA})$ provides the transition to the rotating system, where Θ_{GA} is the Greenwich apparent sidereal time and $(\mathbf{R}_i(\alpha))$ characterizes a rotation around axis i about angle α . Finally, the polar motion matrices $\mathbf{X} = \mathbf{R}_2(x_p)$ and $\mathbf{Y} = \mathbf{R}_1(y_p)$ describe the position of the CIP in the Terrestrial Reference Frame.

To the accuracy level required for the computation of the partial derivatives of the GNSS observable with respect to the parameters of interest, we may approximate the nutation matrix as a product of three infinitesimal rotations and write the transformation equation (16.1) in the form

$$\mathbf{r}_I = \mathbf{P}^T(t) \mathbf{R}_1(\Delta\varepsilon) \mathbf{R}_2(-\Delta\psi \sin \varepsilon_0) \mathbf{R}_3(-\Theta_{GM}) \mathbf{R}_1(y_p) \mathbf{R}_2(x_p) \mathbf{r}_E, \quad (16.2)$$

where $\Delta\psi$ and $\Delta\varepsilon$ denote the nutation in longitude and obliquity, ε_0 denotes the mean obliquity of the ecliptic, and Θ_{GM} stands for the Greenwich mean sidereal time. All five EOPs are contained in Eqn. (16.2).

Unfortunately, due to correlations with the orbital elements, a subset of the EOPs is not directly accessible to the satellite-based techniques such as GNSS or SLR (namely $\Delta\text{UT} = \text{UT1} - \text{UTC}$ and the nutation parameters). It is, e.g., possible to add a constant value to UT1 and adapt the ascending nodes of the satellite orbits by a corresponding value without affecting the ranges between stations and satellites. On the other hand, it is

possible to solve for a drift in UT1–UTC allowing to estimate LOD very well with GNSS. Similarly, drifts in the nutation parameters are accessible by GNSS, as well (Rothacher et al. 1999).

16.4.2.2. General Remarks on Estimation of Earth Orientation Parameters

Today, in view of the products made available through the IERS and the IGS, it will in general not be necessary to solve for EOPs, but to use EOPs consistent with the orbits and coordinates. For research type applications based on data from a global GNSS network it makes sense to set up EOPs. This section is important for advanced users of the *Bernese GNSS Software* who wish to gain insight into global applications of GNSS. Let us start by mentioning a few basic facts:

- You will always estimate EOPs on top of an a priori model, characterized by the values in a pole file (default extension `ERP`). If you want to estimate the Earth orientations from scratch, you have to use an a priori file with all parameters set to zero.
- The (empirical) model for the EOPs is set up in program `GPSEST`. It may be modified in program `ADDNEQ2`, where you have to be aware of the fact that you may simplify but not generalize the model.
- If you solve for EOPs, you will probably process exactly one session of one day in `GPSEST` and produce longer series using `ADDNEQ2`. You should be aware of the fact that for the EOP estimates you may divide the time interval of the session into a number of subintervals of equal length. In program `GPSEST` each EOP (improvement on top of the a priori model) is represented by a polynomial within each subinterval while in `ADDNEQ2` the EOP improvements are represented by a piecewise linear function with nodes at the subinterval boundaries (see Section 7.6).
- For diurnal and semi-diurnal variations of the EOPs, the IERS 2010 model (Petit and Luzum 2010), the IERS 2003 model (McCarthy and Petit 2004), or the model from Ray et al. (1994) may be used. The model name is logged in the pole file header.
- UT1–UTC estimates are special in one respect: due to the correlations with the orbital nodes mentioned above, it is not possible to solve for the zero degree coefficient of the polynomial pertaining to the first sub-interval of the session (as it is used in program `GPSEST`) or the first value in the piecewise linear representation (as it is used in program `ADDNEQ2`) if you introduce the orbital elements as unknowns in the same adjustment. The same is the case for nutation parameters.

16.4.2.3. Options in GPSEST

Panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” handles many special requests in connection with parameter estimation. You have to enable the parameter type “Parameter Setup: Earth orientation parameters”. In this case the menu system gives you access to panel “GPSEST 6.5: Earth Orientation Parameters” (see Figure 16.5), where you may first define the spacing of the EOP sets resulting in the total number of polynomials for each of the selected EOPs. The start and end time of the parameter sets are computed using the general parameter time offset defined in option “Time offset for Parameter intervals” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”.

Subsequently, you may select the number n of polynomial coefficients for each of the five EOPs in the fields “Par/set” in panel “GPSEST 6.5: Earth Orientation Parameters”. The polynomial degree q is simply $q = n - 1$. $n = 0$ means that the corresponding parameters are not set up. You have to be aware of the fact that your estimates will in general not be continuous at the sub-interval boundaries. You may ask for continuity for the pole components x_p , y_p , and for UT1–UTC by specifying ERP in the field “Continuity between sets”. If you want to enforce continuity for the two nutation parameters you specify NUT, and you specify BOTH if you want to have continuity for all parameters.

Attention: If you ask for continuity in the case $q = 0$ ($n = 1$), this actually means that you model the EOPs by a single parameter for the entire session! If you ask for continuity in the case $q = 1$ ($n = 2$), you actually model the EOPs as polygons (standard procedure at CODE). We strongly recommend to use $q = 1$ ($n = 2$) and to ask for continuity. Only EOP values represented by offsets and drifts ($n = 2$) can be properly handled by program ADDNEQ2.

You may constrain the first-degree polynomial coefficients of the EOPs, the nutation, or both parameter sets to zero by activating the option “Drifts constrained to zero”. This makes sense if you intend to estimate drift parameters later with program ADDNEQ2 using more than one session.

The zero-degree coefficients of each parameter set may be constrained independently for each of the five EOP types by specifying an a priori sigma in the fields “Other parameters”. Because, as mentioned above, it is not possible to solve for all orbit parameters and for UT1–UTC or nutation parameters, the zero-degree parameters pertaining to the first sub-intervals can be constrained separately for these parameters with a priori sigma values in the fields “First parameter”.

If you define the EOPs according to the panel displayed in Figure 16.5, GPSEST will generate a section in the program output of the following type:

EARTH ROTATION PARAMETERS:						

CRD.	REQ.	(")	RMS	(")/DAY	RMS	(")/DAY**2
		(S) (DT)	RMS	(S)/DAY	RMS	(S)/DAY**2

X	1	0.0010080	0.0000900	-0.0007370	0.0001536	
Y	1	0.0017345	0.0001013	-0.0013315	0.0001621	
DT	1	0.0000000	0.0000000	-0.0002006	0.0000064	

The spacing in time of the EOP values saved in the output Bernese pole file and the IERS pole file may be specified in option “TIME RESOLUTION OF EXTRACTED VALUES”, independently of the parameter spacing used.

16.4.2.4. Options in ADDNEQ2

With program ADDNEQ2 you may combine normal equation systems generated by GPSEST (or ADDNEQ2). The program allows you to reconsider some aspects of EOP estimation. EOPs estimated by GPSEST are parameterized as polynomials within sub-intervals while ADDNEQ2 uses a piecewise linear parametrization. ADDNEQ2 automatically converts EOPs represented as offset and drift (polynomial of first degree) into the piecewise linear representation if an interval length is specified in the section “PARAMETER SPACING” in panel “ADDNEQ2 8: Interval Length of Parameters” (see Section 9.4.4) which is strongly recommended. You may specify the same or a longer interval (e.g., 24 00 00) than

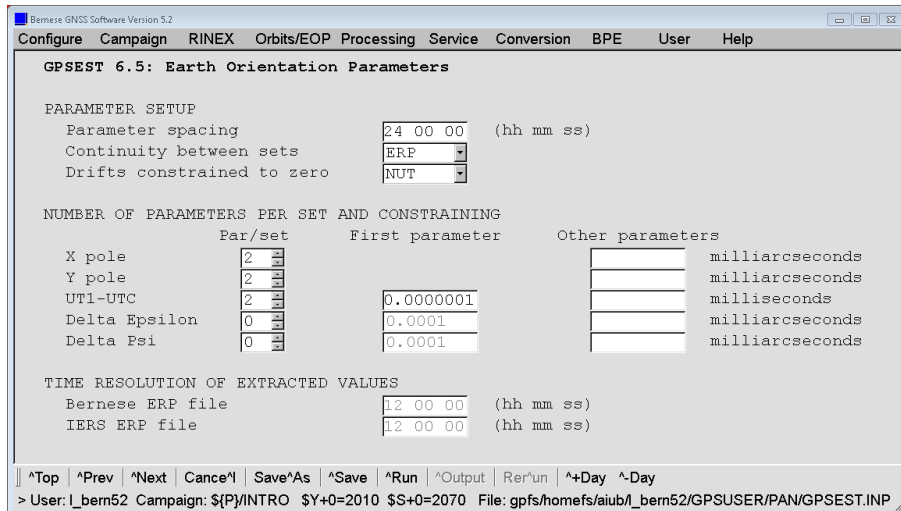


Figure 16.5.: Options for defining the setup for Earth orientation parameters in GPSEST.

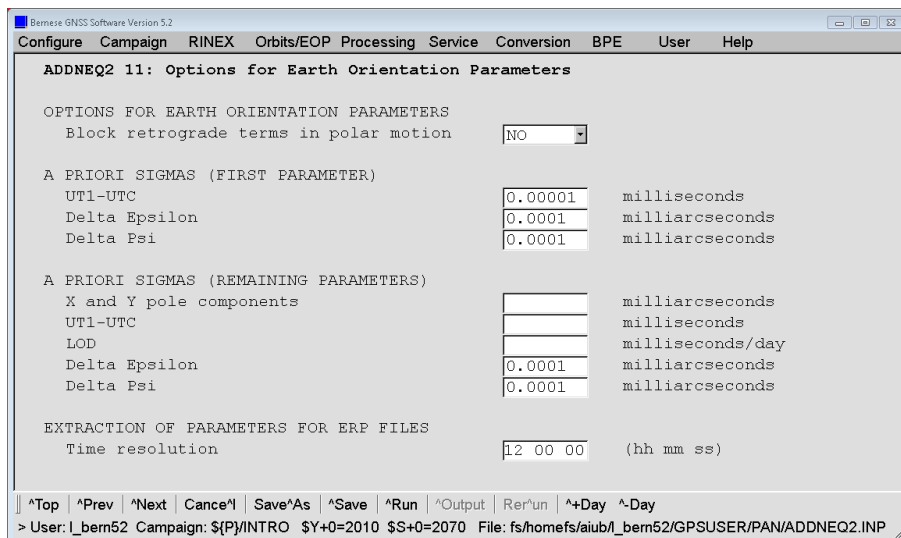


Figure 16.6.: Options for defining the setup for Earth orientation parameters in ADDNEQ2.

the one you originally defined in GPSEST when setting up EOPs. The panel is displayed as soon as EOP parameters are available (non-blank entry for option “Earth rotation parameters (Pole)” in panel “ADDNEQ2 4.1: Parameter Pre-Elimination”).

A panel with EOP-specific options “ADDNEQ2 11: Options for Earth Orientation Parameters” (see Figure 16.6) is available. The options in this panel resemble those in program GPSEST: You may define a priori constraints for the first offset parameters for UT1–UTC and the nutation parameters, as well as for all remaining offset parameters for all parameter types.

The option “Block retrograde terms in polar motion” is only of importance if you are interested in a sub-daily resolution of the EOPs in order to cope with correlations of daily retrograde motion of the pole with the orientation of the satellite’s orbital planes (Hefty et al. 2000).

There is one more important difference between the EOP estimation in GPSEST and ADDNEQ2: Whereas in GPSEST the corrections to the a priori pole are modeled as polynomials, the absolute values and UT1R (obtained from UT1 by removing the tidal variations with periods shorter than 35 days) are represented as piecewise linear functions in ADDNEQ2.

16.4.3. Estimation of Geocenter Coordinates

As satellites are sensitive to the center of mass of the total Earth (geocenter), satellite geodetic techniques are in principle sensitive to motions of the center of mass with respect to the origin of a crust-fixed reference frame. Such motions are expected due to mass displacements in the oceans, the atmosphere, and the interior of the Earth, as well as from surface deformations originating from loading effects.

In the *Bernese GNSS Software Version 5.2*, geocenter coordinates may be estimated in programs GPSEST and ADDNEQ2. It has, however, to be remarked that the sensitivity of GNSS satellites to geocenter motions (in particular the Z component) is low due to correlations of these parameters with radiation pressure modeling parameters (see Meindl et al. 2013, for a more detailed discussion).

In program GPSEST the estimation of geocenter coordinates is initiated by enabling the corresponding checkbox “Geocenter coordinates” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”. The menu system then displays panel “GPSEST 6.6: Geocenter Coordinates” which allows to switch on and to constrain the estimation for each coordinate component individually. Geocenter coordinates are modeled in the Earth-fixed frame as constant values for the entire session.

Program GPSEST does not write a geocenter output file but includes the parameters into the output normal equation file for further analysis with ADDNEQ2, and generates the following output in the general program output file (values in meters):

CENTER OF MASS :		

COOR .	VALUE	RMS

X	0.0131	0.0009
Y	0.0026	0.0010
Z	0.0088	0.0013

Program ADDNEQ2 gets information concerning geocenter coordinates through the input normal equation files. The parameters may be deleted, constrained, or pre-eliminated (before or after stacking). A priori constraints may be defined in panel “ADDNEQ2 12: Options for Geocenter Coordinates”.

Since geocenter coordinates may be interpreted as a common translation of the reference coordinates, the estimation of geocenter coordinates may be initiated in ADDNEQ2 even if the input normal equations do not contain this parameter type (see Section 9.3.6 for more details). The corresponding option “Set up Geocenter coordinates” may be enabled in panel “ADDNEQ2 3.1: Options 1”. The option has no effect if the input normal equations already contain geocenter coordinates.

Estimated geocenter coordinates may be written to an output file (default extension GCC, description in Section 24.6.9) by specifying a filename in the field “Geocenter coordinates” in panel “ADDNEQ2 2.2: Output Files 2”. A geocenter input file may be also specified in panel “ADDNEQ2 1.2: Input Files 2” allowing to transform a priori values from normal equation files to external values.

17. Orbit Determination for Low Earth Orbiters

17.1. Introduction

A Low Earth Orbiter (LEO) is a satellite at orbiting altitudes between 230 and 2000 km above the Earth's surface. If a LEO is equipped with a GNSS receiver the precise orbit determination (POD) may be done using the GNSS data.

TOPEX/Poseidon (Lee-Lueng et al. 1994) was one of the first LEOs for which GPS was operationally used for POD. Several other missions followed, e.g., the dedicated gravity field missions CHALLENGING Minisatellite Payload (CHAMP) (Reigber et al. 2002), Gravity Recovery And Climate Experiment (GRACE) (Tapley et al. 2004), and Gravity and steady-state Ocean Circulation Explorer (GOCE) (Drinkwater et al. 2006).

The *Bernese GNSS Software* is capable to perform a LEO POD using either zero-difference (Jäggi et al. 2007; Bock et al. 2011) or double-difference (Jäggi et al. 2007, 2011a) GPS data. Other GNSS are not yet regularly supported by spaceborne receivers and, therefore, no tests to process other than spaceborne GPS data with the *Bernese GNSS Software* have been done. For most applications we recommend a PPP-style processing and this chapter is, therefore, focused on the zero-difference processing of LEO data. Just like for ground stations, zero-difference observation files are processed introducing precise high-rate GPS clock corrections which may, e.g., be downloaded from CODE (see Section 4.13.1). These clocks have to be consistent with the GPS satellite orbits and the used EOP. PPP for ground stations is described in Section 10.6 and we can focus here on the specialities when processing spaceborne data.

An example BPE on LEO POD, which generates reduced-dynamic and kinematic orbits for GRACE, has been developed and distributed with Version 5.2 of the *Bernese GNSS Software*. Section 23.4.5 describes this LEO processing example in detail.

The following Sections 17.2 and 17.3 briefly review the theoretical background and the differences between dynamic or reduced-dynamic orbits (Jäggi et al. 2006) and kinematic orbits (Švehla and Rothacher 2005). More details on this may be found in Jäggi (2007).

17.2. Dynamic LEO Orbit Determination

In a dynamic representation, the antenna phase center position \mathbf{r}_{leo} is expressed in the inertial frame as

$$\mathbf{r}_{leo}(t_{leo}) = \mathbf{r}_{leo,0}(t_{leo}; a, e, i, \Omega, \omega, u_0; p_1, \dots, p_d) + \delta\mathbf{r}_{leo,ant}(t_{leo}) , \quad (17.1)$$

where

$\mathbf{r}_{leo,0}$	is the LEO center of mass position, expressed in the inertial frame,
$\delta\mathbf{r}_{leo,ant}$	is the antenna phase center offset, expressed in the inertial frame,
$a, e, i, \Omega, \omega, u_0$	are six (unknown) LEO orbital elements O_j , $j = 1, \dots, 6$, and
p_1, \dots, p_d	are d (unknown) LEO dynamical parameters.

$\delta\mathbf{r}_{leo,ant}$ is introduced as known, and follows in the inertial frame from the antenna offsets, the phase center offsets (and variations), and the current LEO attitude. The unknown parameters are the LEO orbital elements O_j , $j = 1, \dots, 6$, and additional dynamical parameters.

Dynamic orbit determination makes use of physical models of the satellite motion to determine a best fitting trajectory to the measurements in the least-squares sense. This allows for some sort of “averaging” measurements from different epochs, which makes the resulting position estimates much less sensitive to bad measurements and data outages. To some extent, a satellite trajectory can even be propagated across data gaps, if good dynamic models are available.

Dynamic force models are used to propagate the satellite’s center of mass position and velocity over time by means of numerical integration techniques (Beutler 2005). The equation of motion of an Earth-orbiting satellite including all perturbations in the inertial frame has already been introduced in Eqn. 2.10 with the initial conditions in Eqs. 2.11 and 2.12. The acceleration \mathbf{a} consists of all gravitational and non-gravitational accelerations taken into account to model the orbit perturbations. More specifically, dynamic force models are used to compute the gravitational and non-gravitational perturbations acting on the spacecraft which may depend on the time t , the position \mathbf{r} , and the velocity \mathbf{v} of the satellite, as well as on additional force model parameters p_0, \dots, p_d to be adjusted.

Often, the perturbation model consists of a known part with accelerations given by analytical models and of a part which includes force model parameters to be adjusted. In the case of the *Bernese GNSS Software*, we use constant and once-per-revolution empirical parameters either in a Sun-oriented (DYX), or orbit-oriented (radial, along-track, out-of-plane) system. Additionally, so-called pseudo-stochastic parameters may be set up. These parameters are either velocity changes at given epochs (pseudo-stochastic pulses) or piecewise constant accelerations over a given time interval. They lead to so-called reduced-dynamic orbit parametrizations.

The dynamic orbit is expressed in the inertial system because this is simpler due to the absence of fictitious forces. Nevertheless, the final results are transferred back into the Earth-fixed system to keep them as independent as possible from any processing models (e.g., modeling of ERP).

17.3. Kinematic Orbit Representation

In contrast to a dynamic representation, which is restricted to objects that obey the equation of motion (Eqn. (2.10)), the kinematic representation can be applied to all different kinds of moving objects, e.g., cars, ships, aircrafts, and satellites. A detailed description of the principle of kinematic positioning using the *Bernese GNSS Software* focusing on ground stations is given in Section 10.5.

The inertial phase center position \mathbf{r}_{leo} is related to the center of mass as

$$\mathbf{r}_{leo}(t_{leo}) = \mathbf{R}(t_{leo}) \cdot (\mathbf{r}_{leo,e,0}(t_{leo}) + \delta\mathbf{r}_{leo,e,ant}(t_{leo})) , \quad (17.2)$$

where

- \mathbf{R} is the transformation matrix from the Earth-fixed to the inertial frame,
- $\mathbf{r}_{leo,e,0}$ is the LEO center of mass position, expressed in the Earth-fixed frame, and
- $\delta\mathbf{r}_{leo,e,ant}$ is the antenna phase center offset, expressed in the Earth-fixed frame.

In analogy to Eqn. (17.1), $\delta\mathbf{r}_{leo,e,ant}$ is introduced as known. The unknown parameters are the epoch-wise kinematic coordinates, which are conventionally expressed in the Earth-fixed system. Note that kinematic positions of the LEO receiving antenna phase center could be established without the knowledge of antenna offsets and satellite attitude, but not the center of mass positions.

A kinematic orbit is a trajectory at discrete measurement epochs. This orbit is independent from any physical model and the positions may, therefore, be used as pseudo-observations for recovery of the long wavelength part of the gravity field (e.g., Jäggi et al. 2011b).

17.4. Data Accessibility

In most cases LEO GPS data is available from the satellite mission operator. The data is made available on dedicated servers and in most cases require registration to get access to the data.

The following URLs give information about registration process and data availability for the mentioned selected LEOs:

- CHAMP <http://isdc.gfz-potsdam.de>
- GRACE <http://isdc.gfz-potsdam.de>
<ftp://podaac-ftp.jpl.nasa.gov/GeodeticsGravity/grace>
- GOCE <https://earth.esa.int/web/guest/home>

The ftp server at JPL may be used without registration. For CHAMP and GOCE RINEX files are made available, but for GRACE the files have a mission-specific binary format. The binary files can, however, easily be converted to RINEX files with a dedicated software available from JPL as well.

Each LEO has its own attitude characteristics and in most cases the real attitude behavior is measured with star cameras onboard the satellite. These measurements are then distributed in dedicated attitude files with different file formats for each satellite mission. Besides the Bernese attitude file format (description in Section 24.6.17), the *Bernese GNSS Software*, Version 5.2 supports the data formats used for CHAMP, JASON-1/-2, GRACE and GOCE missions. The LEO attitude format from GPS High-precision Orbit Determination Software Tools (GHOST) (developed and used at DLR, Montenbruck et al. 2005) is also supported.

If you have an attitude file format which is not supported by Version 5.2, you may add it in the corresponding reading subroutine for LEO attitude files (`#{LG}/READATT.f90`).

17.5. LEO Data Processing

In order to ensure that the software recognizes a receiver as spaceborne and gets the necessary additional information, the satellite has to appear with a well-defined name in several files:

- The satellite may appear in section TYPE 001: RENAMING OF STATIONS in the station information file (description in Section 24.7.6) in order to rename the satellite/receiver name from the RINEX file to a well-defined satellite name being used in all other files (see Section 4.2.3).
- The satellite (with the translated name) has to be listed with the marker type SPACEBORNE in section TYPE 005: HANDLING STATION TYPES in the station information file. Throughout the software, this entry defines a spacecraft-mounted receiver and it is mandatory to select the station information file as input file for the processing. As a consequence, e.g., sensor offsets (in the inertial frame) are computed based on attitude information and neither site displacements (e.g., due to solid Earth tides or loading effects) nor tropospheric corrections are applied. For the two GRACE satellites the corresponding section in the station information file looks like

```

TYPE 005: HANDLING STATION TYPES
-----
STATION NAME          FLG  FROM              TO              MARKER TYPE ...
*****
GRCA L09              001  YYY Y MM DD HH MM SS  YYY Y MM DD HH MM SS  *****
GRCB L10              001  YYY Y MM DD HH MM SS  YYY Y MM DD HH MM SS  *****
SPACEBORNE
SPACEBORNE

```

- The satellite has to be listed in both sections of the satellite information file (e.g., `#{X}/GEN/SATELLIT.I08`, description in Section 24.3.4). The LEO satellite requires a PRN number between 901 and 999¹. The attitude flag has to be specified in the first section of the file (description at the end of the file). The satellite name — the same as the name in the station information file — as well as the sensor offsets, boresight and azimuth vectors in the satellite-fixed frame have to be specified in the second section (definition at the end of the file). Some of the LEOs equipped with GPS receivers are already included in the satellite information file that may be downloaded from CODE (<http://www.aiub.unibe.ch/download/BSWUSER52/GEN>, see Section 4.13.1). The entries for GRACE in PART1 and PART2 look like:

```

...
PART 1: PHYSICAL SATELLITE PARAMETERS
-----
...
909    909    2002-012A    -1    2002 03 17 00 00 00    2006 09 30 23 59 59    ...
909    909    2002-012A     1    2006 10 01 00 00 00    ...
910    910    2002-012B     1    2002 03 17 00 00 00    2006 09 30 23 59 59    ...
910    910    2002-012B    -1    2006 10 01 00 00 00    ...
...
PART 2: ON-BOARD SENSORS
-----
...
909  POD  GRCA L09              2002 03 17 00 00 00    2006 09 30 23 59 59    ...
909  SLR  SLR REFL. L09      2002 03 17 00 00 00    2006 09 30 23 59 59    ...
909  POD  GRCA L09              2006 10 01 00 00 00    ...
909  SLR  SLR REFL. L09      2006 10 01 00 00 00    ...

```

¹The usage of these PRN numbers follows the definition at http://cddis.nasa.gov/sp3c_satlist.html.

```

910 POD GRCB L10 2002 03 17 00 00 00 2006 09 30 23 59 59 ...
910 SLR SLR REFL. L10 2002 03 17 00 00 00 2006 09 30 23 59 59 ...
910 POD GRCB L10 2006 10 01 00 00 00 ...
910 SLR SLR REFL. L10 2006 10 01 00 00 00 ...
...

```

- The phase center file (description in Section 24.3.3) must contain the antenna specified in the RINEX file or in section TYPE 002: STATION INFORMATION of the station information file. Frequency-dependent phase center patterns (if available) and phase center offsets are taken from this file. Sensor offsets from the satellite information file are included in the correction as well. We refer to Section 18.2.5 for more details.
- The receiver, together with the corresponding code tracking information, has to be included in the receiver information file ($\${X}/\text{GEN}/\text{RECEIVER.}$, description in Section 24.3.6).
- Due to technical reasons, the coordinate file must contain an entry for the satellite (with the same name as in all other files). The coordinates may be zero. A coordinate file used, e.g., for GRACE may thus look like

```

Example LEOPOD 31-JAN-12 11:56
-----
LOCAL GEODETIC DATUM: IGS08 EPOCH: 2005-01-01 00:00:00
-----
NUM STATION NAME X (M) Y (M) Z (M) FLAG
  1 GRCA L09 0.00000 0.00000 0.00000 LEO
  2 GRCB L10 0.00000 0.00000 0.00000 LEO

```

Sensor offsets are applied based on the satellite’s attitude information. This information may stem from an attitude file (see Section 24.6.17), or it is computed based on the attitude flag specified in the satellite information file.

In general, the same processing programs as for terrestrial applications are used for LEO GPS data processing. Two exceptions are the programs KINPRE and LEOAUX. They can be found under "Menu>Service>LEO utilities". KINPRE converts kinematic positions from a Bernese-specific format (default extension KIN, description in Section 24.7.4) into the international precise orbit file format (default extension PRE, description in Section 24.6.2). LEOAUX is used to transform star tracker data from GOCE into attitude data and may also be used to concatenate once-per-revolution GOCE attitude files into, e.g., daily files.

Some programs have an option to explicitly activate the LEO data processing. In general, this option can be found in the top panel of the corresponding programs (e.g., "GPSEST 1.1: Input Files 1", "LEO data processing"). Tropospheric refraction is automatically disabled for a spaceborne receiver in all processing programs. At LEO altitudes, the ionosphere has, in general, still a significant effect on the signal propagation. This effect needs to be eliminated by analyzing the ionosphere-free linear combination. Usually, the elevation cutoff angle can be set to a very low value, or even to zero. An elevation-dependent weighting may be appropriate if significant multipath is present.

The processing steps for LEO orbit determination are the following:

0. Prepare the GPS satellite clocks, orbits, and the EOP as described in Chapter 5. Take care that you represent the GNSS satellite trajectories as good as possible (e.g., by adding pulses to ORBGEN) to not degrade the solution by inconsistencies in the PPP approach.
1. RXOBV3: Import the observations from a LEO RINEX observation file following the instructions for ground stations in Section 4.2.3. The option "Marker type" in panel

- “RXOBV3 5.1: Check Content of RINEX Header 1” allows to check for the MARKER TYPE indication in the header of the RINEX file.
2. CODSPP: An initial orbit may be generated based on code observations using program CODSPP in kinematic mode. The option “Estimate coordinates” in panel “CODSPP 2: Input Options” has to be set to KINEMATIC (see Section 6.3.3). Within this program run the receiver clock is synchronized to GPS system time, as well. The checkbox “LEO files” has to be activated in panel “CODSPP 1: Filenames”, although no files are available to be selected at this processing stage for “LEO standard orbit” in panel “CODSPP 1.2: LEO Files”.
 3. KINPRE: The resulting kinematic coordinate file (description in Section 24.7.4) has to be converted to a precise orbit file (description in Section 4.3.1).
 4. ORBGEN: From the precise orbit file a standard orbit is computed, following the instructions in Section 5.4.3. The orbit integration has to be based on a recent gravity field model (e.g., $\{X\}/GEN/EGM2008_SMALL.$) with a degree and order exceeding 70. The maximum degree and order for the ocean tide model should also be increased compared to GNSS orbits. The “SYSTEM FOR DYNAMICAL ORBIT PARAMETERS” can be chosen in panel “ORBGEN 3.1: Options” (see Figure 17.1). The most reasonable choice for a LEO is “System RSW”. “System DYX” only makes sense if the LEO has solar panels which are aligned to the Sun as, e.g, for the Jason satellites.

Select an integration step size of at most 00 03 00 minutes for the equations of motion in panel “ORBGEN 3.2: Options”, option “EQUATION OF MOTION: Length of interval”. You have to pay attention to set the integration step size to the same value for all subsequent ORBGEN runs for the LEO. The selected values from the LEO POD example BPE are shown in Figure 17.2.

In order to have the possibility for a subsequent orbit improvement in GPSEST, a “Radiation pressure coeff.” file has to be specified in panel “ORBGEN 2: Result and Output Files”. The option “Satellite number for stochastic pulses” (panel “ORBGEN 4: Parameter Selection”) is deactivated automatically because, for bookkeeping reasons, no stochastic pulses or piecewise constant accelerations are permitted in ORBGEN if a subsequent orbit improvement step is foreseen.

More details on orbit determination are discussed in Section 16.3.

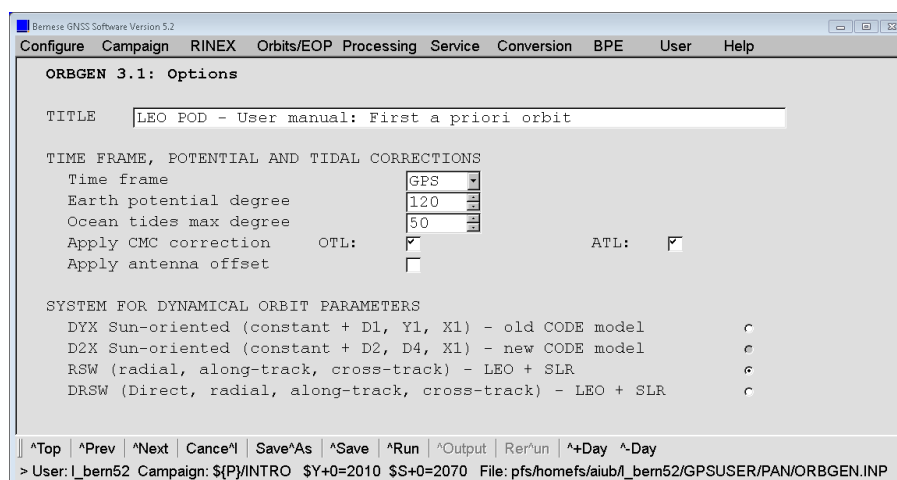


Figure 17.1.: Model settings for LEO precise orbit determination in ORBGEN.

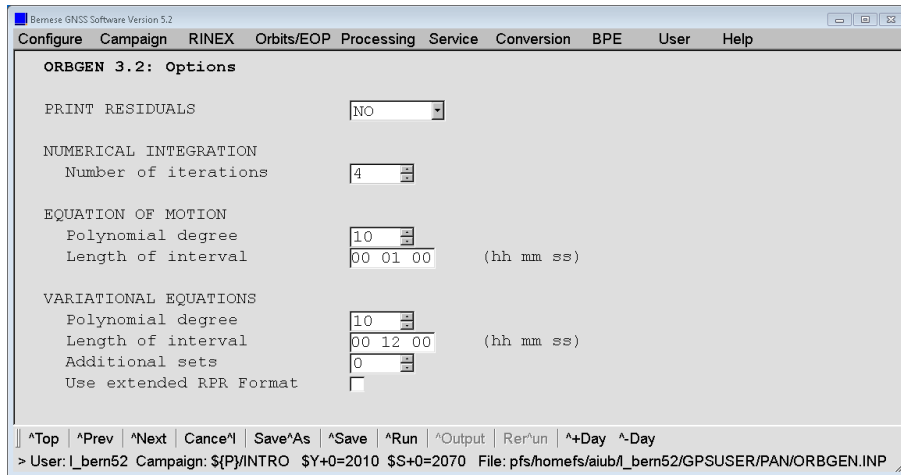


Figure 17.2.: Settings for numerical integration for LEO POD in ORBGEN.

5. MAUPRP: Start the screening of the phase data in zero-difference mode. Enable the “Kinematic coordinate estimation” in panel “MAUPRP 6: Epoch-Difference Solution” (see Figure 17.3). For GNSS satellites, a standard orbit together with a consistent precise GNSS satellite clock file has to be specified in panel “MAUPRP 1: Input Files”. Introduce the initial LEO standard orbit file from processing step (4) in panel “MAUPRP 1.2: LEO Processing”, “LEO standard orbit”. Adjust the options “A priori coordinate/baseline vector sigmas” (settings for first screening iteration in LEO POD example are shown in Figure 17.3), “Sigma for L1 observations”, and “Sigma for L2 observations” to the quality of your LEO orbit in “MAUPRP 6: Epoch-Difference Solution” and “MAUPRP 8: Cycle Slip Detection/Correction”. We refer to Section 6.5 for a detailed program description of MAUPRP.

If an attitude file is available for the satellite, it should be selected in the field “LEO attitude” in panel “MAUPRP 1.2: LEO Processing”.

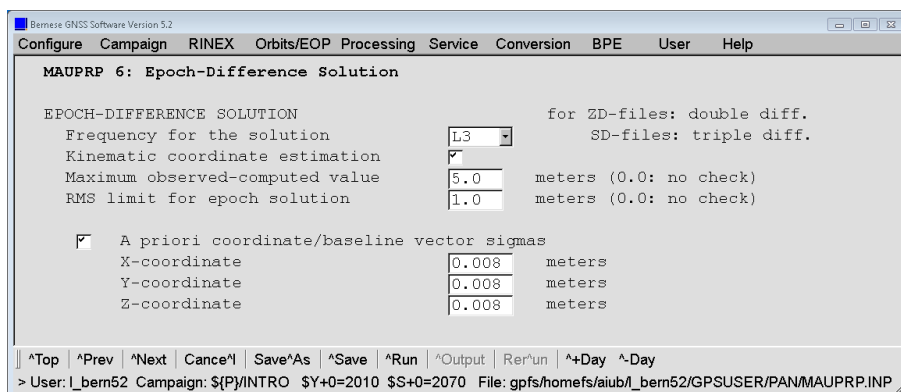


Figure 17.3.: Settings for first iteration of phase data screening of LEO data in MAUPRP.

6. GPSEST: The screened phase observation files are used in GPSEST to improve LEO orbit parameters. The radiation pressure file, together with the corresponding standard orbit (obtained in step (4) — also for subsequent iterations because this orbit may not contain any stochastic pulses or piecewise constant accelerations) has to be introduced for “Orbit partials” and “Standard orbit(s)”, respectively, in the “LEO-SPECIFIC INPUT FILES” section of panel “GPSEST 1.3: LEO- and SLR-specific Input Files”. In panel

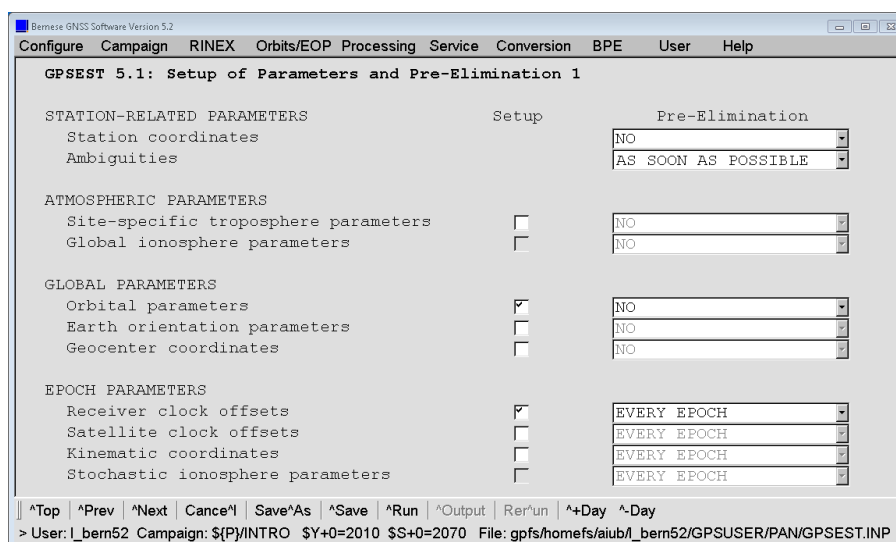


Figure 17.4.: Settings for LEO data processing in GPSEST — enable LEO POD.

“GPSEST 4: Datum Definition for Station Coordinates”, the coordinates (“Coordinates fixed”) should be fixed for ALL stations.

Because of the big number of ambiguity parameters (for LEOs about six to seven times more are expected than for static ground stations), it is recommended to select “Pre-elimination: Ambiguities” AS_SOON_AS_POSSIBLE and “Receiver clock offsets” EVERY_EPOCH in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1”, see Figure 17.4. Because of the pre-eliminated ambiguity parameters, the back-substitution of the epoch-wise pre-eliminated receiver clock parameters is not possible and must be disabled (select no clock result file and enable the printing option “Printing: Suppression of output concerning epoch parameters” in “GPSEST 3.2.1.1: Extended Program Output Options”). If you are interested in the receiver clock corrections for the LEO, you must not pre-eliminate any non-epoch parameter (e.g., ambiguities).

With the activation of “Parameter setup: GNSS or LEO orbit determination” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” (Figure 17.4) the panel “GPSEST 6.4.1: LEO Orbit Determination 1” becomes accessible (Figure 17.5). It is recommended to improve all orbital elements and dynamical parameters, and, most importantly, to activate the option “Estimation of stochastic pulses”.

It is necessary to specify the stochastic pulse parameters in panel “GPSEST 6.4.2: LEO Orbit Determination 2” (Figure 17.6). They may be set up as VELOCITY changes (pulses) or piecewise constant ACCELERATIONS in up to three directions. The “Radial pulses setup”, “Along track pulses setup”, and “Out of plane pulses setup” directions are recommended for LEOs. For the processing of one single LEO, the “Number of parameter sets per day” (e.g., 96 means every 15 minutes) may be set directly and the “A priori sigma” may be filled for each selected direction (5.0D-6 m/s is suitable for the selection of VELOCITY as parameters).

If more than one LEO is processed the “SATELLITE-SPECIFIC PARAMETER SETUP” should be used. Figure 17.6 shows the entries for the two GRACE satellites from the LEO POD example.

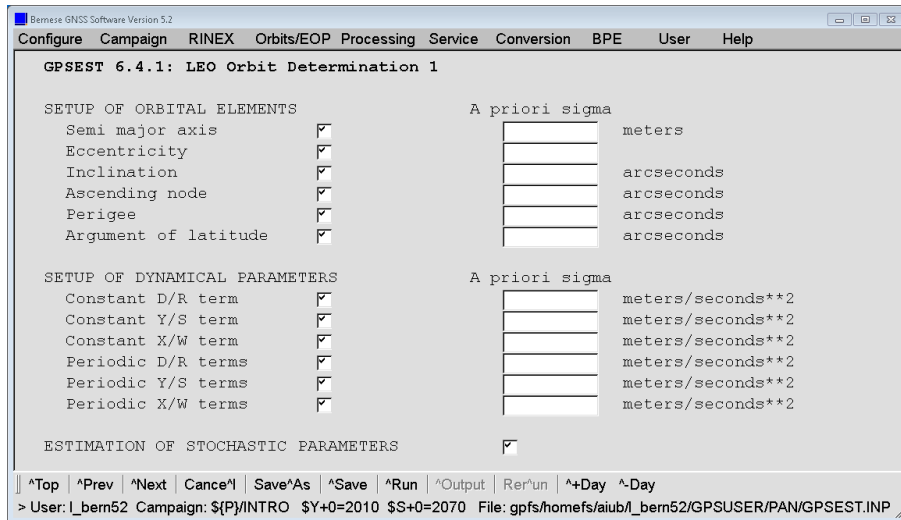


Figure 17.5.: Settings for LEO data processing in GPSEST (1).

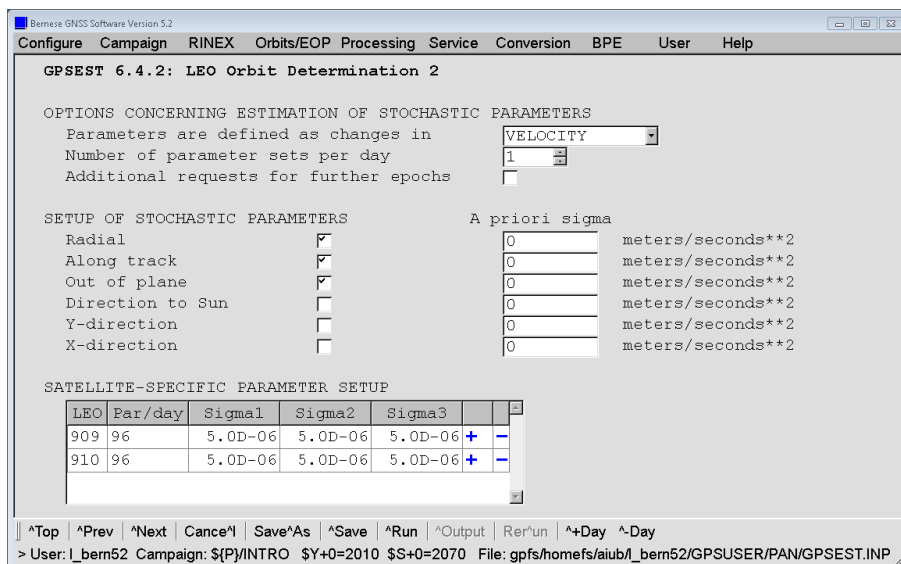


Figure 17.6.: Settings for LEO data processing in GPSEST (2).

- For the subsequent update step with ORBGEN it is important to write an orbital element file by choosing option “LEO orbital elements” in panel “GPSEST 2.3: LEO- and SLR-specific Output Files”.
- ORBGEN: The improved LEO orbital elements are introduced in the input field “Update standard orbits” of the top panel of ORBGEN. The result is an improved standard orbit for the LEO.
 - The screening procedure should be performed iteratively, repeating the processing steps (5) to (7).

Introduce the improved orbit from the previous iteration to MAUPRP. You may now reduce the screening level for the zero-difference observations. Make sure that you reset the marking flags in the observation files from the previous run (disable the option “Mark if marking flags in observation file” in “MAUPRP 4: Marking of Observations”).

As no stochastic pulses or piecewise constant accelerations are allowed when improving the orbit in GPSEST, you still have to introduce the orbit from the initial ORBGEN (step (4)) as a priori orbit to GPSEST in step (6) in the subsequent iterations.

Check the corresponding options and input files in the LEO POD example BPE. Depending on the LEO mission characteristics and the performance of the onboard GPS receiver, the thresholds may need to be adapted. Usually, the screening is finalized after the second iteration

9. After cleaning the observation files based on the algorithm in MAUPRP, the postfit residuals shall be checked for potential remaining outliers by program GPSEST again.

Introduce the standard orbit from ORBGEN (step (7)) of the last iteration. No orbit improvement is done in this step (option “Parameter setup: GNSS or LEO orbit determination” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” is deactivated). In order to obtain residuals, you cannot pre-eliminate any non-epoch parameters — option “Pre-elimination: Ambiguities” in panel “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” has to be switched to NO. You can verify these settings in Figure 17.7.

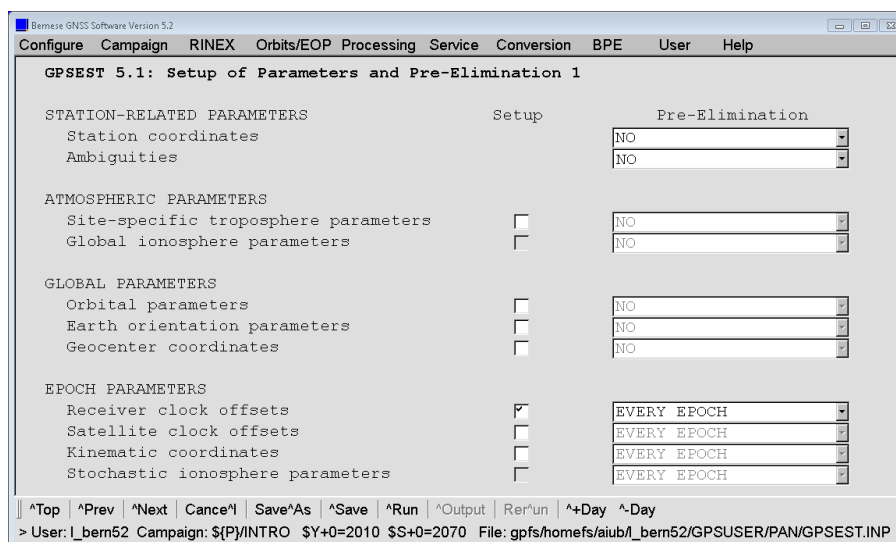


Figure 17.7.: Settings for residual screening for LEO data in GPSEST.

Since we want to examine the residuals, it is obvious that an output file for “Residuals” has to be specified (panel “GPSEST 2.2: Output Files 2”). As long as no weighting scheme is applied to the observations (option “Elevation-dependent weighting” in panel “GPSEST 3.1: General Options 1” is set to NONE) REAL, residuals may be requested in option “Type of computed residuals” (see Section 7.4.4 on residual computation in the program GPSEST).

RESRMS: The residual file is screened for residuals exceeding the threshold specified in option “Detect large residuals: phase limit” (panel “RESRMS 2: Options”). If real residuals are analyzed, a value of 4 cm is recommended for LEO data processing, but this may need to be adapted depending on the GPS data quality. Do not forget to set the “Sampling interval of residual files” to the same rate you have used in GPSEST when you have generated the residual file (see Section 6.6.2 for an explanation and the description of the program in general).

SATMRK: After checking the output and the edit request file (default extension EDT) written by program RESRMS, it can be applied to the observations by using program SATMRK.

10. STDPRE: The reduced–dynamic orbit resulting from the last update from ORBGEN (obtained in step (7) in your last iteration) is already of good quality. The sampling of the pulses is, however, normally too small (we recommend 15–minutes pulses for the screening procedure) for the best possible reduced–dynamic orbit result. In order to generate a reduced–dynamic orbit with a shorter interval for the stochastic pulse parameters, or piecewise constant accelerations instead of stochastic pulses, some more steps are necessary. Convert the standard orbit from the last update step to a precise orbit file with program STDPRE.
11. ORBGEN: A new a priori standard orbit based on this precise orbit file has to be generated. This standard orbit, together with the corresponding “Radiation pressure coeff.” file, will then serve as a priori information for the final reduced–dynamic orbit determination in GPSEST. If you would like to estimate piecewise constant accelerations for the reduced–dynamic orbit, you have to add one “VARIATIONAL EQUATIONS: Additional sets” in panel “ORBGEN 3.2: Options”.
12. GPSEST: The program GPSEST from step (6) shall be repeated, after changing the type of stochastic parameter (Option “Set up pulses as accelerations/velocities”) from VELOCITY to ACCELERATION, as well as increasing the “Number of parameter sets per day” for the final reduced–dynamic orbit determination. It is important to make sure that the interval between subsequent stochastic parameters is a multiple of the integration step size for the equation of motion previously specified in ORBGEN.

The resulting orbit is again given as an element file (default extension ELE). It is numerically integrated to a standard orbit using the program ORBGEN (as in step (7)). Afterwards, a precise orbit file shall be extracted to exchange the results with other groups — again with program STDPRE as in step (10).

13. At this point, it is also possible to compute a kinematic trajectory for the LEO. The reduced–dynamic orbit generated in step (12) should be selected as a priori information. The screened phase observation files may also be reused for the determination of the kinematic trajectory. Technically, the same procedure as for roving ground stations (see Section 10.5) apply: The “Kinematic coordinates” have to be set up and pre–eliminated EVERY_EPOCH in “GPSEST 5.1: Setup of Parameters and Pre–Elimination 1”. The “Station selection” for “STATIONS TO BE TREATED AS KINEMATIC” has to be set to ALL in panel “GPSEST 6.9: Kinematic Coordinates”. Special attention should be given to the “Minimum number of obs per station clock” in panel “GPSEST 6.8.1: Clock Estimation 1” and the “kin. Pos.:min. number of obs. per epoch” in panel “GPSEST 6.9: Kinematic Coordinates”. These two numbers should be set to the same values because otherwise it may happen that for a given epoch kinematic positions are available but no receiver clock correction or vice–versa.

In order to exchange the kinematic orbit with other institutions, or simply to compare it with the reduced–dynamic orbit, a KINPRE run is needed to get a precise orbit file. The orbit comparison may be done with ORBCMP, where you may select RSW as “System for comparison”. The RSW–system gives the differences in the radial, along–track and out–of–plane directions of the in–orbit system. Please be referred to Section 5.5.2 for a description of the programs for orbit comparisons in the *Bernese GNSS Software*.

Ground station networks designed for reference frame purposes nowadays typically sample the GNSS measurements with 30 s. As a consequence, satellite clock corrections from the IGS are only available with a sampling of 30 s as well. On the other hand, most of the modern LEO missions provide GPS data with a higher sampling. Unfortunately, the GPS satellite clocks cannot be linearly interpolated (Bock et al. 2009). For that reason CODE is providing an ultra high-rate clock product with a 5 s sampling for the GPS satellite clock corrections (see Section 4.13.1) based on its final orbit product. According to the experience from Bock et al. (2009), these 5 s sampled satellite clock corrections may be interpolated down to 1 Hz. The *Bernese GNSS Software* is supporting this by the option “Clock interpolation allowed over” in various processing programs.

18. Antenna Phase Center Offsets and Variations

18.1. Introduction

When introducing the observation equations in Section 2.3, the term ϱ_k^i was denoted as the “geometric distance between satellite i (at signal emission time $t - \tau_k^i$) and receiver k (at signal reception time t)”. The points with respect to which the geometrical distance ϱ_k^i are really measured, have to be specified precisely. These points are called *antenna phase centers*.

GNSS signals from individual satellites arrive at the receiver antenna from different directions. The position of the antenna phase center depends on this direction. This direction-dependence is what we call *antenna phase center variations*. We also have to take into account that the antenna phase center offset (with respect to the antenna reference point) and the antenna phase center variations (with respect to the mean antenna phase center) are not identical for different carrier frequencies. Furthermore, radomes that are used at many stations to protect the GNSS receiver antennas from multipath and environmental effects have an impact on the antenna phase center variations.

If highest accuracy is required, each individual antenna has to be calibrated to obtain its phase center corrections which then have to be applied in the analysis. For most applications it can be assumed that antenna phase center variations depend only on antenna and radome type. Nevertheless, the effect has to be carefully modeled, especially if different antenna/radome combinations with individual characteristics are used simultaneously. Ignoring the antenna phase center corrections may cause relative station height errors reaching values of up to 10 cm — independent of the baseline length. If only antennas of the same type are used, the main effect is a scale factor in the network of up to about 0.015 ppm.

For the transmitting antennas of the satellites a similar antenna phase center variation is expected. The nadir angles of the lines of sight from one satellite to the individual stations in a large scale network are different. Analogous to the receiver antennas, a scale factor for the network solution is thus expected.

The first antenna phase center models used within the IGS were the relative models (model name: IGS_01). One antenna type (AOAD/M_T without radome) was assumed to represent a “perfect” antenna without any direction dependence of the antenna phase center. All other antenna types were calibrated relative to this reference. Only elevation-dependent corrections and no azimuthal dependencies were taken into account. Antenna radomes have not been considered for most of the antennas. In addition, the variations of the satellite antenna phase centers were neglected — only a constant antenna offset vector from the center of mass of the satellite to the satellite antenna was considered.

In GPS week 1400 (November 5, 2006, day of year 309) the IGS has switched to an absolute antenna phase center model — model name: IGSyy_www, yy=05 where yy denotes

the year, indicating a certain model, and `www` the week of the released updates (see IGS Mail 5272). It is based on a set of robot-calibrated receiver antenna phase center variation models considering also the azimuthal dependence (Wübbena et al. 2000). At the same time the satellite antenna phase center variations started to be considered in a nadir-dependent model (Schmid and Rothacher 2003). These two changes correspond to each other because the satellite antenna phase center model was determined based on the absolute receiver antenna phase center model. In addition, the impact of different antenna radomes is considered: phase patterns for antennas with radome are either used directly from the robot calibration, or converted from the relative model, or — if no corrections are available — the model for the same antenna type without radome is used instead.

This first absolute antenna phase center model used within the IGS assumed that receiver antenna phase patterns for GLONASS frequencies are equal to those of the corresponding GPS frequencies. However, studies have shown small differences between receiver antenna phase center variations for the same frequencies for different GNSS. The number of calibrated GNSS receiver antennas with separate GPS and GLONASS patterns did increase during the phase of completing the GLONASS constellation. The IGS published the first set of separate corrections for GPS and GLONASS with the `IGS08_www` model series. Calibrations for other GNSS (e.g., Galileo or BeiDou) and for the new GPS frequency L_5 are still rare. Missing calibrations are usually derived from the GPS L_1 and L_2 calibrated values.

In the recent years absolute antenna phase center models have been applied also to old GNSS data dating back to 1994 in the frame of the IGS reprocessing campaigns (see, e.g., Steigenberger et al. 2011).

18.2. Antenna Phase Center Corrections in the *Bernese GNSS Software*

18.2.1. Mathematical Representation of Antenna Phase Center Corrections

In the *Bernese GNSS Software* the following mathematical representation of the antenna phase center variation correction is used, that is also illustrated in Figure 18.1:

$$\Delta\phi(\alpha, z) = \Delta\phi'(\alpha, z) + \Delta\mathbf{r} \cdot \mathbf{e}, \quad (18.1)$$

where

- $\Delta\phi(\alpha, z)$ is the total phase center correction applied to the geometric distance between satellite and receiver,
- α, z is the azimuth and the zenith angle of the satellite as seen from the receiver, and
- $\Delta\mathbf{r}$ defines the position of the mean antenna phase center with respect to the mechanically defined antenna reference point. This vector is uniquely defined by imposing the condition

$$\int_{\alpha=0}^{2\pi} \int_{z=0}^{z_{max}} \Delta\phi(\alpha, z) \sin z \, dz \, \partial\alpha = \min. \quad (\text{e.g. } z_{max} = 75^\circ).$$

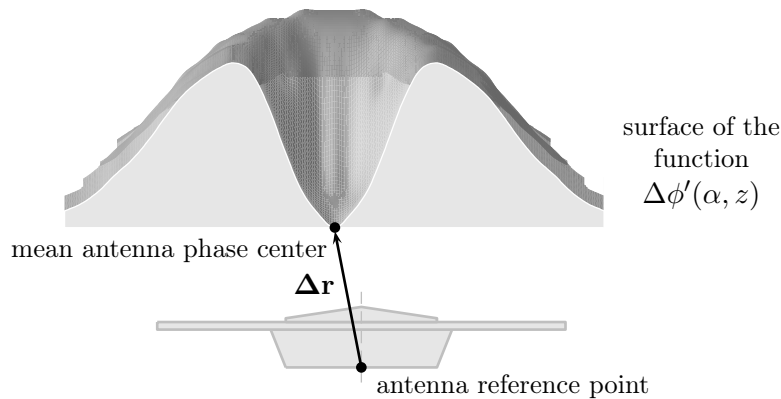


Figure 18.1.: Representation of an azimuth- and zenith-angle-dependent antenna phase center variation model in the *Bernese GNSS Software*.

The antenna reference points for different antenna types are defined in RINEX and IGS standards. For most antenna types the reference points are given in file `ftp://ftp.igs.org/pub/station/general/antenna.gra`.

e denotes the unit vector in the direction from the receiver antenna to the satellite, and

$\Delta\phi'(\alpha, z)$ is the function modeling the phase center variations. Two different model functions may be used in the *Bernese GNSS Software*:

1. Piecewise linear function in elevation (and optionally in the azimuth): polygon approach.
2. Spherical harmonic function of maximum degree n_{max} and maximum order $m_{max} \leq n_{max}$:

$$\Delta\phi'(\alpha, z) = \sum_{n=1}^{n_{max}} \sum_{m=0}^n \tilde{P}_{nm}(\cos z) (a_{nm} \cos m\alpha + b_{nm} \sin m\alpha),$$

where \tilde{P}_{nm} are normalized associated Legendre functions of degree n and order m , and a_{nm}, b_{nm} are the coefficients of the harmonic series development.

The representation based on a series of spherical harmonics is physically more meaningful, in particular for azimuth-dependent variations, but the polygon model is more efficient for processing GNSS data (linear interpolation between tabular values) and may be introduced more easily into other software packages (e.g., via the ANTEX format, see Section 4.7).

Thus, Eqn. (18.1) describes the range correction of the geometric distance between satellite and receiver due to the phase center variation. It can be used to represent both, the phase center correction $\Delta\phi_k(\alpha_k^i, z_k^i)$ for the receiver antenna k in the direction to the satellite i and the phase center correction $\Delta\phi^i(\alpha_i^k, n_i^k)$ for the satellite antenna as a function of nadir angle n and azimuth α (measured in the satellite-fixed reference frame). The geometrical distance ϱ_k^i between station k and satellite i is corrected for both effects, $\Delta\phi_k(\alpha_k^i, z_k^i)$ and $\Delta\phi^i(\alpha_i^k, n_i^k)$.

18.2.2. Satellite Antenna Phase Center

GNSS Observations

The information related to the satellite antenna phase center model is contained in two files:

- The second part of the satellite information file (description in Section 24.3.4, example in Figure 24.5) contains the offset of the physical antenna reference point with respect to the satellite's center of mass. It is frequency-independent but may change in time, e.g., due to fuel-consumption of the spacecraft during maneuver events.
- The phase center eccentricity file (description in Section 24.3.3, example in Figures 24.3 and 24.4) contains the mean offset of the antenna's phase center with respect to the physical antenna reference point and the (azimuth- and) nadir-dependent antenna phase center variations. Both components are frequency-dependent.

For a given PRN and time window, the sensor name listed in column `SENSOR NAME`_____SVN in the second part of the satellite information file has to match the corresponding name in the phase center eccentricity file (column `ANTENNA/RADOME TYPE`). The sensor name is a unique string of 20 characters length consisting of three parts:

- Positions 1 and 2 are MW, the identification of a microwave transmitter.
- Positions 5 to 16 identify the GNSS satellite type (e.g., `BLOCK IIA`, `BLOCK IIR-M`, or `BLOCK IIF` for GPS and `GLONASS` or `GLONASS-M` for GLONASS, respectively).
- Positions 18 to 20 contain the SVN of the satellite (not PRN) to allow for an unambiguous identification over the entire constellation history.

This convention results in sensor names of the type `MW BLOCK IIR-M 048` or `MW GLONASS-M 730`. It is recommended to use the entry in the `TYPE` field in the `ANTEX` files distributed by the IGS to identify the satellite antenna type (even if the satellite information file contains a separate column for the identification of the satellite antenna in the `ANTEX` file by program `ATX2PCV` — the type identification string in `ANTEX` is simply longer than allowed in this `SENSOR NAME` field).

GNSS satellite antenna offsets are applied according to the nominal attitude of the satellite. When a satellite passes through the Earth's shadow, however, it cannot orient itself correctly with respect to the Sun (see, e.g., Bar-Sever 1996). This situation occurs during the shadow pass itself, which can last up to 55 minutes in the case of GPS satellites, and may persist up to 30 minutes after reentering into sunlight. For satellites whose antenna is not located on the z-axis of the satellite reference frame (e.g., GPS Block II, Block IIA, Block IIF, and GLONASS-M), the resulting mis-orientation may lead to biases in the geometrical distance between satellite and receiver antenna of up to about 10 cm in the worst case for very long baselines. Since this effect is not considered in the *Bernese GNSS Software* Version 5.2, the related observations are typically excluded in the pre-processing procedure. If this is not the case (e.g., in case of a kinematic solution with low redundancy), the related measurements may also be excluded by setting the "Special data selection" (panel "GPSEST 3.1: General Options 1") to `NON-ECLIPSING` or `SPEC.NON-ECL`.

To apply the antenna phase center positions from the satellite information file it is necessary to know if the satellite positions (given in the precise orbit file) represent the center of

mass (standard case) or directly the positions of the antenna phase center. The user has to specify this in the option “Apply antenna offset” in panel “ORBGEN 3.1: Options” when running program ORBGEN (“Menu>Orbits/EOP>Create/update standard orbits”). CODE and IGS orbits always refer to the center of mass of the satellite, whereas the satellite positions given in the navigation messages refer to the antenna reference point.

SLR Observations

For SLR measurements, only the offset of the retroreflector with respect to the satellite’s center of mass has to be considered, which is given in the satellite information file. The “SENSOR NAME_____SVN” starts with “SLR REFL.” to identify the sensor type followed by an identifier for the satellite type (resulting for instance in SLR REFL. GLONASS-M). Entries for SLR retroreflectors also need to be included in the phase center eccentricity file, even though they are usually zero (but may accommodate variations of the optical center).

18.2.3. Receiver Antenna Phase Center

The receiver antenna phase center model is stored in the phase center eccentricity file (description in Section 24.3.3). An example can be found in the Figures 24.3 and 24.4. The file contains an information block for each antenna calibration. The start of a new antenna block is indicated by the keyword ANTENNA/RADOME TYPE. Each antenna calibration is identified by the antenna name (including the radome code at the positions from 16 to 20) and an integer antenna number (no characters allowed here). Both are compared to the corresponding information in the observation file header.

In the phase center eccentricity file there is now a distinction between two cases (which must be mixed up):

- If *individual antenna calibrations* shall be considered in a campaign, individual antenna numbers ranging from 1 to 999998 are used for individually calibrated antennas, while the antenna number “999999” is used to indicate type-specific calibrations (i.e., applied to all antennas of the same type with no individual calibration available) in the phase center eccentricity file.
- If only *type-specific calibrations* shall be considered in a campaign, all antennas are stored with the antenna number “0” in the phase center eccentricity file (i.e., there is only one calibration per antenna type).

Both modes require separate phase center eccentricity files, whose generation requires different option settings in the program ATX2PCV (see description on option “Set number of generic antennas to 999999” in Section 18.3.1).

It is also important to know that all processing programs have to find all expected entries in the antenna phase center eccentricity file. As soon as an antenna is connected to a receiver that supports other systems than only GPS, the corresponding corrections are requested for all additional GNSS as well. To allow for some consistency checks on NEQ level, this is necessary even if only a subset of the systems is currently processed. Otherwise the program GPSEST will stop with an error messages looking like:

```
*** SR SEARCH_OFF: No offset values found for
                   satellite system R of
                   Antenna: LEIAT504GG      SCIS
                   Number:      999999
```

This problem can easily be solved by running the program ATX2PCV using the complete “Station information file” file together with the “Receiver information” to complete the antenna phase center eccentricity file to be used for the processing.

The antenna phase center offsets and antenna phase center variations are different for different carrier frequencies. The antenna phase center corrections for a linear combination of L_1 and L_2 observations are, e.g., computed by forming the corresponding linear combination of $\Delta\phi_{L_1}(\alpha, z)$ and $\Delta\phi_{L_2}(\alpha, z)$.

In order to correctly apply horizontal antenna phase center offsets as well as azimuth-dependent corrections, a North-pointing of the antenna is important. A differing orientation (e.g., when rotating the antenna during a calibration field campaign) may be specified in a “Receiver antenna orientation” file (description in Section 24.7.8). It can be selected in panel “GPSEST 1.2: Input Files 2”.

18.2.4. Technicalities on the Receiver Antenna Handling

In the RINEX observation files the antenna type (including the radome) and the antenna serial number are each indicated by strings of 20 characters length. Both can be verified with the expected station equipment configuration with the columns `ANTENNA TYPE` and `ANTENNA SERIAL NBR` in the station information file, when importing RINEX observations (see description on program RXOBV3 in Section 4.2.3.4). The full string for the antenna type and the internal integer number (column `ANT #` in the station information file) is written in the Bernese observation header file and is used to access the antenna phase center corrections during the processing.

When program ATX2PCV imports the antenna phase center corrections from an external ANTEX file, the same fields are taken to identify an antenna. They are put into the resulting “Bernese phase center offsets” file again with the string for the antenna type and the internal integer number, if antenna-specific calibration values shall be used. In this case, the internal number 999999 is reserved for type-specific calibrations. If only type-specific calibrations shall be considered, the checkbox in “Set number of generic antennas to 999999” has to be cleared and the antenna type is stored in a different “Bernese phase center offsets” file with 0 as the internal integer numbers for all antennas. This indicates to the processing programs that the internal integer number must not be used to find the antenna

Table 18.1.: Bookkeeping of the antenna number in the *Bernese GNSS Software*.

File type	Consider individual calibrations		Use group calibrations only	
	individual	other	individual	other
RINEX observation	Antenna # (20 char)	Antenna # (20 char)	Antenna # (20 char)	Antenna # (20 char)
BSW observation	Antenna # (6 digit)	999999	Antenna # (6 digit)	999999
ANTEX	Antenna # (20 char)	0	Antenna # (20 char)	0
BSW phase center	Antenna # (6 digit)	999999	0	0
NEQ	Antenna # (6 digit)	999999	Antenna # (6 digit)	999999
SINEX	Antenna # (5 char)	-----	-----	-----

phase center corrections for a specific antenna from the Bernese observation file (in that case only the antenna type string is checked). With this procedure, solutions considering type-specific or individual antenna phase center correction may be used with the same set of observation files.

When a NEQ is stored into a file by GPSEST, all relevant information on the antennas used in the processing are stored as well. This includes, among others, the mean phase center offsets for each GNSS that might be relevant for the receiver/antenna combination, as well as the name of the antenna phase center model (field SINEX in the “Phase center eccentricities” file specified in GPSEST). If several NEQs are combined later on in ADDNEQ2, the compatibility of the antenna phase center corrections may be checked. In this way it is also possible to ensure that the meta data reported in a resulting SINEX file are fully consistent with the used antenna phase center corrections. When writing a SINEX file, the internal integer number used within the processing is translated back into the official string of 20 characters length by the related entry in the “Station information” file. Unfortunately, SINEX only supports a string with length 5 characters here. The *Bernese GNSS Software* Version 5.2 uses simply the 5 last characters of the official antenna serial number. If you need to change this behavior you may adapt the subroutine SUBROUTINE `sinstore_getsn` at the end of the file `#{LG}/SINSTORE.f90`.

The antenna number traceability within the *Bernese GNSS Software* described in this section is shown as an overview in Table 18.1.

18.2.5. LEO Processing

The LEO receiver antennas for precise orbit determination (POD) are marked with the keyword POD in column TYPE in the second part of the satellite information file. The sensor name (stored in column SENSOR NAME_____SVN) can be freely chosen. The sensor offsets (position of the antenna reference point with the relation to the satellite’s center of mass) are stored in this file, as well.

The frequency-dependent antenna phase center offset and variations are stored in the antenna phase center file in the same way as for antennas of GNSS satellites and ground receivers. The SLR retroreflectors of LEOs are treated in the same way as the corresponding sensors of GNSS satellites (see Section 18.2.2).

Antenna phase center offset as well as variation refer to the antenna fixed coordinate system. The proper antenna orientation as well as antenna offsets are computed from the azimuth and boresight unit vectors specified in the satellite fixed reference frame in the satellite information file. The attitude information is either computed from nominal attitude (attitude flag in satellite information file) or read from an input attitude file. More information about LEO processing can be found in Section 17.

18.2.6. Antenna Phase Center Models

Antenna phase center corrections are strongly correlated to the obtained station coordinates. For that reason, the antenna phase center models of the IGS are related to the reference frame releases. The currently used model within the IGS is published at `ftp://ftp.igs.org/pub/station/general/`, filename: `igs08_www.atx` (e.g., `igs08_1793.atx`). It is related to the IGS realization of the ITRF 2008 reference frame. The `www` indicates the GPS week of file creation (see IGS Mail 5272). File updates take

place regularly, e.g., when a new antenna radome combination is added or a new satellite was launched. The link <ftp://ftp.igs.org/pub/station/general/igs08.atx> points to the most recent version of the file. Older IGS phase center files like the relative antenna phase center model (`igs_01.atx`) used until GPS week 1400 and the first absolute phase center model (`igs_05.atx`) used until early 2012 are still available — but not maintained anymore.

At the AIUB/CODE's anonymous ftp server (<http://www.aiub.unibe.ch/download/BSWUSER52/GEN>) the latest antenna phase center model is available already converted into Bernese file formats:

`SATELLIT.XXX` contains satellite-specific information, in particular satellite-specific sensor offsets that need to be consistent with the corresponding satellite antenna phase center information.

`PCV_COD.XXX` contains the phase center information of the satellite and receiver antennas, and SLR retro-reflectors used by CODE for the daily processing.

`XXX.ATX` is a copy of the latest ANTEX file of the IGS. It is ensured that all time intervals related to satellite antennas are fully consistent with the satellite information file (which may not be the case with the official one during certain intervals when satellites are activated or deactivated).

The abbreviation `XXX` in the above filenames is currently `XXX=I08`.

Regularly download at least the satellite information file. The CODE's phase center eccentricity file (`PCV_COD.XXX`) is used in the IGS processing chains at the CODE AC and contains antennas for those stations that are included in the solution. You may download this file and use it also for your purposes. It is, however, recommended to generate your own Bernese phase center file using the ANTEX converter `ATX2PCV` (see Section 18.3) in order to ensure that all receiver antenna/radome combinations (for all GNSS) needed for your particular processing are available. The ANTEX converter `ATX2PCV` may also be used to extend existing phase center eccentricity files with new antenna types. Individually calibrated antennas must be used in a separate phase center eccentricity file.

The resulting phase center eccentricity files depend on the station information file of your project. To express the difference between your and CODE's phase center eccentricity files, it is recommended to replace the string `COD` in the filename by a proper identification of your own organization. Furthermore, we recommend to keep the naming convention for all your files, i.e., using the antenna phase center model type as extension to indicate the relation between the satellite information and phase center eccentricity files.

Initially, when a new satellite is launched, there are no estimated satellite antenna offsets available for this satellite. The corresponding entry will be missing in the official ANTEX file (e.g., `igs08_1793.atx`) as well as in the Bernese phase center eccentricity file. Without these entries any (near real-time) processing will be aborted. In order to make corresponding information available before tracking of brand new satellites, AIUB/CODE maintains its own ANTEX file (`I08.ATX`) and provides them at <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>. These files contain mean antenna offset values for the new satellite taken from other satellites of the same type. Apart from these values for the new satellites, this ANTEX file is identical to the official ANTEX file. After the publication of the official satellite antenna offsets, the updated ANTEX file will be distributed by the IGS. From that moment on, the ANTEX file at our anonymous FTP will again be identical to the official ANTEX file from the IGS.

The above described handling of files related to the antenna phase center information is well established in the distributed processing examples. We recommend to follow this strategy if you are developing your own BPEs. The following four BPE server variables are related to this:

```
#
VARIABLE DESCRIPTION                                DEFAULT
8***** 40***** 16*****
...
V_MYATX ANTEX file for update (name incl. ext)
V_PCV Absolute/relative PCV model I08
V_SATINF Satellite information file SATELLIT
V_PCVINF PCV information file PCV
...
#
# DO NOT USE V_D, V_J, V_M, V_Y VARIABLES!
#
```

They are used to construct the names of the “Satellite information” and “Phase center eccentricities” files in all programs of the BPE. The value for the variable `V_PCVINF` can easily be extended to a name in recommended style of `PCV_CCC.$(PCV)` (with `CCC` being a proper identifier). With the `V_MYANTEX` even the automated update of the antenna phase center eccentricity file is prepared. Please read through the description of the processing examples in Section 23.4.

18.3. ANTEX Converter ATX2PCV

18.3.1. General Description

The program for importing the ANTEX files into the *Bernese GNSS Software* environment is named `ATX2PCV` (“Menu>Conversion>ANTEX to Bernese format”, replacing the converter `PHCCNV` in Version 5.0 and earlier versions). The ANTEX converter is capable of performing the following tasks:

- Generation of a new Bernese phase center eccentricity file. (relative or absolute) from an ANTEX file up to **version 1.4**.
- Updating of an existing Bernese phase center file with newer antenna calibration values.
- Merging new or individually calibrated antenna patterns from ANTEX into an existing Bernese phase center eccentricity file.
- Adding patterns of antenna radome combinations that are not included in ANTEX to the Bernese phase center eccentricity file according to the antenna list in the station information file.
- Updating an old Bernese phase center eccentricity file containing old satellite antenna names and no receiver antenna radome codes.

The converter requires the `SATELLIT.XXX` file made available at <http://www.aiub.unibe.ch/download/BSWUSER52/GEN> (currently `XXX = I08`).

The program `ATX2PCV` has three input panels. In the first panel “ATX2PCV 1: Input” you can select input, result, and output files. The panel “ATX2PCV 2: ANTEX Conversion” (see Figure 18.2) is specific to the ANTEX file conversion. It provides options allowing to fill missing phase pattern values up to a specified elevation (or nadir) angle. Depending on the measurement technique, pattern values close to the limiting zenith (or nadir) angle may be missing. These values may be filled with zeroes or with the value of the last available zenith (or nadir) angle. For ground antennas the missing values may be alternatively substituted by the values of the `AOAD/M_T` NONE antenna, the reference antenna in case of relative antenna patterns.

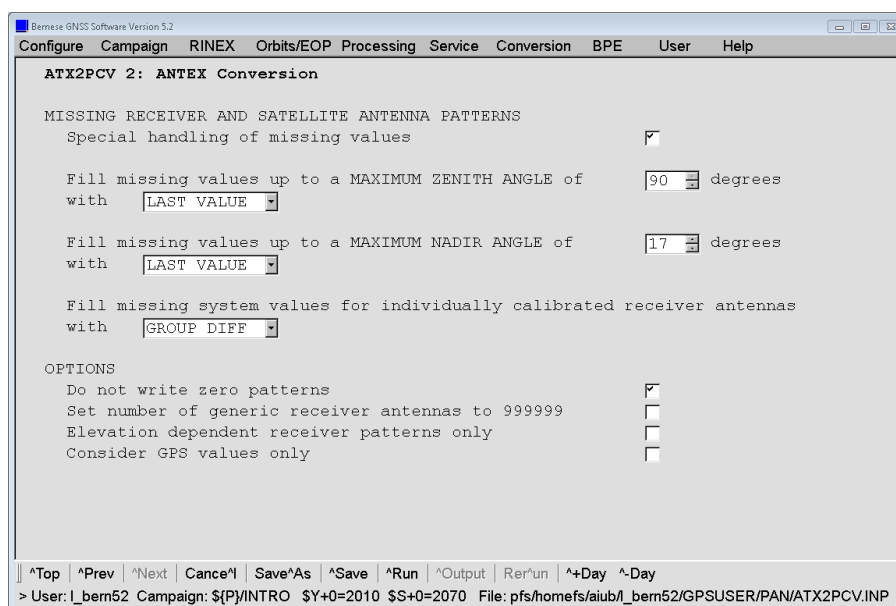


Figure 18.2.: Program input panel for processing options in program ATX2PCV.

If GNSS-specific group calibrations for a GNSS other than GPS are missing, then they are automatically adopted from the GPS L_1 and L_2 calibrations (indicated by the comment **ADOPTED from GPS** in the resulting phase center eccentricity file). If GNSS-specific calibrations are missing for individually calibrated antennas they might be adopted either from the GPS calibrations of the same antenna, or from group calibrations of the same antenna type, or from the difference between the group calibrations of GPS and the requested GNSS added to the GPS-specific calibrations of the individually calibrated antenna in question. Missing calibrations for a certain antenna and radome combination are automatically derived from the same antenna type without a radome (see comment **ADOPTED from NONE** in the phase center file).

The option “Set number of generic antennas to 999999” in panel “ATX2PCV 2: ANTEX Conversion” is important, because it is the switch between consideration or non-consideration of individual antenna calibrations in your processing: It must be activated if individual antenna calibrations shall be considered. All group-specific calibrations then get the antenna number “999999” in the phase center file, while the individually calibrated antennas have their individual 6-digit numbers. If only group calibrations are to be considered in the processing, the option must be de-activated. In this case, the phase center file will only contain group calibrations with the antenna number “0”. (see Section 18.2.4 for more details).

A further description of the options can be found in the online help or in the examples in Section 18.3.2. In any case, it is worth checking the detailed program output carefully in order to verify that the information for all antennas was properly handled and that the output phase center eccentricity file is ready for use.

18.3.1.1. Input and Result Files

The input files are read from different directories. The “External phase center offsets” file (ANTEX format) has to be stored in the OUT directory of the campaign. The “Input

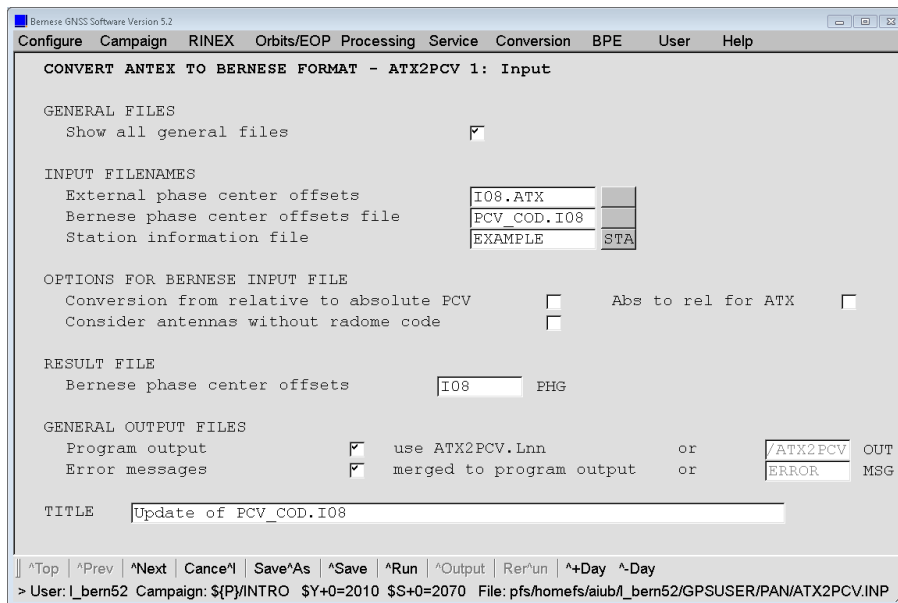


Figure 18.3.: Program input panel for input and result file of program ATX2PCV.

Bernese phase file” is read from the $\${X}/GEN$ and the “Station information file” is read from the `STA` directory of the campaign. The resulting “Bernese phase center offsets” file is stored in the `OUT` directory of the campaign and is labeled with the default extension `PHG`. Please verify the content of the created phase center eccentricity file before copying it to the $\${X}/GEN$ directory for further use. In addition, you should rename the extension from `PHG` to the phase center model identifier (e.g., `I08`).

The name of the antenna model is saved in the header of the Bernese phase center eccentricity file. The model name of the Bernese input file is replaced by the model name of the ANTEX file if characters 1–3 and 6 of the model are equal (matching, e.g., `IGS??_` assuming that the Bernese phase center file is updated with a new IGS phase center model). If you use your own model it is recommended to use a similar convention for the model name, e.g., `LPT08_`.

18.3.1.2. Program Output

The program output provides a detailed summary of the conversions performed. The first section lists all satellite antennas from the satellite information file as well as corresponding information from the ANTEX file. A second section deals with all other antennas and details where the offsets and pattern values were taken from (whether from the “External phase center offsets” file in ANTEX format or “Input Bernese phase file”). These two sections are always provided. Additional sections depend on the selected options and are self-explanatory.

18.3.1.3. Warning and Error Messages

The program provides detailed warnings and error messages in case of potential problems. Please check the warning messages carefully and decide whether the indicated

problem is relevant for you or not. The following description will help you with this decision.

The program, e.g., generates a warning message for each satellite included in the satellite information file for which no antenna information is available in the ANTEX file. Since for most GPS Block I and older GLONASS satellites no absolute offsets and patterns are available, you may ignore the corresponding warnings as long as you do not process data from these satellites. However, do not overlook new satellites that are not yet included in ANTEX (see also Section 18.2.6).

Further warning messages are issued if you select an input Bernese phase center eccentricity file with missing antenna radome codes for one or more antennas. Depending on the setting of the option “Consider antennas without radome code”, missing radome codes are substituted with a string “????” in the output phase center eccentricity file or the antennas are not written at all to the output file. A similar warning is issued if a station information file with missing antenna radome codes in section TYPE 002: STATION INFORMATION is selected. For that reason, please add the correct antenna radome codes in the “Input Bernese phase file” and in the “Station information file” before executing the ANTEX converter.

Error messages are generated if you try to combine, e.g., an absolute Bernese phase center eccentricity file with an old relative ANTEX file or a relative ANTEX file with an absolute satellite information file. In this case no result file will be written. You have to rerun the program with the correct combination of files and options.

If you want to change the satellite antenna names in your satellite information file, you have to ensure that the characters 5 to 16 of the satellite antenna name in the satellite information file are identical to the characters 1 to 12 of the corresponding satellite antenna name in the ANTEX file. Note that the SVN and validity time window (given by “START TIME” and “END TIME”) in the satellite information file must correspond with the PRN and time window (given by “VALID FROM” and “VALID UNTIL”) in the ANTEX file. Otherwise, the satellite antenna will not be included in the Bernese phase center eccentricity file and the program will issue a warning message. To avoid such problems, we advise to use the satellite antenna naming of the provided satellite information file SATELLIT.I08.

18.3.2. Examples

The following examples describe the handling of the most important conversion scenarios.

18.3.2.1. Creation of a New Bernese Phase Center File from an ANTEX File

The basic function of the program ATX2PCV is the conversion of an ANTEX formatted file into a new Bernese phase center eccentricity file. Select the name of the input ANTEX file (e.g., I08.ATX) in the field “External phase center offsets” and of the related “Station information file” in panel “ATX2PCV 1: Input”. Select also the “Receiver information” and “Satellite information” files in panel “ATX2PCV 1.1: General Files”.

The resulting Bernese phase center eccentricity file contains the information from the ANTEX file plus the necessary information that can be derived from it. The station

information file is used by ATX2PCV in order to check, which antenna types may actually occur in your network. Only the patterns of those antenna radome combinations are converted and stored in the resulting phase center information file. Phase center information for antenna radome combinations not contained in the input ANTEX file are derived from the antenna of the same type, but without radome (i.e., **ADOPTED from NONE**) — if available. Furthermore, the station information file is used to check, which receiver types are used in connection with the selected antennas. The GNSS tracked by each receiver type are indicated in the receiver information file. With this information the program ATX2PCV decides for which GNSS the phase center information is required per selected antenna radome combination. Missing GNSS-specific and/or frequency-specific antenna calibrations are adopted from GPS-calibrations as explained in Section 18.3.1. The station information file is also used to assign the 20 character antenna serial number in the ANTEX file to the 6 digit Bernese-specific antenna number used in the phase center file (see, Section 18.2.4).

Note that the specification of an external (i.e., ANTEX) phase center filename is always necessary for an ATX2PCV program run.

18.3.2.2. Update of an Existing Bernese Phase Center Eccentricity File

One of the features of the program ATX2PCV is the possibility to update a Bernese phase center file with information from ANTEX. This is the procedure needed in most of the cases. In addition, it corresponds exactly to the procedure to be applied when an updated ANTEX file is distributed by the IGS.

The difference to the creation of a new Bernese phase center file (described in Section 18.3.2.1) is that an existing Bernese phase center eccentricity file is selected in the field “Input Bernese phase file” in the panel “ATX2PCV 1: Input” in addition. The program will update all antenna patterns in this file that are available in the ANTEX file. All other antennas (incl. SLR, etc.) will be adopted from the input Bernese phase center eccentricity file.

For updating individual antenna calibrations, the input Bernese phase center file must contain individually calibrated antennas and the option “Set number of generic antennas to 999999” must be activated (see also Section 18.3).

18.3.2.3. Elevation-Dependent Antenna Phase Center Corrections Only

Check the box “Only elevation dependent patterns required” in the panel “ATX2PCV 2: ANTEX Conversion” if you wish to get only elevation dependent receiver antenna patterns from ANTEX. By selecting this option the program converts only the “NOAZI” line from the ANTEX file. Note, that this works exclusively for antennas converted from an ANTEX file. Antennas from an input Bernese phase center eccentricity file that are not included in ANTEX will not be reduced.

18.3.2.4. Handling of Antenna Phase Center Corrections for LEOs

If you plan to process LEO data you may need to acquire nadir-dependent corrections for the GNSS up to 17°. This information is available in the ANTEX files provided by the IGS.

If you are going to estimate your own set of GNSS satellite antenna phase center pattern (see receiver-part of Section 18.4), you will only obtain corrections up to a nadir angle of 14° (for GPS). In such a case, it makes sense to run an update of your phase center eccentricity file in order to increase the nadir-range of your GNSS satellite antenna patterns above 14° using the option “Fill missing values up to a MAXIMUM NADIR ANGLE of”. . . . Missing values can be filled-up with zeros or the values corresponding to the highest available nadir angle using “Fill missing values for satellite antennas”.

18.3.2.5. Handling of Antenna Phase Center Corrections for IGS Realtime Stations

Within the realtime networks the receiver antenna phase center corrections may already be applied to the raw data prior to the writing of the RINEX observation files (which is not in agreement with the IGS conventions). This is indicated in the RINEX header of these stations with the antenna type `NULLANTENNA`. Note, that this kind of antenna treatment is not compliant with the RINEX format description.

Because it is not clear by default whether the applied corrections are compatible to those used for the GNSS satellites, the processing of such data with the *Bernese GNSS Software* should stop. This is simply realized in the way that the antenna type `NULLANTENNA` is not contained in the ANTEX files provided by the IGS. Therefore, the *Bernese GNSS Software* is not adapted to it.

If, however, you intend to use such data you must manually add the corresponding realtime stations to your station information file with the antenna type `NULLANTENNA` `NONE` and the antenna number `999999` (in column `ANT #`). Furthermore, you have to manually add a block for this antenna type in your Bernese phase center eccentricity file(s). Note, that the antenna number must be `999999` if this file contains individual antenna calibrations and `0` if the file contains only type-specific calibrations. Set all phase center offset and variation values for this antenna type to `0.0`. In order to make the RINEX observation files of the realtime stations pass the consistency test of the Bernese RINEX converter, you must change the antenna type in the RINEX headers from `NULLANTENNA` to `NULLANTENNA` `NONE`. Alternatively, you may also create an exception rule in the file with known RINEX header inconsistencies and enter the name of this file into the field “Accepted station information” of the RINEX converter `RXOBV3`, as described in Section 4.2.3.4.

If you use data with already applied receiver antenna corrections please be aware of the fact that the quality of your results depends on the correct handling of the antenna calibrations by the data provider. Make sure that the applied receiver antenna corrections are consistent with the satellite antenna corrections you are using for your processing.

18.3.3. Routinely Running ATX2PCV

For permanent network analysis, users of the *Bernese GNSS Software* are advised to download the satellite information file (e.g., `SATELLIT.I08`) on a regular basis from <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>. When using the file in a routine processing, updating your Bernese phase center eccentricity file in a BPE process becomes indispensable in order to avoid aborting your processing. The main reason for that is to keep the satellite-specific antenna phase center corrections up to date in your phase center file (e.g., with respect to new satellites; see Section 18.2.6).

Another reason for updating the phase center eccentricity file is the occurrence of new receiver antenna/radome combinations after updating the station information file. Such updates are necessary after adding new stations with new equipment to the network, after antenna or radome changes, or after receiver changes (if the new receiver is capable of tracking additional GNSS). The close interaction with the station information file means that you need separate Bernese phase center files if you use separate station information files for different processing efforts (e.g., for different regional networks). Note, that you also need separate phase center files for processing campaigns with or without consideration of individual antenna calibrations.

It is worth mentioning that the phase center model identifier (keyword `SINEX` in the Bernese phase center file) gets automatically updated, ensuring proper phase center model declaration in the `SINEX` results (see Section 18.2.4). It is recommended to use the `ANTEX` file maintained at CODE (i.e., `I08.ATX`) and regularly posted to <http://www.aiub.unibe.ch/download/BSWUSER52/GEN>. It is recommended to include this update procedure into your BPE following the example in the distributed processing examples (see Section 23.4).

18.4. Estimation of Phase Center Corrections

The *Bernese GNSS Software* allows to estimate the antenna phase center offsets $\Delta\mathbf{r}$ as well as the phase center variations $\Delta\phi'(\alpha, z)$ for both, receiver and satellite antennas. The estimation of the parameters can be enabled in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”. All four parameter types are highly correlated and cannot be estimated at the same time.

Note that the term $\Delta\phi'(\alpha, z)$ may be modified by an arbitrary constant $\Delta\phi_0$ that corresponds to a clock offset. When estimating the function $\Delta\phi'(\alpha, z)$ a singularity arises that may be avoided, e.g., by a zero mean condition or by defining $\Delta\phi'(\alpha, 0) = 0$ (as the model is provided by the IGS).

18.4.1. Set up of Receiver Antenna Model Parameters

Today receiver antenna phase center information is usually acquired by robot calibrations or measurement chamber calibrations. The receiver antenna calibration by parameter estimation is most interesting for the in-flight calibration of LEO receiver antennas. For illustrative reasons, however, we give a brief information of how a relative antenna field calibration could look like:

The first problem that has to be solved is how to determine the correct station positions (ground truth). It is, e.g., possible to use the following approach: let us assume that the calibration campaign consists of two sessions (the sessions should be quite long — at least 24 hours) and let us further assume that only two antennas were present. We select one antenna as reference. We want to estimate the antenna phase center variations $\Delta\phi'(\alpha, z)$. Processing the first session (without estimating antenna phase center offsets and/or variations) the resulting relative position of both stations is corrupted by an unknown mean antenna phase center offset $\Delta\mathbf{r}$. If we exchange both antennas before the second session, the result of the second session is corrupted by $-\Delta\mathbf{r}$. The mean position (stemming from processing both sessions together) is correct. Now, it is possible to fix the station positions and to compute the coefficients defining the function $\Delta\phi'(\alpha, z)$. The receiver

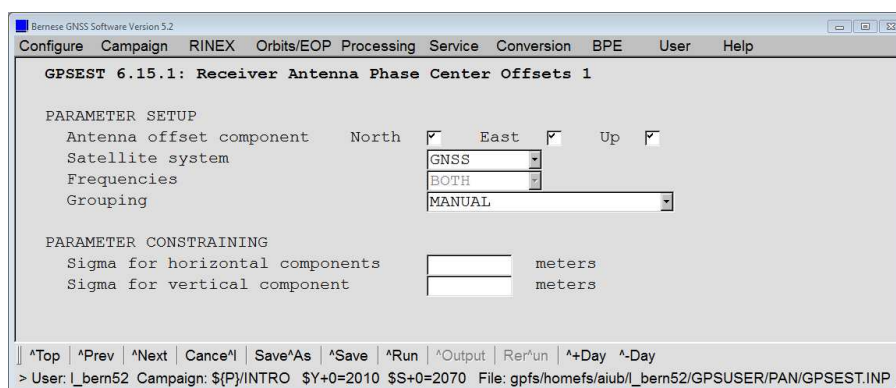


Figure 18.4.: Program input panel for the set up of receiver antenna offset parameters in program GPSEST.

antenna calibration is performed in a local network where data from both frequencies can be individually processed. For more details about the setup of a relative antenna field calibration campaign we refer to Rothacher et al. (1995b).

In the panel “GPSEST 6.15.1: Receiver Antenna Phase Center Offsets 1” (displayed in Figure 18.4) the components of the receiver antenna offsets, the frequencies, the GNSS, and the constraints for the parameters can be defined. Furthermore, different grouping-options are available (option “Rec. ant. off.: Manual setup: Grouping”):

RECEIVER-INDEPENDENT One (common) receiver antenna offset is estimated for every antenna type (independently of the receiver type attached to the antenna). In a separate selection list the reference antenna (or a group of reference antennas) has to be specified.

RECEIVER-DEPENDENT One (common) receiver antenna offset is estimated for every combination of receiver type and antenna type. In a separate selection list the reference antenna (or a group of reference antennas) has to be specified.

INDIVIDUAL From a selection list you can choose individual antennas (i.e., including the antenna serial number) for the receiver antenna offset estimation.

MANUAL In an additional panel you may manually specify the parameter setups for each antenna or antenna type in detail.

Depending on the chosen grouping option, detailed selections can then be done in a second panel. Note that you cannot estimate more than $N - 1$ offsets if you have N different receivers because you can only relatively calibrate receiver antennas in a field campaign.

In the panel “GPSEST 6.16.1: Receiver Antenna Phase Center Variations 1” (see Figure 18.5), the parameters to be estimated are selected for the elevation and azimuth dependent part of the receiver antenna phase center variation model. To estimate azimuth independent variations you have to set the “Rec.Ant.PCV: azimuth increment” to 360 degrees for the polygon model and the “Rec.Ant.PCV: order m” to 0 for the spherical harmonics representation, respectively.

The selection of the antennas is analogous to the estimation of the receiver antenna offsets. If no reference antenna is specified, an a priori sigma for each parameter is required in order to prevent the normal equation system from becoming singular. If a reference antenna is specified, in general no a priori sigma is required, because the singular (0, 0) term is not

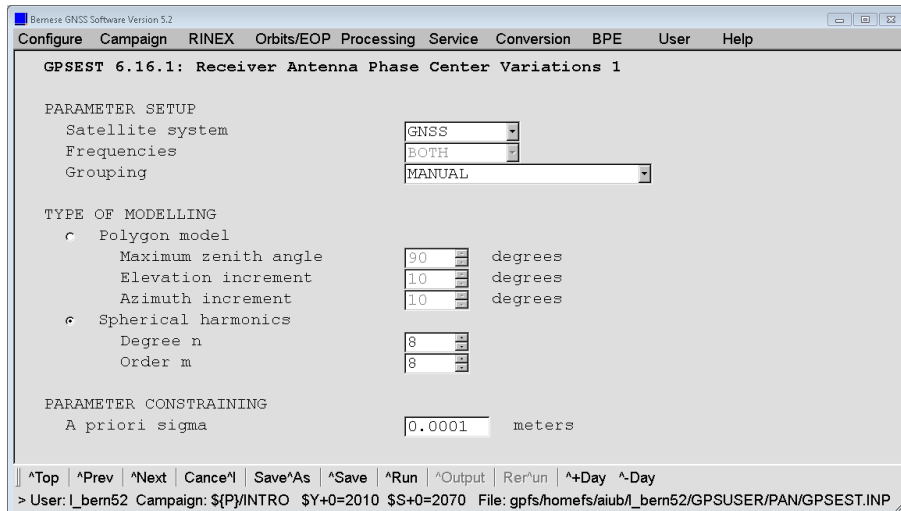


Figure 18.5.: Program input panel for the set up of receiver antenna phase center variation parameters in program GPSEST.

estimated in the spherical harmonics model and a zero mean condition is imposed on all grid points for the piecewise linear model. Because of the correlations, it makes no sense to estimate receiver antenna offsets and azimuth and elevation dependent variations together in one program run.

The set up receiver antenna parameters may be stored in a normal equation file and solved for by ADDNEQ2. Alternatively, the receiver antenna model estimation may be performed by GPSEST itself with the results being stored in files specified in the panel “GPSEST 2.2: Output Files 2”. Please note, that these files are written into the campaign directory (default: OUT), whereas the input antenna phase center eccentricities are introduced from files located in $\${X}/GEN$. Furthermore, it has to be noted that the elevation and azimuth dependent part of the antenna phase center variations need to be equal in terms of resolution for the a priori and the estimated model. The only exception is that from an introduced spherical harmonic model any piecewise linear model can be extracted.

18.4.2. Set up of Satellite Antenna Model Parameters

In contrast to the estimation of the receiver antenna phase center corrections, the generation of satellite antenna model parameters requires a global network. Precise station coordinates and satellite orbits are required, too. Preferably, long time series of data should be analyzed to obtain reliable results. Please note, that uncertainties of the introduced receiver antenna model may map into the satellite antenna model. We refer to Schmid and Rothacher (2003) for more details on the estimation of satellite antenna model parameters.

Due to a high correlation, satellite antenna offsets and phase center variations cannot be estimated together in one processing step. Depending on the expected result, different technologies for estimating offsets and variations should be applied. A very common way is to start with no variations for the satellites and estimate the offsets only. In this way, the pattern is as flat as possible because all nadir-independent component are already absorbed by the estimated offsets. In a second step, the estimated offsets are introduced

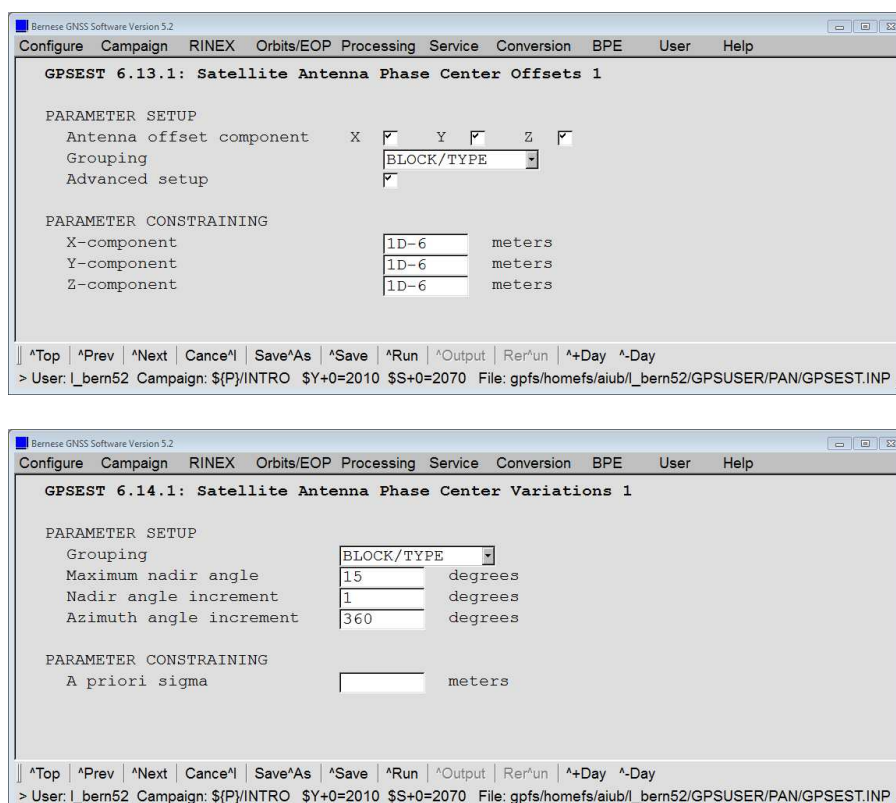


Figure 18.6.: Program input panels for the set up of satellite antenna parameters in program GPSEST.

and the corresponding variations are computed applying a zero-mean condition. This technology is only well suited if you solve for satellite-specific offset and pattern. If the pattern shall only be satellite type-specific, the offsets need to be solved after the pattern.

In the panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” of the program GPSEST, you may activate the set up of satellite antenna parameters. It is a reasonable assumption that all satellites of one type (Block for GPS) have the same antenna offset and pattern. Therefore, the *Bernese GNSS Software* supports the grouping of satellites according to satellite blocks, as well as the individual grouping of satellites (see the panels: “GPSEST 6.13.1: Satellite Antenna Phase Center Offsets 1” and “GPSEST 6.14.1: Satellite Antenna Phase Center Variations 1” in Figure 18.6).

BLOCK/TYPE: The groups are defined by the satellite blocks specified in the satellite information file.

MANUAL: Define the satellite groups manually in an additional panel “GPSEST 6.13.3: Satellite Antenna Phase Center Offsets 3” (for phase center offsets) or “GPSEST 6.14.2: Satellite Antenna Phase Center Variations 2” (for phase patterns).

SAT_SPECIFIC: Own offset/pattern for each individual satellite.

The grouping is possible for both — satellite antenna offsets and satellite antenna phase center variations. If block-wise or manual grouping are selected for the phase center offsets, more advanced options can be defined in an additional panel “GPSEST 6.13.2: Satellite Antenna Phase Center Offsets 2” if the checkbox “Sat. ant. offset: advanced setup” is selected as well. The grouping has to be equal for offsets and patterns if both parameter types are set

up together in the same GPSEST run and stored in a normal equation file. Normal equation files containing satellite antenna offsets and patterns can be processed with ADDNEQ2. All normal equation files stacked together in ADDNEQ2 must have the same satellite grouping. Furthermore, it has to be noted that the elevation and azimuth dependent part of the antenna phase center variations need to be equal in terms of resolution for the a priori and the estimated model.

18.4.3. Antenna Model Parameter Estimation with ADDNEQ2

Normal equation files belonging to different clusters and/or sessions may be introduced into ADDNEQ2. Antenna parameters might be stacked (if they are of the same type), pre-eliminated, or deleted according to the settings in panel “ADDNEQ2 4.2: Parameter Pre-Elimination”. Option “Satellite antenna offsets (XY)” allows to estimate the z-component of the satellite antenna offset only and pre-eliminate or delete the x- and y-components.

The a priori values might be changed by introducing a “Phase center variations” file and/or “Satellite information” file in panel “ADDNEQ2 1.3: General Files”. When estimating phase center variations, the elevation and azimuth dependent part must be equal in terms of

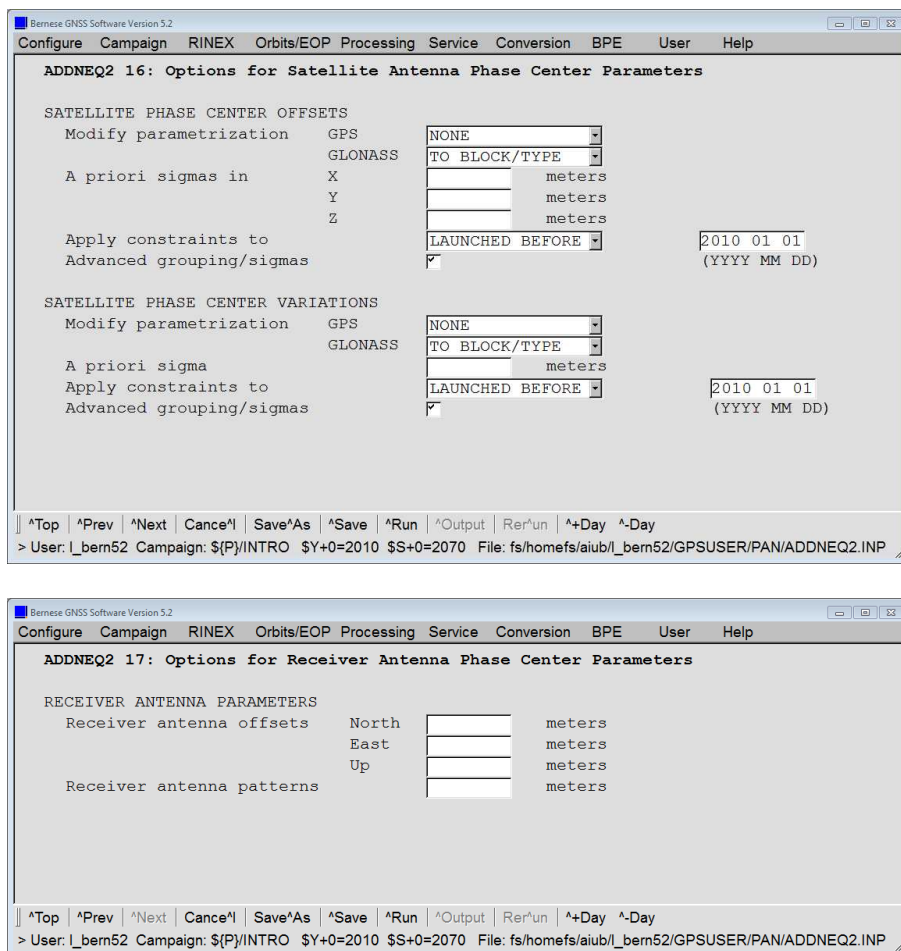


Figure 18.7.: Program input panels for the modification of satellite (top) and receiver (bottom) antenna parameters in program ADDNEQ2.

resolution for the a priori model and the parameters contained in the input normal equations. When satellite antenna parameters should be estimated, the satellite grouping must be the same for all input normal equations.

The parametrization for satellite antenna phase center offsets and variations might be changed in panel “ADDNEQ2 16: Options for Satellite Antenna Phase Center Parameters” (see Figure 18.7 top). Possible modifications include the change from individual to group-wise, change from individual to frequency-specific (for GLONASS) grouping, and change of the constraints. The selection of “LAUNCHED_BEFORE” for options “Apply satellite antenna offsets sigmas” and/or “Apply satellite antenna pattern sigmas” allows to heavily constrain the calibrations of older satellites with well calibrated antennas (in order to define the scale of the satellite constellation), while freely estimating the antenna parameters of newer satellites. These options allow a very flexible parameter handling that has covered all needs at CODE side so far (as, for instance, they have been used in Dach et al. 2011c). The a priori sigmas of receiver antenna parameters can be modified in panel “ADDNEQ2 17: Options for Receiver Antenna Phase Center Parameters” (see Figure 18.7 bottom).

19. Satellite Laser Ranging (SLR)

The Satellite Laser Ranging (SLR) technique is a precise and independent way to validate and assess the quality of GNSS orbits. The global network of SLR stations tracks the selected GNSS satellites following the recommendations of the ILRS. However, observing GNSS satellites is very demanding due to their high altitude and the low energy of the reflected laser pulses.

The strength of the SLR observation technique lies in particular in the absolute range information, which is disturbed by less error sources compared to microwave observations, and in the accuracy of SLR normal points at the mm-level (Thaller et al. 2011a, b; Sośnica et al. 2012; Fritsche et al. 2014; Sośnica 2015). The SLR-derived range residuals are indicators for the radial accuracy of the microwave-derived orbits because — due to the high satellite orbits — the maximum angle of incidence of the laser pulses to GPS and GLONASS satellites is only about 13° and 14° , respectively. Unfortunately, only two GPS satellites are equipped with a Laser Retroreflector Array (LRA), namely GPS 36 (launched March 10, 1994) and GPS 35 (launched August 30, 1993). GPS 36 was observed continuously by SLR stations between 1994 and 2014, whereas GPS 35 was observed between 1993 and 2009. Today, both GPS satellites are decommissioned from active service. However, all GLONASS, Galileo, QZSS, and BeiDou satellites are equipped with LRAs for laser tracking. All GPS satellites of Block III might be equipped with LRAs as well.

Among the LEO satellites there are also plenty of targets equipped with LRAs, e.g., CHAMP, GRACE-A/B, GOCE, SWARM, Terra-SAR, TanDEM-X, Jason-1/2, TOPEX-Poseidon, Envisat, and Cryosat-2.

The orbits of all aforementioned satellites can be validated using SLR data in the *Bernese GNSS Software*. The distribution contains a dedicated example BPE for this purpose, see Section 23.4.6 for a detailed description. The data flow through this example may also help you to understand the more general description of processing SLR measurements given in the subsequent sections.

19.1. Processing SLR Data in Bernese

The *Bernese GNSS Software* Version 5.2 allows processing of SLR data. SLR observations may be used for GNSS and LEO orbit validation (Urschl et al. 2007) or for SLR-related parameters estimation and orbit determination (Thaller et al. 2012; Sośnica et al. 2014). SLR range residuals are calculated with the program GPSEST. The distance between an SLR station and an observed satellite, given by the SLR measurement, is compared with the distance derived from station coordinates and a standard orbit. GPSEST provides the range residuals in the residual output file (description in Section 24.11.9) and allows for solving and saving the NEQ for further usage in ADDNEQ2.

In the *Bernese GNSS Software* Version 5.2 the capability of GNSS and LEO orbit validation using SLR data is fully operational. Other applications related to the estimation of parameters on the basis of SLR data, however, are in the experimental stage.

SLR measurements are expected to be introduced as Normal Points (NPs) either in the old format (agreed by the SLR subcommission of Coordination of Space Techniques for Geodesy and Geodynamics (CSTG)) or in the new CRD format (Consolidated Laser Ranging Data Format).

19.1.1. SLR–Dedicated Programs

Most of the programs in the *Bernese GNSS Software* are adapted for processing both SLR and GNSS data. This is in particular true for all programs related to satellite orbits, e.g., ORBGEN, PRETAB, STDPRE, and CCPREORB because orbits are independent from the observation technique (processing satellite data needs just corresponding inputs in the satellite information file). This is also true for programs related to station coordinates, e.g., HELMR1, FODITS, COMPAR, COOVEL, CRDMERGE, GRDS1S2, etc. Two main programs which are used for parameter estimation, namely GPSEST and ADDNEQ2, also support processing SLR data. In GPSEST the SLR–related options and data have to be set up, whereas in ADDNEQ2, which works on existing NEQs, there is no explicit distinction whether the NEQs are based on GNSS or SLR data.

There are also several programs in the *Bernese GNSS Software* that are dedicated specifically to SLR data processing, namely:

Observation Programs

- QLRINEXO ("Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX") to convert SLR normal point data (in the old CSTG format) to RINEX observation files and RINEX meteo files.
- CRD2RNEXO ("Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX") to convert SLR normal point data (in the new CRD format) to RINEX observation files and RINEX meteo files.

Orbit Programs

- IRV2STV ("Menu>Service>SLR utilities>Convert IRV/PRE to state vectors") to convert a state vector, e.g., the prediction for SLR satellites in the IRV file format into Bernese element files (default extension ELE). Starting from these files standard orbits may be created (see Section 16.3.1.3) for further use, e.g., as a starting point for orbit improvement. Conversion is necessary for a priori orbits of SLR geodetic satellites before 2006 (only if no other orbit source is available).
- CPFSP3 ("Menu>Service>SLR utilities>Convert CPF to precise orbit files") to convert orbit predictions for SLR satellites from the Consolidated Prediction Format (CPF) (default extension CPF) to precise orbit format (default extension PRE). They may be integrated by ORBGEN to a standard orbit to be used as a priori orbits of SLR satellites after 2006 (only if no other orbit source is available).

- SP3CPF ("Menu>Service>SLR utilities>Convert precise orbits to CPF files") to extract orbits from the precise (default extension PRE) into the Consolidated Prediction Format (default extension CPF), e.g., for generating orbit predictions for SLR stations.

Statistic Programs

- QLRSUM ("Menu>Service>SLR utilities>Create quick-look residual statistics") to generate a report and statistics from the residuals of SLR observations. The program enables outlier detection and additional criteria for the minimum number of SLR observations.

Station Programs

- SNX2SLR ("Menu>Service>SLR utilities>Prepare SLR data handling file") to extract or merge relevant information from the SLR data correction file (provided by the Analysis Working Group (AWG) of the IIRS in SINEX format)¹ to Bernese SLR data handling files (e.g., with range and time biases, default extension SLR) and to station information files (e.g., data exclusions, default extension STA).

19.1.2. Station-Related Files Relevant for SLR Processing

Processing SLR data requires the preparation of all station-related files for SLR tracking stations. Basically, the set of files needs to be created as described for GNSS data processing in Section 3.6. Here, we focus on the SLR-related aspects:

Files Used in a Similar Manner as for GNSS

Coordinate file has to contain a priori coordinates for all stations to be processed. For most of the SLR stations the coordinates are available in the ITRF 2008 or in the SLRF 2008 reference frame.

The reference frame information is typically provided in the SINEX format. Using the program SNX2NQ0 ("Menu>Conversion>SINEX to normal equations") the coordinates, velocities, and a list of stations may be extracted according to the description in Section 9.4.9.2 (typically no NEQ file is needed). Using the program CRDMERGE ("Menu>Service>Coordinate tools>Merge coordinate/velocity files", description in Section 10.7.7) you can merge the files with the reference frame coordinates (and velocities) with your existing coordinate (and velocity) file.

Velocity file has to contain velocities for all SLR stations. In analogy to coordinate files, VEL files can be extracted from a reference frame file (using the program SNX2NQ0) or, when no other source of information is available, from a NUVEL plate motion model using the program NUVELO ("Menu>Service>Coordinate tools>Compute NUVEL velocities", description in Section 10.7.8).

¹http://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snix

Abbreviation table must be generated for all sites used in the processing. As no baselines are generated for SLR, unique 4-character abbreviations are sufficient.

Ocean and atmospheric tidal loading corrections for SLR stations should be generated in the same way as for GNSS stations.

Files with an Extended Use with Respect to GNSS

Station selection files (default extension `FIX`) have twofold applications in SLR data processing:

- The list of the fiducial (core) stations that are used for the datum definition. It is typically generated when the reference frame information is extracted from the SINEX file (see above). The usage corresponds to the use for GNSS data processing as described in Chapter 10.
- The list of stations for which the range biases (RGBs) are estimated.

Station information file has the usual functionality as for the GNSS data analysis. Only the section `TYPE 002: STATION INFORMATION` needs special attention in the context of SLR data processing. The receiver- and antenna-related fields are not applicable when processing SLR measurements. They should be filled as follows:

```
RECEIVER TYPE:      SLR
RECEIVER SERIAL NBR: left blank
REC #:              999999
ANTENNA TYPE:       SLR
ANTENNA SERIAL NBR: left blank
ANT #:              999999
```

The fields for the antenna eccentricity is used to apply the SLR station eccentricities that are provided by the ILRS eccentricity file². The values may be extracted by the program `SNX2STA` ("Menu>Service>Station information files>Extract information from SINEX", description in Section 4.5.2). The downloaded SINEX file must be located in the `SOL` directory of your campaign — do not forget to change at least the filename extension to upper-case.

Problems occur if several eccentricities are given for the identical time interval. In this case, the redundant lines have to be removed from the SINEX file. The resulting `STA` file should be checked for eccentricities larger than an allowed maximum (100 m). If such stations are present they should be removed from the section `TYPE 002` and included in section `TYPE 003: HANDLING OF STATION PROBLEMS`.

Data intervals where the ILRS does not recommend to use the observations are published in a specific SINEX formatted file available at http://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx. The related information can be transferred into the section `TYPE 003` of a station information file using the program `SNX2SLR` ("Menu>Service>SLR utilities>Prepare SLR data handling file").

²ftp://cddis.gsfc.nasa.gov/slr/slrocc/ecc_une.snx

```

Example of a Station Information File for SLR
-----
FORMAT VERSION: 1.01
TECHNIQUE: GNSS
TYPE 001: RENAMING OF STATIONS
-----
STATION NAME      FLG   YYYY MM DD HH MM SS   FROM          TO          OLD STATION NAME      REMARK
*****
1893 12337S006    001 1976 05 01 00 00 00   1893*
7035 40436M003    001 1988 06 24 00 00 00   7035*
7040 49901S001    001 2005 01 01 00 00 00   7040*
7046 40438M002    001 1991 08 25 00 00 00   7046*
7062 40436M002    001 1974 08 28 00 00 00   7062*
7063 40451M112    001 1976 05 01 00 00 00   7063*
...

TYPE 002: STATION INFORMATION
-----
STATION NAME      FLG   YYYY MM DD HH MM SS   FROM          TO          RECEIVER TYPE      ANT #   NORTH   EAST   UP   DESCRIPTION
*****
1893 12337S006    001 1976 05 01 00 00 00   SLR
1953 40701S001    001 1976 05 01 00 00 00   SLR
7040 49901S001    001 2005 01 01 00 00 00   SLR
7046 40438M002    001 1991 08 25 00 00 00   SLR
7062 40436M002    001 1974 08 28 00 00 00   SLR
7062 40436M002    001 1990 08 03 00 00 00   SLR
7062 40436M002    001 1974 08 28 00 00 00   SLR
7062 40436M002    001 1976 09 14 00 00 00   SLR
7062 40436M002    001 1978 06 29 00 00 00   SLR
7062 40436M002    001 1981 10 04 00 00 00   SLR
7062 40436M002    001 1983 09 12 00 00 00   SLR
7063 40451M112    001 1976 05 01 00 00 00   SLR
...

TYPE 003: HANDLING OF STATION PROBLEMS
-----
STATION NAME      FLG   YYYY MM DD HH MM SS   FROM          TO          REMARK
*****
7307 21736S001    001 1970 01 01 00 00 00   ecc > 100m
7307 21736S003    001 1970 01 01 00 00 00   ecc > 100m
7841 14106S011    001
7941 12734S008    001 2010 08 09 00 00 00   2004 02 18 23 59 59 DATA-HANDLING
...
uncorrected time bias (DATA-HANDLING)
-----

```

Figure 19.1.: Example of an SLR station information file (STA), generated and/or merged on the basis of different ILRS SINEX files.

If you have obtained several station information files after evaluating the different sources of information you may use the program STAMERGE ("Menu>Service>Station information files >Merge station information files") to combine these files into one file.

An example for a station information file prepared for processing SLR measurements is given in Figure 19.1. Please note the **TECHNIQUE**: keistring at the beginning of the file that should indicate the processing of SLR data (by replacing GNSS with SLR).

Files Exclusively Used for SLR Processing

Frequency information file (default extension FRQ, located in $\${X}/GEN$, example in Figure 19.2) stores the wavelength information used by the SLR stations. Wavelength information is required for an appropriate modeling of troposphere refraction.

Most SLR stations use one wavelength for their measurements, indicated as observation type R_1 in the processing (analogue to the L_1 GNSS phase measurements from the first frequency). The information is complemented by a time window to account for equipment changes at SLR tracking stations. Some other SLR stations such as Zimmerwald (7810) and Concepcion (7405), however, perform two-color SLR observations at the same time. The particular wavelength is specified by R_1 and R_2 in the frequency information file (see Figure 19.2).

The frequency information file can be automatically updated on the basis of the wavelength record in the SLR observation files when importing the measurements using the program RXOBV3 (see Section 19.3.3.1).

SLR data correction file (default extension SLR, expected location is the STA directory of the campaign) includes range biases (correction type RGB), which are subtracted from laser range observations and center-of-mass corrections (correction type COM), which are added to the measured ranges for spherical satellites. Time biases (correction type TIM) and pressure corrections (correction type P) are not yet supported in the current version of the *Bernese GNSS Software*.

Each correction may be specified per station, satellite, and observation type. If one of these fields remains empty the correction is applied to all stations, satellites, and observation

Frequencies of observation types										
Type	Satellite/Station	Name	Value	Unit	Valid from	to				
*****	*****	**	*****.*	****	**** ** ** ** **	****	**	**	**	**
RANGE	1824 12356S001	R1	532.0	nm						
RANGE	1831 12368S001	R1	532.0	nm						
RANGE	7810 14001S001	R1	532.0	nm	1992 11 23 00 00 00					
RANGE	7810 14001S007	R1	423.0	nm		2008 03 03 23 59 59				
RANGE	7810 14001S007	R1	532.1	nm	2008 03 04 00 00 00					
RANGE	7810 14001S007	R2	846.0	nm		2008 03 03 23 59 59				
RANGE	7810 14001S007	R2	1064.2	nm	2008 03 04 00 00 00					
RANGE	7810 14001S001	R1	532.0	nm	1992 11 08 00 00 00					
RANGE	7405 41719M001	R1	423.5	nm						
RANGE	7405 41719M001	R2	847.0	nm						
...										

Figure 19.2.: Example of a frequency information file (FRQ). The file specifies which wavelength was used by an SLR station in a particular time window.

```

ILRS Data Handling + Site-specific CoM values
-----
Format Version: 1.00

TYP  Station name          Sat  WL  Value (m)   Sigma (m)   Valid from          to
***  *****
RGB  7810 14001S001          R1   0.050000   0.000000   1988-05-24 00:00:00 1989-09-30
RGB  7810 14001S007          R1  -0.026000   0.000000   1998-01-01 00:00:00 2002-05-29
RGB  7810 14001S007          R1  -0.015000   0.000000   2002-05-29 00:00:00 2003-03-11
RGB  7810 14001S007          R1  -0.022000   0.000000   2003-03-11 00:00:00 2004-12-28
RGB  7810 14001S007          R1  -0.026000   0.000000   2004-12-28 00:00:00 2006-02-06
RGB  1873 12337S003          R1  -0.270000   0.000000   1995-01-01 00:00:00 2000-01-01
RGB  7080 40442M006          R1  -0.040000   0.000000   1988-01-01 00:00:00 1989-12-15
RGB  7080 40442M006          R1   0.025000   0.000000   1990-04-04 00:00:00 1993-06-17
P     7080 40442M006          -2.100000   0.000000   1995-03-06 00:00:00 1996-01-26
P     7080 40442M006          -10.300000  0.000000   1996-01-26 00:00:00 1996-04-25
P     7080 40442M006          -9.700000   0.000000   1996-04-25 00:00:00 1996-05-09
RGB  7820 21609S002          R1  -0.020000   0.000000   2000-10-19 00:00:00 2012-01-01
TIM  7831 30101S001          R1   0.085000   0.000000   1987-01-01 00:00:00 1990-07-01
RGB  7109 40433M002          951  R1   0.164900   0.000000   1997-01-17 23:11:00 1997-01-18
COM  1864 12340S002          952   0.248000   0.008000   1990-10-01 00:00:00 2050-12-31
COM  1868 12341S001          951   0.248000   0.008000   1992-05-01 00:00:00 2050-12-31
COM  1868 12341S001          952   0.248000   0.008000   1992-05-01 00:00:00 2050-12-31
COM  1869 12343S001          951   0.251000   1.000000
COM  8834 14201S018          953   0.608000   0.010000   1989-03-01 00:00:00 2050-12-31
COM  8834 14201S018          954   0.608000   0.010000   1989-03-01 00:00:00 2050-12-31
COM  7840 13212S001          950   1.010000   0.000000
COM  7840 13212S001          950   0.985000   0.000000
COM  7840 13212S001          961  -0.209600   0.000000
...

```

Figure 19.3.: Example of an SLR data correction file. The file includes range biases (RGB) and center-of-mass corrections (COM).

types. The use of this file when processing SLR measurements is not mandatory but highly recommended in order to implement an analysis in agreement with the recommendations of the AWG of the ILRS. The reader is referred to Figure 19.3 for an example of an SLR data correction file.

19.1.3. SLR Satellite-related Files

Satellite Numbering Convention

The satellite numbering convention within the *Bernese GNSS Software* assumes for GNSS satellites PRN numbers smaller than 900, active LEO satellites are expected to have PRN numbers between 900 and 949, and passive SLR geodetic satellites currently have PRN numbers in a range between 950 (AJISAI) and 961 (BLITS). Recently, numbers above 970 are again used for active satellites (Sentinel and SPOT series). The PRN numbers for LEOs (above 900) correspond to the list maintained at http://cddis.nasa.gov/sp3c_satlist.html for precise orbit files in the SP3c format. This convention is fixed since the satellite handling within the processing programs (in particular in GPSEST) depends on it.

All satellites have to be listed in the *satellite information file* in PART 1.

Laser Retroreflector Array Corrections

All satellites, which are tracked by SLR, should have entries in the satellite-related files that describe the offsets of LRAs. For this purpose two files are relevant:

- The *satellite information file* (PART 2) should contain not only the entries for microwave antenna offsets but also for LRA offsets. The **SENSOR NAME** has to start with SLR.

The values are typically provided by the ILRS³. Note that the definition of the satellite axes in this file are different for GPS, GLONASS, and Galileo satellites. In the *Bernese GNSS Software* the orientation of the axes is the same as the ILRS definition for GPS satellites, whereas for other satellites system the orientation has to be transformed to GPS-like orientation.

- The *antenna phase center file* must include the entries corresponding to the sensor description from PART 2 of the satellite information file (even for spherical satellites):

ANTENNA/RADOME	TYPE	NUMBER	SYS	FRQ	TYP	D(O)	D(Z)	D(A)	M(Z)	SINEX
*****	*****	*	***	***	***	***	***	***	***	*****
SLR REFL.	GLONASS-M	0		2	0	0	0	0	90	
	NORTH MM	EAST MM	UP MM	FACTOR						
	*****	*****	*****	*****						
01	0	0.00	0.00	0.00	0.100E+01					
02	0	0.00	0.00	0.00	0.100E+01					
ANTENNA/RADOME	TYPE	NUMBER	SYS	FRQ	TYP	D(O)	D(Z)	D(A)	M(Z)	SINEX
*****	*****	*	***	***	***	***	***	***	***	*****
SLR REFL.	GPS	0		2	0	0	0	0	90	
	NORTH MM	EAST MM	UP MM	FACTOR						
	*****	*****	*****	*****						
01	0	0.00	0.00	0.00	0.100E+01					
02	0	0.00	0.00	0.00	0.100E+01					
ANTENNA/RADOME	TYPE	NUMBER	SYS	FRQ	TYP	D(O)	D(Z)	D(A)	M(Z)	SINEX
*****	*****	*	***	***	***	***	***	***	***	*****
SLR REFL.	L51	0		2	0	0	0	0	90	
	NORTH MM	EAST MM	UP MM	FACTOR						
	*****	*****	*****	*****						
01	0	0.00	0.00	0.00	0.100E+01					
02	0	0.00	0.00	0.00	0.100E+01					

Satellite Problem File

If needed, SLR satellites can be excluded from the solution according to the entries in the *satellite problem file*. The procedure is exactly the same as for microwave observations from GNSS satellites as described in Section 6.7.2.

Orbit Modeling of Spherical Geodetic Satellites

The *satellite information file* should contain in PART 1 information concerning mass, area-to-mass ratio, and solar radiation pressure coefficient C_R . They are needed for an appropriate modeling of the solar radiation pressure for spherical geodetic satellites. Atmospheric drag modeling is not supported in *Bernese GNSS Software* Version 5.2.

19.2. SLR Processing Flow

Figure 19.4 gives an overview of the processing scheme of SLR data using the *Bernese GNSS Software*. First, the SLR observations are transferred into RINEX observation and

³http://ilrs.gsfc.nasa.gov/missions/spacecraft_parameters/center_of_mass.html

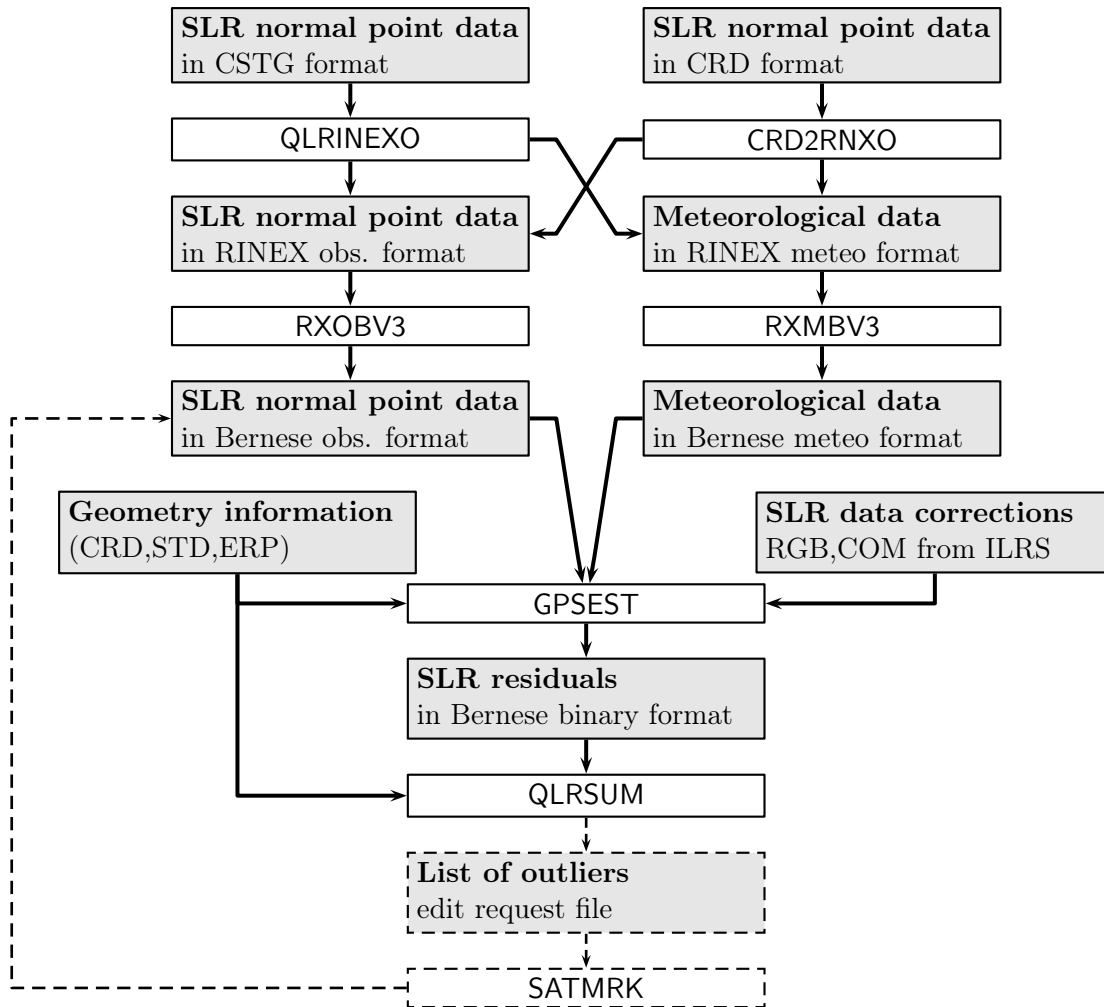


Figure 19.4.: Overview of the SLR processing flow in the *Bernese GNSS Software*.

meteo files. Later, these RINEX files are imported into Bernese internal formats. This data transfer is described in Section 19.3.

After the data import, the measurements can be analyzed with the main processing program `GPSEST`. This step is discussed in Section 19.4. On the one hand, it is possible to directly compute and store residuals of the observations with respect to a given geometry. These residuals can be analyzed with the program `QLRSUM` (see Section 19.5). Outliers are identified and edit requests may be collected in an edit information file. The edit requests may be applied to the Bernese observation files using the program `SATMRK`.

The program `GPSEST` may also be used to estimate relevant parameters that may improve the geometry information (coordinate, satellite orbits) or SLR-specific parameters (range biases, offsets of Laser Retroreflector Array) and others. Regarding the small number of SLR measurements, the solution can often be improved by combining parameters over a longer interval using the program `ADDNEQ2` (and possibly also `FODITS`).

This description already shows that several iterations on different levels are needed.

19.3. Importing SLR Observations

19.3.1. SLR Observations Normal Points

The basic SLR data product are Normal Points (NPs) that is used with the *Bernese GNSS Software*. NPs replaced on-site sampled data and later full-rate data as the primary station data product. Forming NPs decreases the noise of observations, reduces the size of observation files, and reduces the number of observations, which are typically strongly correlated and thus do not introduce further important information for most SLR applications. The so-called restated Herstmonceux algorithm⁴ is nowadays used for the formulation of NPs.

Two data formats of normal points are currently in use:

- Consolidated Laser Ranging Data Format (CRD), and
- On-Site Normal Point Data format (agreed by the SLR subcommission of CSTG, in use until May 2012).

Both formats contain information such as station name, satellite number, time of observation, time system, laser system used, calibration, time system, two-way time-of-flight, air pressure, temperature, and humidity at the station, number of raw observations, and RMS of calibration. In addition, both formats contain a revision index that is increased after every resubmission of a NP measurement.

The Herstmonceux NP definition specifies a standard normal point interval (also called bin size) for different satellites based on their orbital altitude. The bin size of normal points formed from SLR observations to low orbiting satellites is 5 s for GRACE, GOCE, CHAMP, TerraSAR-X, and TanDEM-X, and 15 s for Jason-1, Jason-2, and Cryosat-2. A NP to low orbiting geodetic satellites is typically created from 30 s of laser observations (AJISAI, LAsER Relativistic Satellite (LARES), Larets, Stella, Starlette, and BLITS). Whereas the bin size of NPs to LAsER GEodynamic Satellite (LAGEOS)-1 and LAGEOS-2 is 120 s, it amounts to 300 s for high orbiting satellites such as those from the GPS, GLONASS, Galileo, and BeiDou constellations as well as for Etalon. The maximum intervals result from the assumption of linearity of the measurements w.r.t. their predictions.

19.3.2. Import of SLR Observations to RINEX Format

SLR NP measurements can be downloaded from the ILRS data centers, see http://ilrs.gsfc.nasa.gov/data_and_products/data_centers/index.html.

The import of SLR observations into the structures of the *Bernese GNSS Software* is — due to technical reasons — the same as for GNSS measurements: starting from RINEX observation and meteo files. For that reason the SLR measurements have first to be transformed into a SLR-RINEX file.

For the generation of RINEX files, two programs are provided within the *Bernese GNSS Software*:

⁴http://ilrs.gsfc.nasa.gov/data_and_products/data/npt/npt_algorithm.html

- CRD2RN XO "Menu>Service>SLR utilities>Convert normal point files (new format) to RINEX" for converting SLR NPs in the CRD format, and
- QLRINEXO "Menu>Service>SLR utilities>Convert normal point files (old format) to RINEX" for converting SLR NPs in the CSTG format (which was used until May 2012).

Both programs read SLR NP data and write RINEX observation files and RINEX meteorological files separately for each SLR tracking station. The SLR station names obtained from the NP file may be adapted if indicated in section TYPE 001: RENAMING OF STATIONS of the station information file. The naming of the output files follows the usual convention: cccccsss.yy0 and cccccsss.yyM for RINEX observation and RINEX meteo files, respectively. The 4-character station abbreviation cccc is taken from the abbreviation table (description in Section 24.7.15). The session ssss is specified in option "Session ID used for RINEX observation file names", the year yy is specified in option "Year ID used for RINEX observation file names". The station needs to be listed in the abbreviation table. Otherwise, the writing of the output files is skipped for the corresponding station.

The format of the RINEX file containing SLR observations is not an official format but closely follows the RINEX conventions. The observation types R1 and R2 indicate range measurements that are not provided by the RINEX format definition. The observation records written to the RINEX file are the observed SLR ranges adapted to consider only the one-way light travel time. Thus, the observation epoch refers to the time of signal reception (as for GNSS measurements) and not to the time of signal reflection at a satellite.

The RINEX observation file contains only SLR observations for selected satellites defined in the option "LIST OF SATELLITES". The satellite numbers have to correspond to those given in the satellite information file.

19.3.3. Import from RINEX to Bernese Files

The RINEX files may now be converted to the *Bernese GNSS Software* binary format using RXOBV3 for observations and RXMBV3 for meteorological data as they might be used in GPSEST for parameter and residual estimation.

19.3.3.1. Import of SLR Observation RINEX

The RINEX range observation files may be converted to Bernese observation files using the program RXOBV3 ("Menu>RINEX>Import RINEX to Bernese format>Observation files", see Section 4.2.3 for details). Enable option "Select measurement types to save (Range)" in panel "RXOBV3 1: Filenames" to create Bernese binary range observation files (default extension RZH for the header and RZO for the observations itself).

The satellites to be processed are already pre-selected. For that reason the option "Satellite system to be considered" in panel "RXOBV3 2: Input Options 1" is typically set to ALL. Furthermore, the "Sampling interval" (also panel "RXOBV3 2: Input Options 1") should be set to zero for range data.

With the option "Check frequency information file for frequency" in panel "RXOBV3 4: Input Options 2" RXOBV3 offers different choices for the case that the wavelength in the observation file disagrees with the wavelength given in the frequency information file. The optimal choice depends on the reliability of the records in the frequency information file.

19.3.3.2. Import of SLR Meteo RINEX

The RINEX meteo files written by QLRINEXO or CRD2RNEXO contain measured meteo records from the SLR tracking stations. They have to be converted into Bernese meteo files using the program RXMBV3 ("Menu>RINEX>Import RINEX to Bernese format>Meteo files", see Section 4.11). The meteo information is needed by the processing programs in order to compute the signal delay due to tropospheric refraction.

19.4. Processing SLR Data

After importing the SLR observations and meteo data into Bernese-formatted files, no further pre-processing is necessary. The files can directly be introduced into the main processing program GPSEST. It is essential though to switch first the program into the SLR mode by using the option "Space geodetic technique". This enables the selection of the "Range observation files". Do not forget to specify the "Meteorological data" files for all selected SLR stations in panel "GPSEST 1.2: Input Files 2" that are needed for modeling the troposphere. The selection of the "Frequency information" in panel "GPSEST 1.4: General Files" is requested as well.

In order to process all SLR data, the "Sampling interval" is automatically set to zero (panel "GPSEST 3.1: General Options 1"). In the same panel, one should select ALL for "Satellite system" and L1&L2 for "Frequency/linear combination".

In panel "GPSEST 3.2: General Options 2" you will realize that only a combobox with troposphere models is active that are relevant for optical wavelengths, namely MARINI-MURRAY and MENDES-PAVLIS. The currently recommended refraction model, developed by Mendes and Pavlis (2004), consists of the formulae for hydrostatic and non-hydrostatic zenith delay components and a common mapping function FCULa (due to the small contribution of water vapor to atmospheric refraction for laser observations). The maximum correction due to the non-hydrostatic zenith path delay is 6 mm, which is 70 times smaller than for microwave observations. The zenith delay models have overall RMS errors for the total zenith delay below 1 mm across the whole frequency spectrum above an elevation angle of 3° (Mendes and Pavlis 2004). The formerly recommended troposphere delay model for SLR, derived by Marini and Murray (1973), includes the zenith path delay and, implicitly, also the mapping function to project the zenith delay to a given elevation angle. The troposphere is dispersive for laser observations implying that the total delay can be derived from the simultaneous laser observations at two different frequencies (two-color ranges). The ionosphere signal delay for laser observations does not exceed $1.0 \cdot 10^{-7}$ m and is therefore neglected in SLR data analysis. This is the reason why it is sufficient (and therefore highly recommended) to correct the troposphere refraction based on the introduced ground measurements provided by the meteo files for SLR data. No further estimation of troposphere parameters is necessary.

A simple outlier rejection can also be done in GPSEST using the option "Maximum tolerated O-C term" in panel "GPSEST 3.3: General Options 3". This option is useful, however, only for the detection of the largest outliers — a more sophisticated outlier detection algorithm is available in the program QLRSUM described below.

So far you are able to directly compute residuals of the SLR measurements without estimating any parameters primarily to validate the introduced standard orbit that may be stored in "Residuals" output file for further analysis (see Section 19.5). Typically, no

“Elevation-dependent weighting” is applied which allows to store REAL residuals (see option “Type of computed residuals”).

Of course you can also enable the usual parameters for estimation in the panels “GPSEST 5.1: Setup of Parameters and Pre-Elimination 1” and “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” (as far as they are relevant for SLR measurements). GPSEST even allows solving for SLR-specific parameters such as LRA offsets and RGBs. They can be stored in NEQ files and further manipulated in the program ADDNEQ2.

To set up LRA offsets you have to enable the option “GNSS antenna offsets” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2” as described in Section 18.4.2. The program automatically switches from estimating the offset for the microwave antenna to the Laser Retroreflector Array because of the selected observation type.

The estimation of RGBs can be activated via the option “Pre-elimination: Range Biases” in panel “GPSEST 5.2: Setup of Parameters and Pre-Elimination 2”. The stations for which RGB parameters shall be set up can be selected in panel “GPSEST 6.19: SLR Range Biases”. The option “Range Bias set-up for satellites” allows estimating RGBs

- SAT_SPECIFIC: individual for all satellites and stations,
- SYS_SPECIFIC: one RGB per station for all GPS satellites and one RGB value for all GLONASS satellites, and
- PER_STATION: one RGB for all satellites per SLR.

Independent from this initial selection, the program ADDNEQ2 allows for stacking and reducing the number of estimated RGB parameters. However, introducing new RGBs or restoring satellite-specific RGBs is not possible in ADDNEQ2 (all RGB parameters have to be explicit in the NEQ). Estimated RGB values can be stored to a result file (default extension SLR) and re-introduced in GPSEST and ADDNEQ2. Of course also a SLR data correction file directly derived by the program SNX2SLR based on the ILRS information can be introduced.

19.5. Analyzing SLR Data

The analysis of SLR residuals resulting from GPSEST is typically done by the program QLRSUM. In contrast to the program RESRMS (see Section 6.6.2), which is used for the same purpose for microwave data, QLRSUM contains a residual analysis that is particularly developed for SLR measurements considering aspects specific to the ILRS-style analysis.

The input and output files of the program QLRSUM are indicated in Figure 19.5. It consists, first of all, of the residual files to be analyzed. Typically, they result from the program GPSEST. To allow for more statistical information, the observation geometry for each residual may be recovered. For this purpose the “Station coordinates file”, “Standard orbit files” together with the related “A priori pole file” is needed. These are preferably the same files that have been used in GPSEST for the residual computation.

The program QLRSUM generates a quick look residual analysis, creates reports, and an edit information file that may be applied to the observation files by the program SATMRK (see Section 6.7.1 for further description).

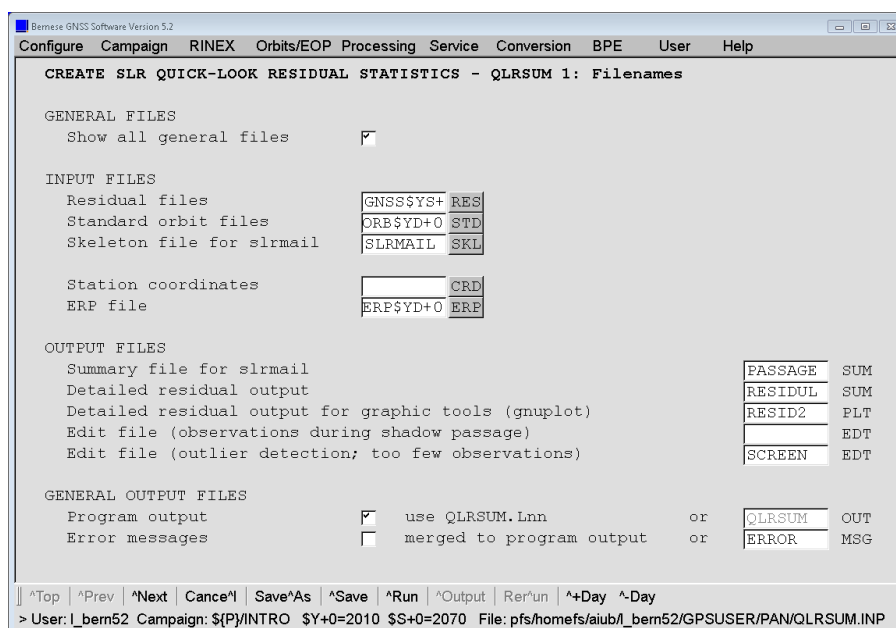


Figure 19.5.: SLR Quick-Look residual statistic input and output options in QLRSUM.

19.5.1. Reports on Residual Statistics

QLRSUM generates three kinds of reports differing in the level of detail in the different output files indicated in panel of Figure 19.5:

- “Detailed residual output”: *Normal point residuals* (example in Figure 19.6)
A detailed list of residuals for all SLR measurements is provided with additional information as displayed in Figure 19.6: azimuth of the satellite as seen from an SLR station (column AZI), elevation angle of the satellite (column ELE), azimuth and nadir angles as seen from a satellite (columns AZI-SAT and NAD), satellite argument of latitude with respect to the argument of latitude of the Sun (column AGL), and the Sun elevation angle above the orbital plane (column BETA). The two latter columns are not included in Figure 19.6 for technical reasons.
- “Summary file for slrmail”: *Passage residuals* (example in Figure 19.7)
A report with statistics for all registered satellite passes as shown in Figure 19.7 may also be provided. The report comprises the duration time of a pass, the number of good and bad observations (outliers), the mean residual offset and the standard deviation of normal points within one pass. For the definition of outliers please use the options in section “EDITING LEVEL” in panel “QLRSUM 3: Outlier detection” (see Figure 19.9).

Note that this summary file is sent as a feedback to the SLR tracking stations by the AIUB on a regular basis.
- “Program output”: *Station residuals* (example in Figure 19.8)
The output file “Program output” contains a report with statistics for all station-satellite pairs as given in Figure 19.8. The report comprises mean residual offsets, absolute RMS values (without removing the mean offset), and sigma values (after removing the mean offset).

STATION ID	SAT PRN	START yy/mm/dd	PASSAGE hh:mm	DUR (min)	#OBS	RESIDUAL (mm)	AZI (deg)	ELE (deg)	AZI-SAT (deg)	NAD (deg)
7810	14001S007	G06	11/07/06 19:32	0	1	4.4	290.55	54.38	287.23	8.02
7810	14001S007	G06	11/07/06 19:53	0	1	1.0	297.80	63.12	282.71	6.22
7810	14001S007	G06	11/07/06 20:03	0	1	-1.4	301.51	67.20	280.54	5.33
7810	14001S007	G06	11/07/06 20:05	0	1	-1.4	302.33	68.04	280.05	5.14
7810	14001S007	R11	11/07/06 17:14	0	1	33.3	315.98	48.79	223.04	9.49
7810	14001S007	R11	11/07/06 17:15	0	1	38.2	315.50	49.27	224.20	9.40
7810	14001S007	R11	11/07/06 17:49	0	1	33.4	289.15	60.62	268.62	7.05
7810	14001S007	R11	11/07/06 17:51	0	1	26.8	286.87	60.93	271.77	6.97
7810	14001S007	R08	11/07/06 01:59	0	1	-46.0	36.14	55.56	268.06	8.15
7839	11001S002	R16	11/07/06 13:20	0	1	-2.9	35.11	72.93	110.29	4.25
7839	11001S002	R16	11/07/06 13:21	0	1	-3.3	37.78	72.99	108.55	4.23
...										

Figure 19.6.: Example of a residual report of SLR normal points generated by QLRSUM.

STATION ID	SAT PRN	START yy/mm/dd	PASSAGE hh:mm	DUR (min)	#OBS GOOD	MEAN (mm)	STD (mm)	#OBS BAD	MEAN (m)	STD (m)
7810	14001S007	R03	14/05/31 07:39	37	4	-21	13			
7810	14001S007	R03	14/06/01 06:37	16	4	-40	5			
7810	14001S007	R17	14/05/30 16:52	0	1	-16	0			
7810	14001S007	R17	14/05/31 13:18	99	7	-45	6			
8834	14201S018	R08	14/06/03 10:32	0	0	0	0	1	4	0
8834	14201S018	R23	14/05/31 23:08	7	3	-26	3			
...										
					1252	-6	45	7.6%		
		1.0	1000.0	1000.0						

Figure 19.7.: Example of a satellite pass-wise residual summary file as used for the ILRS reports generated by QLRSUM.

```

Input options
-----

Absolute maximum of the o-c residuals:          0.20 m
Maximum overall sigma:                        1000.00 mm
Multiplication factor for overall sigma:       10.0

List of satellites:   5   6   1  25  30  101  102  103  104  105  106  107
Edit residuals according to criteria above
No check for minimum number of observations

Residual Statistics
-----

SAT  STATION      #OBS      MEAN (mm)      RMS (mm)      SIGMA (mm)
-----
R04 7810 14001S007    2       -54.8          54.9          3.6
G06 7810 14001S007    4         0.6           2.4           2.7
R08 7810 14001S007    2       -46.3          46.3           0.5
R17 7810 14001S007    2        20.0           20.3           4.7
R12 7810 14001S007    2       -11.2           11.2           0.9
R13 7810 14001S007    7       -21.1           21.3           2.9

R08 8834 14201S018   11       -21.9           29.8           21.2
...

Total                242        -12.0           32.8           30.6

NUMBER OF EDIT REQUESTS:    0

```

Figure 19.8.: Example of an output file from QLRSUM containing the SLR residual analysis per station and satellite.

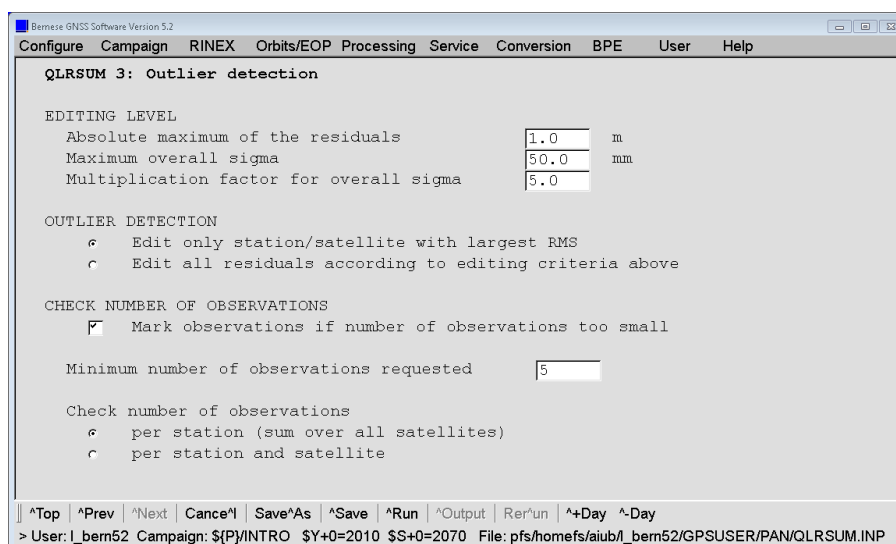


Figure 19.9.: Options for SLR outlier detection in QLRSUM.

19.5.2. Outlier Detection

The option “Absolute maximum of the residuals” in panel “QLRSUM 3: Outlier detection” (displayed in Figure 19.9) allows to specify a threshold for the observation residuals. If the absolute value of a residual exceeds this threshold, an entry in the corresponding edit information file (default extension EDT, output file from option “Edit file (outlier)”) will be introduced for this observation.

This functionality corresponds to the option “Maximum tolerated O-C term” in the program GPSEST used to exclude large outliers from further analysis. If you have specified in GPSEST a value larger than zero, no residuals are provided for the corresponding observations. For that reason QLRSUM is neither able to detect them nor to add them to the list of outliers to be marked due to the edit information file. Consequently, you have to keep the value in the option “Maximum tolerated O-C term” for all subsequent runs of the program GPSEST on the same dataset.

Each pair of station and satellite is treated independently in QLRSUM. At first, the mean offset of the residuals per station–satellite combination is computed. The RMS of the residuals with respect to the mean offset is compared with the value in the option “Maximum overall sigma” in panel “QLRSUM 3: Outlier detection”. The smaller one of the two values is used for the outlier detection. This RMS is multiplied with the factor given in option “Multiplication factor for overall sigma”. A residual is expected to be smaller than this product — otherwise it is assumed to be an outlier. By specifying a large multiplication factor, e.g. 1000, the outlier detection is de facto switched off.

The option “Edit only station/satellite with largest RMS” allows to screen the observations of the station with the largest RMS. In contrast to the previous option, “Edit according to settings above” allows for outlier screening for all stations.

19.5.3. Checking the Number of Observations

The AWG recommends to use a minimum number of observations per station to be included in the ILRS solution. For that reason, the program QLRSUM may add stations

to the edit request file if less than a certain number of observations is available (use option “Minimum number of observations”). This option specifies the minimum number of observations for a station or a station–satellite pair. You can choose whether the minimum number of observations should be requested per station (computed as the sum over all satellites tracked by this station) or whether the minimum number of observations should be requested for each pair of station and satellite.

20. Data Simulation Tool GPSSIM

20.1. Introduction

The *Bernese GNSS Software* provides the simulation tool GPSSIM ("Menu>Service>Generate simulated observation data"). It generates synthetic GNSS (i.e., GPS and GLONASS) observations for terrestrial stations and for LEOs. Code and phase zero-difference observation files may be created which can be processed by all standard Bernese programs. SLR observations are not yet supported.

The use of GPSSIM is quite straightforward. The scope of the observation scenario is defined by basically two files, namely:

1. a standard orbit, containing the satellites for which data will be simulated, and
2. a coordinate file defining the set of stations for which observations can be simulated.

Several additional files may be introduced in the simulating process, such as satellite clock corrections, differential code biases, and many more. Troposphere and ionosphere can be modeled while observation noise and cycle slips can be added. Utilizing all GPSSIM options, it is quite challenging to distinguish between simulated and real observation data.

Although GNSS observations for both terrestrial receivers and LEOs can be simulated (even in the same program run), the focus throughout this chapter is put on ground stations. The differences arising when generating LEO observations are addressed in Section 20.9.

20.2. Underlying Principles

The models applied in GPSSIM are identical to those used in the main parameter estimation program GPSEST ("Menu>Processing>Parameter estimation"). Therefore, so-called "zero tests" are possible, if exactly the same geometry and options are used in the simulation and processing parts. This is only true, however, if the observations were simulated without any random errors.

To generate more realistic data, normally distributed noise may be added during the simulation process. Only white noise can be added, colored noise models are not implemented. Furthermore, it is not possible to inflict errors on satellite orbits or station coordinates directly — but this might be realized by introducing specific "inconsistencies" between the geometry for simulating and processing the observation files.

One GPSSIM run produces observation files for a single session. A complete observation campaign can be simulated by executing the program several times.

20.3. Supported Input Files

Figure 20.1 (panel “GPSSIM 1: Filenames”) shows all supported input files. Only a few of them are mandatory: the “GNSS Standard orbit”, “Pole file”, and “Coordinate file”.

Observations are simulated for all satellites contained in the standard orbit. The “Satellite problems” file (panel “GPSSIM 1.1: General Files”) is used to handle maneuvers but not to remove satellites from the simulation. Satellites may be removed later using program SATMRK (“Menu>Service>Bernese observation files>Mark/delete observations”) or by introducing a “Satellite problems” file in GPSEST.

Station positions are defined in a coordinate file. The same models for station motion due to solid Earth, pole tides and other effects are applied as in GPSEST. Furthermore, ocean and atmospheric tidal loading tables as well as gridded crustal deformation models caused by non-tidal loading effects may be introduced. If data for a kinematic station should be simulated, a corresponding file containing the kinematic positions must be selected. Antenna orientations can be considered as well.

By default, satellite and receiver clocks are set to zero for all epochs. Different values may be defined, though: satellite clock corrections may be introduced via a Bernese satellite clock file (either containing epoch-wise values or polynomial coefficients, see Section 24.6.10 for description and example), while the receiver clock behavior can be defined in a receiver clock file (see Section 24.6.11).

A file containing satellite- and station-specific P1–C1 and P1–P2 differential code biases may also be selected in panel “GPSSIM 1: Filenames”. In order to apply these biases to the code observations on both carriers, a receiver information file (see Section 24.3.6) specifying the tracking technology of receivers must be given in panel “GPSSIM 1.1: General Files”.

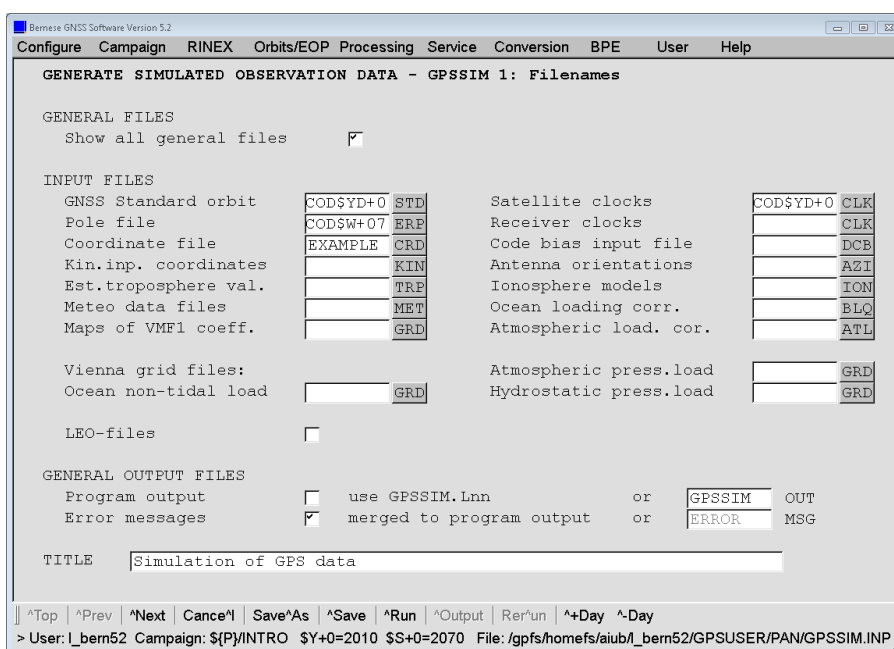


Figure 20.1.: Filenames for GPSSIM.

Atmosphere-related input files are addressed in Sections 20.5 and 20.6, while LEOs-related files are addressed in Section 20.9.

Please be aware that if you want to do a “zero test”, all input files and options have to be strictly *the same* as in the subsequently used processing programs.

20.4. Basic Options

Stations for which GNSS observations should be simulated must be selected in the panel “GPSSIM 2: Stations and Observation Window”. Any number of stations from the coordinate file may be chosen.

The observation window is either “Defined by year and session” or “Defined by start and end time”. If the latter is used, a “Session for observation files” must be specified for filenaming as well. This is because the observation window may run over midnight, that is, more than one session may be covered by the simulated data. In that case the observation file naming would be ambiguous. The time interval of the simulated campaign can be selected freely as long as it is covered by the satellite orbits.

The measurement type(s) to be simulated (code and/or phase) can be selected in panel “GPSSIM 3.1: Simulation Options” (see Figure 20.2).

The options under “OBSERVATION HEADER FILE INFORMATION” define the content of the header files to be created. This includes the campaign name and for each station the receiver/antenna type, serial number, and an operator’s name. All fields except of “Antenna type” may remain empty.

The program automatically prefixes the string `SIMULA` to the receiver names you specify.

This indicates to the program `SNGDIF` (“Menu>Processing>Create baseline files”) that the observation files stem from simulation. This way, it is possible to guarantee that the expected estimates for the ambiguities remain zero even on the double difference level.

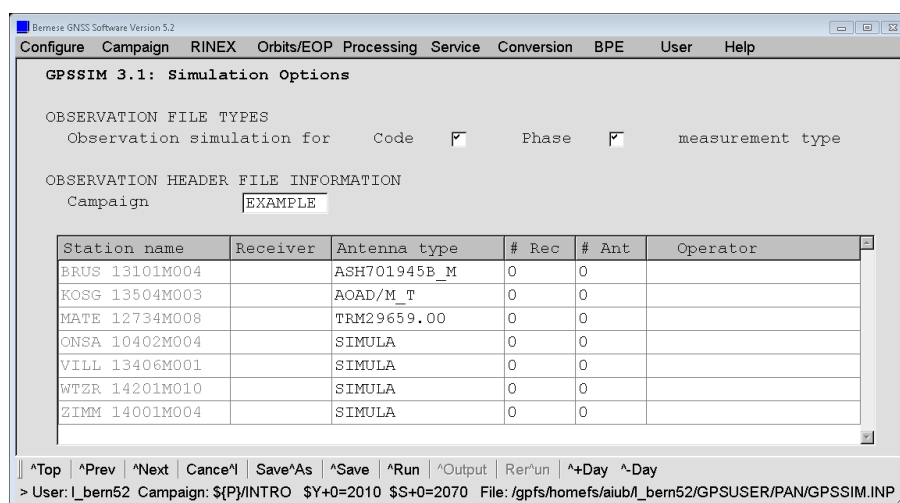


Figure 20.2.: Simulation options for GPSSIM.

Take care that the receiver names (including SIMULA) are properly defined in the “Receiver information” file where it is specified, which types of code observations should be generated.

The selected antenna type must be listed in the “Phase center eccentricities” file.

The first group of options in panel “GPSSIM 3.2: Simulation Options” defines the desired sampling rate, the minimum elevation to be processed and the maximum number of simultaneously observed satellites. Additional options “Maximum clock interpolation interval” and “Per. Relativistic J2-Correction” are related to the satellite clock corrections and have the same meaning as in the processing programs. The “Maximum number of observed satellites” may be set to the total number of channels of the receiver. In particular when simulating GPS and GLONASS measurements together, a sufficient number of channels should be assumed. The simulator starts to track the satellite with highest elevation when a channel gets free.

20.5. Troposphere Modeling

Basically, the troposphere modeling in GPSSIM is identical to the one in GPSEST. There are three ways to model the tropospheric delay for terrestrial stations:

- Specifying a model in “ZPD model and mapping function”.
The selected troposphere model is used to compute the troposphere delay with extrapolated meteorological data based on a standard atmosphere. Option NONE deactivates the use of any troposphere model.
- Introducing “Estimated troposphere values” in panel “GPSSIM 1: Filenames”.
The option “ZPD model and mapping function” will then be ignored. If a station is missing in the input file, the tropospheric delay will be computed based on the model specified in the input file (with standard atmosphere).
- Selecting “Meteo data files” (one for each station) in panel “GPSSIM 1: Filenames”.
The tropospheric delay values are computed using the data from the files as input values for the model selected in option “ZPD model and mapping function”. Extrapolated meteorological data from a standard atmosphere are used for all stations without meteo data in the input files.

Note that if the same troposphere modeling settings are used in the processing program GPSEST as for the simulation, it is expected that the estimated troposphere parameters (*corrections* upon the a priori model) are zero. In other words: if you are not specifically interested in a simulation study on the effect of troposphere modeling, it is not necessary to setup troposphere parameters at all.

20.6. Ionosphere Modeling

The deterministic part of the ionosphere may be applied to the simulated observations by specifying a global ionosphere model in option “Ionosphere models” in panel “GPSSIM 1: Filenames”. Alternatively, night time and day time electron contents of a very simple single

layer model (layer height=350 km) may be specified. The number of electrons E in the layer is a function of local time (T_{loc}) only:

$$T_{loc} = UT + \lambda$$

$$E = \begin{cases} E_0 & \text{for } T_{loc} \in \langle 20^h, 8^h \rangle \\ E_0 + E_1 \cos\left(\frac{T_{loc} - 14}{12} \pi\right) & \text{for } T_{loc} \in \langle 8^h, 20^h \rangle \end{cases} .$$

where:

- UT is the Universal Time,
- λ is the geographical longitude,
- E_0 is the night time electron content, and
- E_1 is the day time variation of the ionosphere.

E_0 (“Night time electron number”) and E_1 (“Day time electron number”) are input parameters to be specified in panel “GPSSIM 3.3: Simulation Options”. At this point no azimuth dependence is modeled.

In addition to this deterministic component, an irregular part may be superposed. The following term is added at epoch i :

$$\delta E_i = (E_{i1} \cos a + E_{i2} \sin a) \cdot d/200$$

where:

- δE_i is the random part of the electron content in the atmosphere,
- d is the distance in kilometers between the station considered and the ionosphere “Reference station” (panel “GPSSIM 3.3: Simulation Options”),
- a is the azimuth of the station considered with respect to the ionosphere reference station, and
- $E_{ik}, k = 1, 2$ is the result of the following random walk:

$$E_{1k} = 0 ,$$

$$\text{var}(E_{i+1,k} - E_{ik}) = \Delta t_i \cdot \text{var}_{1min} ,$$

where Δt_i is the time between the observations i and $i + 1$ in minutes and var_{1min} is the variance of the difference of the electron contents at time t and $t+1$. var_{1min} has to be specified in panel “GPSSIM 3.3: Simulation Options”, option “Variance of irreg. change of ionosphere content”.

This model certainly is a crude simplification for the random behavior of the true ionosphere. It shares, however, important aspects with the real situation: (1) the irregular contribution increases linearly with the baseline length; for distances > 200 km this distance dependence “stops”, and (2) baselines which are close to each other geometrically will show similar random contributions. The strength of the irregular contribution may be tuned by option “Variance of irreg. change of ionosphere content”.

If you do not want to model the ionosphere at all, specify 0 for the three numbers and * for the “Reference station”.

20.7. Statistical Information

Error-free observations are certainly desirable for several applications. But if a good approximation of the reality is needed, the options in “GPSSIM 3.4: Simulation Options” (Figure 20.3) offer the possibility to inflict errors on the simulated observations. A priori sigmas can be selected for both frequencies and both observation types independently. A normally distributed random error with the specified sigma is added to each simulated measurement.

The random number generator is initialized with the random seed selectable in option “Initial integer random number”. If the same number is used in consecutive runs of GPSSIM together with unchanged sigmas, the same “random” errors result. This offers the possibility to create the same observations several times.

If low-elevation data (below 15°) is simulated, elevation-dependent sigmas may be applied. The aforementioned a priori sigmas then refer to an observation in the zenith direction. The a priori sigma of observations at a zenith angle z will then be computed related to the factor $1/\cos z$.

20.8. Cycle Slips

If simulated data should be used for preprocessing purposes or if a high level of realism is intended, cycle slips may be introduced. Then it is quite challenging to distinguish between simulated and real observations.

The number of introduced cycle slips can be specified with the option “Introduce cycle slips per file” in panel “GPSSIM 3.4: Simulation Options” (Figure 20.3). The program assumes that a cycle slip may occur with the same probability at each epoch and for each satellite, and that its size is uniformly distributed in the interval $I = \langle -slip_{max}, +slip_{max} \rangle$ (“Maximum size of slip”).

You may wish to enable the “Same cycle slips in L1 and L2” option. But keep in mind that these slips are particularly hard to discover because they are not accompanied by a wide-lane cycle slip.

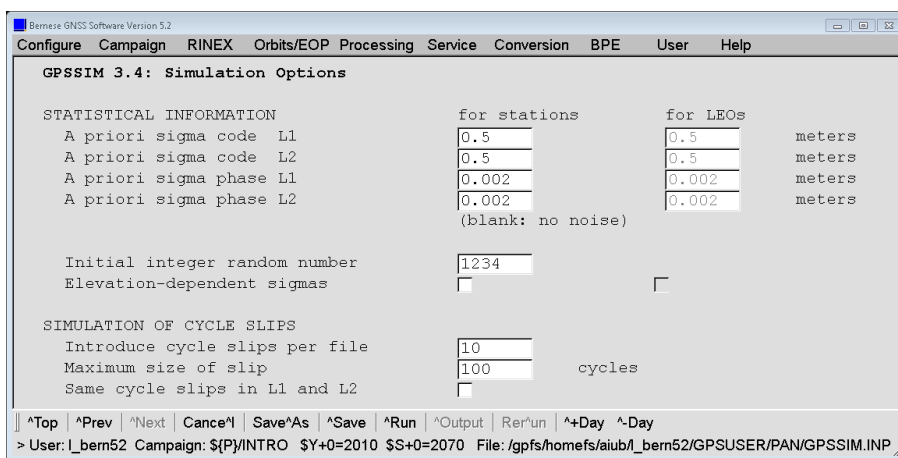


Figure 20.3.: Statistical and cycle slip options for GPSSIM.

20.9. Low Earth Orbiters

The simulation of GNSS observations for a LEO is basically the same as for a terrestrial station. Only a few input files and settings call for special attention. The important differences for the simulation of GNSS observations for LEOs are listed below:

1. Although a LEO does not have defined station coordinates, its name must appear in the “Coordinate file” in panel “GPSSIM 1: Filenames” with the same name as in the “Satellite information” file (panel “GPSSIM 1.1: General Files”). The coordinates of the LEO are of no importance and can be set to zero.
2. The LEO must be listed in section TYPE 005: HANDLING STATION TYPES of the “Station information” file (panel “GPSSIM 1.1: General Files”) with marker type SPACEBORNE. If the keyword SPACEBORNE is missing, program GPSSIM interprets the LEO as a ground based station.
3. Option “LEO-files” in the first panel must be checked in order to display the LEO-specific panel “GPSSIM 1.2: LEO Options”.
4. You either need a “LEO standard orbit” file or a file with “Kinematic input coordinates” to define the trajectory of the low satellite (note both files are specified in different panels).
5. If you have specified “Kinematic input coordinates” in the first panel, you may select a file containing “Kinematic velocities” in panel “GPSSIM 1.2: LEO Options” as well. This information is used to define the local orbit frame needed to compute the satellite’s attitude. Alternatively, you can specify a “LEO attitude” file. The attitude is necessary to apply antenna offsets.
If the LEO trajectory is obtained from a standard orbit, no velocity file is required. An attitude file may be used, though.
6. No troposphere model is applied for LEO satellites. The option “ZPD model and mapping function” in “GPSSIM 3.2: Simulation Options” is ignored.
7. The modeling of the ionosphere should be deactivated.
8. The a priori sigmas and the “Elevation-dependent sigmas for LEOs” checkbox are separately available for LEOs in panel “GPSSIM 3.4: Simulation Options”.

20.10. Applications for Simulated Data

Simulated data can be used in a number of different ways. Most of the applications, however, may be assigned to one of the following three main categories:

Verifying software algorithms: A well defined set of simulated observation data can be helpful while testing the correct implementation of software algorithms. The testing procedure benefits from the fact that, as opposed to real data, the correct results (e.g., number of cycle slips) are known a priori.

Pre-analyses: Satellite scenario, network layout, statistical properties, and systematic errors are known for simulated data. Thus, one may study the expected quality of the results depending on different processing strategies and option settings. A pre-analysis makes sense, e.g., to learn what to expect from a planned campaign or how to design a new campaign to get optimal results.

Research oriented analyses: Simulated data is well suited to carry out various research related analyses. The main advantage of the simulated data in this regard is that

“the truth” (e.g., satellite and station positions, ambiguities) is known to the user. Topics of interest may cover cycle slip detection and repair, use of GNSS orbits of different quality, ambiguity resolution strategies for very long baselines, etc.

With simulated observations from GPSSIM, preprocessing may be skipped because the program includes the correct receiver clock corrections and ambiguity parameters in the observation files. If no cycle slips were set up during the generation process, the resulting data can be considered as successfully cleaned, with synchronized receiver clocks and fixed ambiguities.

If a double-difference analysis is intended, the only preparatory step is the baselines creation with program SNGDIF. The program preserves the receiver clock and ambiguity information to produce “ready-to-use” single-difference files. This is, of course, not necessary in case of a zero-difference approach. After this step, the data can directly be introduced in the parameter estimation program GPSEST.

It goes without saying that the simulated data can be processed with all *Bernese GNSS Software* programs, not only GPSEST.