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Bernese GPS Software Version 4.2

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February 2001

Documentation of the *Bernese GPS Software* Version 4.2
February 2001

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1. Introduction and Overview

1.1 Philosophy Behind the *Bernese GPS Software*

The *Bernese GPS Software* is a sophisticated tool meeting highest quality standards for geodetic and further applications using the GPS as well as the GLONASS. This documentation is intended to give insight into theoretical aspects of GPS data processing, the working principles and concepts of the *Bernese GPS Software*, and the practical use of the package for a reader who already does have a basic knowledge of GPS data processing. The attendance of the *Bernese GPS Software Introductory Course* is presupposed. Despite the large number of pages of this documentation, not all issues related to GPS and GLONASS data processing may be highlighted and discussed. The reader may, however, get a good idea of possible analysis strategies which promise to meet his accuracy requirements for his particular applications. The *Bernese GPS Software* team offers support in case of users' questions not covered by this documentation.

1.2 Main Objectives and General Characteristics

The *Bernese GPS Software* is currently released as Version 4.2. In March 1988 the *Bernese GPS Software* Version 3.0, a software 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 *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.

The *Bernese GPS Software* Version 4.2 is based on Version 4.0 (released September 1996), which in turn is based on Version 3. Version 4.2 may be used to process any campaigns which were processed with Version 4.0 (downward compatibility). The new components of Version 4.0 with respect to Version 3 were:

- Completely revised orbit part. The full new Bernese orbit model [*Beutler et al.*, 1994] is available in Version 4.0. The new model is a generalization of the one used in Software Version 3.
- The processing program ADDNEQ may be used to combine normal equation systems generated with program GPSEST. ADDNEQ does not handle observations but normal equation systems. This leads to a dramatic improvement for, e.g., multi-campaign analyses or the management of permanent arrays. New parameters (e.g., station velocities) may be set up in ADDNEQ.

- The ionosphere modeling part was completely revised [*Schaer et al.*, 1995], [*Schaer et al.*, 1996]. Version 4.0 allows to produce regional or global ionosphere models which may be used to resolve the initial phase ambiguity parameters even on baselines up to 2000 km [*Mervart*, 1995]. The model parameters are established using the double-difference phase observable.
- Version 4.0 contains options to process special pseudo-kinematic data in the post-processing mode.
- The *Bernese Processing Engine*, developed together with Ch. Rocken and J. Johnson from UCAR, is particularly well suited to process data from permanent GPS arrays in a completely automatic and very efficient way.
- The documentation consists of two components: there are help panels accompanying (almost) every panel of the Version 4.0 menu system. In addition there is the off-line documentation focusing on theory, models, and on commented typical applications.
- Last but not least it should be mentioned that the processing speed of Version 4.0 could be improved by about an order of magnitude in programs GPSEST and ADDNEQ. Version 4.0 is designed to be used for big networks (≥ 100 receivers), too.

The enhancements of Version 4.2 with respect to Version 4.0 are:

- Capability to process not only GPS, but also GLONASS observations stemming from GLONASS or combined GLONASS-GPS receivers.
- Very much improved capabilities to process undifferenced observations to allow for satellite and receiver clock estimation and to enable time and frequency transfer (see Chapter 16).
- Capability to process SLR observations to GPS and/or GLONASS satellites.
- Improved troposphere modeling and estimation (see Chapter 12).
- Elevation dependent weighting of observations is possible.
- In addition to the program ADDNEQ, which, as mentioned above, was an essential new tool of Version 4.0, the new program ADDNEQ2 is included (description see Chapter 19). The new program and the menu program associated with it are written in Fortran 90 and therefore require a Fortran 90 compiler. ADDNEQ2 may be characterized as follows:
  - Consequent use of Fortran 90 features,
  - Consequent use of transformations of parameters (instead of weighting),
  - Identical treatment of all parameter types (step-wise linear functions of time),
  - Many new options.
- Eventually, ADDNEQ2 will totally replace ADDNEQ. Program ADDNEQ is mainly included for those users of Version 4.2 not yet having access to Fortran 90.

Version 4.2 of the *Bernese GPS Software* is a tool meeting highest accuracy standards. Typical users are:

- Scientists using it for research and education,
- Survey agencies responsible for high-accuracy GPS surveys (e.g., first order networks),

- Agencies responsible to maintain arrays of permanent GPS receivers,
- Commercial users with complex applications demanding high accuracy, reliability, and high productivity.

The software package is particularly well suited for:

- Rapid processing of small-size single and dual frequency surveys (typical example included in documentation),
- Permanent network processing,
- Ambiguity resolution on long baselines (up to 2000 km using high accuracy orbits),
- Ionosphere and troposphere modeling,
- Clock estimatino and time transfer,
- Combination of different receiver types (taking into account antenna phase center variations),
- Simulation studies,
- Orbit determination and estimation of Earth rotation parameters,
- Generation of so-called free network solutions.

General features of the software are:

- All principal observables recorded by high-accuracy geodetic GPS and GLONASS receivers may be processed (code and phase data on both carriers, see next section).
- Six different linear combination of L1 and L2 may be used (see next section).
- Data from various receiver types may be processed and combined in the same processing steps (this includes the establishment and the use of receiver-type specific antenna phase center variations).
- Single and dual frequency data may be processed in the same estimation step, ionosphere models may be used to minimize the impact of ionospheric biases on coordinates.
- The parameter estimation programs GPSEST, ADDNEQ, and ADDNEQ2 may be used for baseline-, session-, campaign-, and multiple-campaign processing. ADDNEQ and ADDNEQ2 make it possible to generate many different complex solutions (e.g., annual coordinate- and ERP-solutions) using, e.g., daily normal equation systems without having to re-process observations.
- A big variety of parameter types may be solved for simultaneously.
- The observations, broadcast ephemerides, etc., are passed to the *Bernese GPS Software* uniquely through the RINEX format, (the Receiver INdependent EXchange format, see [*Gurtner*, 1994]). It may thus be said that data from all receiver types for which a RINEX interface exists, may be processed by the *Bernese GPS Software*. Table 1.1 gives an impression of the receiver types which have actually been successfully “handled” by Version 4.2 of the software package.
- Let us point out once more, however, that data from every receiver type may be processed, provided its data are available in RINEX files.

Table 1.1: Receiver types used by the *Bernese GPS Software* 1988–1999.

Company	Receiver Type
	GPS only:
Aerospace	Minimac 2816AT
Texas Instruments	TI-4100
Trimble	4000SX, SL, SLD, STD, STT, SST, SSE, SSI, ...
Wild/Magnavox	WM-101, WM102
Leica	SR299, SR399, SR510, SR520, SR530, SR9500, ...
Ashtech	Ashtech L-XII, LM-XII, P-XII, Z-XII, ...
Osborne	Rogue, Minirogue, Turborogue, Benchmark
	GPS/GLONASS combined:
Ashtech	GG24, Z18
TPS (Topcon Positioning Systems)	Javad Legacy GGD
3S Navigation	R100-30T, R100-40T

Technically, the *Bernese GPS Software* Version 4.2 may be characterized as follows:

- High modularity on the program and subprogram level.
- Computer-system independence:
  - Standard Fortran 77 used (where possible).
  - Standard Fortran 90 is used for the program ADDNEQ2 and for the menu program associated with it.
  - All data files are accessed through a translation table containing the transformation from internal to external file names.
- There are implementations of the *Bernese GPS Software* Version 4.2 on all major computer platforms (PC, VMS, UNIX).
- Consequent use is made of the PARAMETER statement: easily adjustable maximal dimensions of arrays in main programs and highest level subroutines.
- No numerical constants are in the source modules. The numerical values used are in files accessible to the user.
- The use of option input files allows a high degree of automation.
- Version 4.2 is menu driven: the user no longer has to actually edit any option input files. This job is taken over by the menu system. User-friendliness is a pleasant attribute of Version 4.2.
- The entire menu system (except for program ADDNEQ2) is written in Fortran 77, as well. The menu system may thus be easily used on all computer platforms. There are implementations on Personal Computers, UNIX-, Linux-, and VMS-platforms.
- The *Bernese GPS Software* Version 4.2 is Y2K (year 2000) compliant.

1.3 Program Structure and Functional Flow Diagram

The system contains more than 100 different program units (not counting the menu system). They are arranged logically in the five Parts of the *Bernese GPS Software*:

Transfer Part: Generating files in the Bernese Format from RINEX data format (observations, broadcast information, meteorology).

Orbit Part: Generate a source-independent orbit representation (standard orbits), update orbits, generate orbits in precise orbit format, compare orbits, etc.

Processing Part: Code processing (single station), dual frequency code and phase pre-processing, parameter estimation based on GPS and/or GLONASS observations (program GPSEST) and on the superposition of normal equation systems (programs ADDNEQ and ADDNEQ2).

Simulation Part: Generate simulated GPS and GLONASS observations (code and/or phase, L1 or L1/L2) based on statistical information (RMS for observations, biases, cycle slips).

Service Part: Edit/browse binary data files, compare coordinate sets, display residuals, etc.

The *Bernese Processing Engine* is a tool operating on top of the five program parts which is ideally suited to set up automated processing procedures, like, e.g., the processing of data stemming from a permanent array. The processing strategy is set up once and for all from the RINEX files to the final results with all the programs necessary. It is even possible to set up a parallel processing on different machines.

The functional flow diagram for the normal use of the *Bernese GPS Software* Version 4.2 is given in Figure 1.1.

The Processing Part is the *core* of the *Bernese GPS Software*. The parameter estimation programs GPSEST, ADDNEQ, and ADDNEQ2 in turn are the essential routines of the Processing Part. Let us briefly characterize GPSEST on one hand and ADDNEQ, ADDNEQ2 on the other hand.

General Characterization of Parameter Estimation Program GPSEST

- The observation equations for phase and/or code observations are set up, normal equations are built up and inverted, results are written into files, the (not inverted) normal equation system is written into an output file for later use.
- Consequent use is made of the double-difference observable for code and phase observations.
- Processing of zero-difference data, e.g., for the purpose of time transfer, is now possible as well.
- All results are based on a least squares estimation where you have the possibility to model mathematical correlations correctly.
- There is a fully automatic book-keeping for the initial phase ambiguities. Ambiguities which were resolved once (e.g., in a baseline-mode) may be introduced as known at a later stage (e.g., in a session mode).
- There is no numerical integration in the parameter estimation programs. This is done in program ORBGEN of the orbit part. One and the same orbit may be used in many different processing steps.
- Parameters which were estimated once (ambiguities, orbits, coordinates, troposphere, ionosphere) may be used as known a priori values in subsequent program runs.

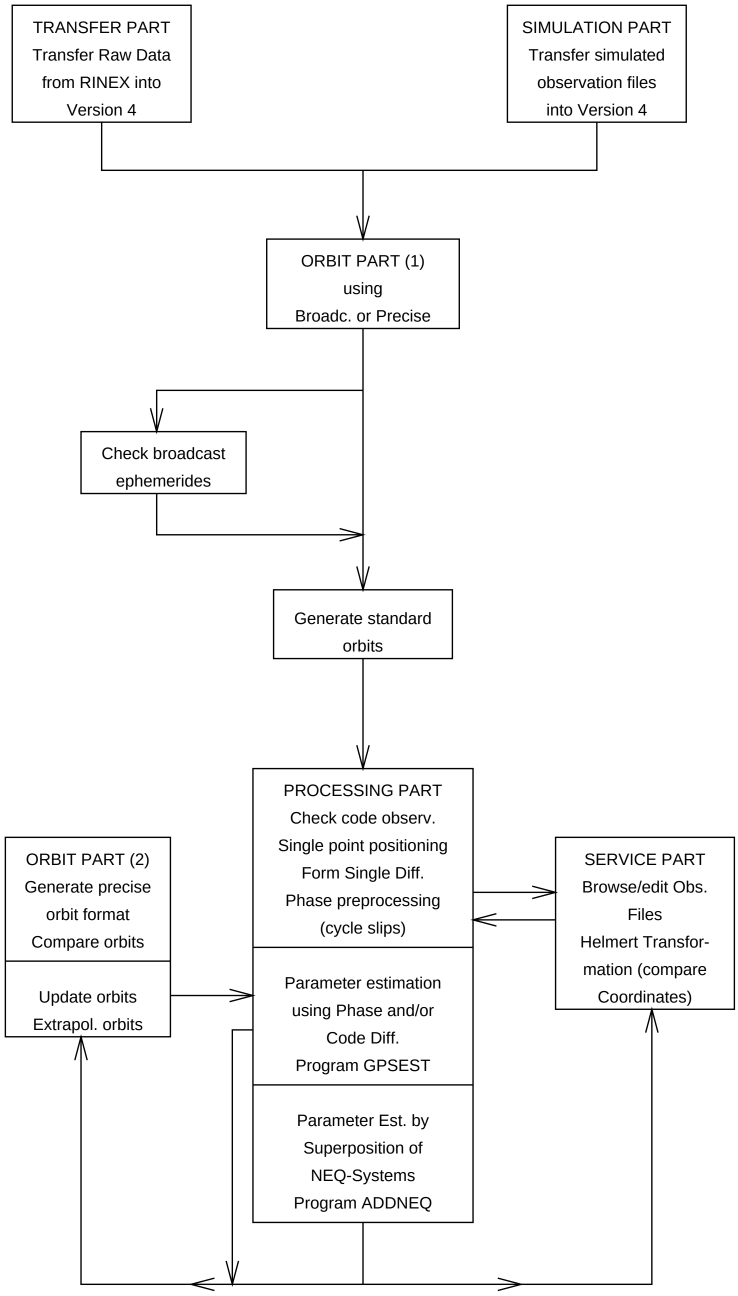

Figure 1.1: Functional flow diagram of normal processing in *Bernese GPS Software* Version 4.2.

- In Version 4.2 the program GPSEST is used to produce results for what we call a session, i.e., for a time interval containing all observations which have to be processed together (usually one day or a fraction of a day).

General Characterization of Parameter Estimation Programs ADDNEQ and ADDNEQ2

- The normal equation systems as generated either by program GPSEST or by the program ADDNEQ or ADDNEQ2 may be overlaid in programs ADDNEQ and ADDNEQ2. Result files are written as in program GPSEST.

- All results are based on a least squares process where extensive use is made of methods related to sequential least squares, parameter pre-elimination, parameter transformations, etc.
- ADDNEQ and ADDNEQ2 offer unique options like the possibility to combine $n \geq 1$ one-day arcs into an n-day arc or to introduce new parameters like, e.g., velocities for station coordinates for annual solutions.
- Weights added to the NEQ-systems in GPSEST may be removed or modified in ADDNEQ.
- For ADDNEQ2 no weights are written into the NEQ files in order to minimize numerical problems.
- The physical model may be changed in programs ADDNEQ and ADDNEQ2. It is, e.g., possible to add stochastic orbit parameters, to change the number of troposphere parameters (per station and day), to apply parameter transformations, etc.
- Because there is no necessity to set up the observation equations, the programs ADDNEQ and ADDNEQ2 greatly improve the efficiency and performance of the entire *Bernese GPS Software*. Solution series covering years may be produced in minutes.

The data files relevant to Version 4.2 may be divided into three groups:

General Information: Constants, geodetic datum, gravity potential of the Earth, Earth rotation parameters, etc.

Campaign Specific Information: Observation files, orbits, coordinates, troposphere parameters, etc.

Program Specific Information: Input option files, files with lists of file names (e.g., observation file names), etc.

1.4 Observables and Linear Combinations

In the *Bernese GPS Software* Version 4.2 the double-difference still is the key observable, although many options to process undifferenced observations exist, as well. The double-difference allows to approximate the satellite clocks by the simple single point positioning program CODSPP before the precise parameter estimation program GPSEST is invoked.

Phase and code observations may be used in the same program run, which is why weights have to be introduced for different observation types. The weight ratio between code and phase observations is an input variable. At present we recommend to use $\sigma^2(code) : \sigma^2(phase) = 1 : 10'000$ if the precise or P-Code is used, $1 : 100'000$ if the C/A-Code is used.

Six different linear combinations of the original L1 and L2 observations may be analyzed by the processing programs. It is even possible to use different linear combinations in the same program run (see Chapter 9). Table 9.1 lists the linear combinations used by the *Bernese GPS Software* and their properties.

1.5 Parameter Estimation

Geodesists are mainly interested in the site coordinates and their development in time. Orbit parameters and Earth rotation parameters (ERPs) are of primary interest to agencies using the *Bernese GPS*

Software 4.2 for orbit determination. Recently, atmosphere modeling using the GPS (GPS meteorology) became an important issue as well: it is, e.g., possible to extract (with a high time resolution) the precipitable water content of the atmosphere over a station by subtracting from the estimated zenith tropospheric delay the dry component of tropospheric refraction by using the readings of a high quality barometer and thermometer at the observation site.

Other agencies are primarily interested in producing ionosphere maps based on a regional or a global GPS tracking network. The *Bernese GPS Software* allows to estimate ionosphere maps of high quality and high time resolution.

Still other agencies are mainly interested in time transfer. With the zero-difference capabilities added to Version 4.2 the *Bernese GPS Software* may be used for such applications as well.

Table 1.2 gives an overview of the parameter types of the programs GPSEST and ADDNEQ, ADDNEQ2 implemented in Version 4.2.

Table 1.2: Parameter types implemented in the *Bernese GPS Software* Version 4.2.

Parameter	Description	Available in	
		GPSEST	ADDNEQ, ADDNEQ2
Station Coordinates	Rectangular coordinates X, Y, Z in the ITRF (at present the ITRF97 resp. IGS_97 is used). The results are also expressed in the (user defined) geodetic datum ($\lambda,\ \beta, h$).	Yes	Yes
Station Velocities	In program ADDNEQ resp. ADDNEQ2 station velocities may be set up if a long time series of NEQ systems containing the same stations is available.	No	Yes
Epoch Specific Station Coordinates	A set of station coordinates is assigned to each epoch (pseudo-kinematic surveys).	Yes	No
Receiver Clocks	Estimation using code and phase zero-difference data (e.g., for time transfer) relative to a reference clock.	Yes	No
Satellite Clocks	Estimation using code and phase zero-difference data.	Yes	No
Ambiguities	One initial phase ambiguity parameter has to be assigned to each (linearly independent) double-difference. If ambiguities were resolved once they may be introduced as known in subsequent program runs.	Yes	No
Differential Code Biases	Differential (P1−P2) code biases for satellites and receivers.	Yes	No
Antenna Phase Center Variations	Antenna phase center variations may be modeled using different techniques. Model parameters may be determined.	Yes	No
Mean Receiver Antenna Offsets	May be estimated for antenna calibration experiments if site coordinates are accurately known.	Yes	No
Satellite Antenna Offsets	Such offsets may be assigned to different types of spacecrafts (Block I, Block II satellites).	Yes	Yes
Orbit Elements	Osculating Orbital Elements at initial time t_0 of arc: semi-major 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
Radiation Pressure Parameters	Radiation pressure parameters: A total of nine 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, sin-, and cos - terms with the argument of latitude $u(t)$ of the satellite as an argument may be introduced.	Yes	Yes

Parameter	Description	Available in	
		GPSEST	ADDNEQ, ADDNEQ2
Pseudo-Stochastic Orbit Parameters	Velocity changes in pre-determined directions at user-defined epochs may be introduced for each satellite. Up to three directions (radial, along-track, out-of-plane) may be defined per (stochastic) epoch.	Yes	Yes
Earth Rotation 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
Center of Mass	The center of mass of the Earth may be estimated, which makes sense for global analyses.	Yes	Yes
Station Specific Troposphere Parameters	Time and station-specific zenith delay parameters may be introduced and solved for. High temporal resolution is possible, as well as reduction of number of parameters in ADDNEQ, ADDNEQ2.	Yes	Yes
Local Troposphere Models	In small survey areas (e.g., 10km$\times$10km) a height-dependent (polynomial) model for the tropospheric zenith delay may be established.	Yes	No
Ionosphere Maps	Regional or global ionosphere single-layer maps may be determined. The electron density in the layer is described by spherical harmonics.	Yes	No
Stochastic Ionosphere Parameters	Epoch- and satellite-specific ionosphere parameters may be introduced (together with a priori weights) to support ambiguity resolution.	Yes	No

Let us mention that ionosphere maps based on the observations of one dual-band receiver only may also be established using the program IONEST.

1.6 Accuracy and Performance

Table 1.3 addresses the question of accuracy achievable with the *Bernese GPS Software* by listing the estimated formal and actually achieved accuracies. Formal uncertainties are always too optimistic. The actual coordinate accuracies either stem from terrestrial comparisons (e.g., for the Turtmann campaigns) or from comparisons with other space geodetic techniques like VLBI and SLR.

We must make a clear distinction between processing activities before and after 1992: up to this date it was necessary to establish the orbits for the campaigns of considerable ($\geq 10\ km$) size with the material of the campaign (e.g., in the EUREF-89 campaign), afterwards the results of the *International GPS Service (IGS)* could be used.

The three last entries in Table 1.3, namely CODE, EUREF, and IGEX, stand for global solution stemming from the Center for Orbit Determination in Europe, for solutions for the permanent European Network of EUREF (operated by the IAG Commission on the European Reference Frame), and for solutions in the context of the International GLONASS Experiment 1998 (IGEX-98).

CODE is one of seven IGS Analysis Centers. It is located at the *Astronomical Institute of the University of Berne*. It goes without saying that CODE uses the *Bernese GPS Software*. This particular application is a cornerstone for the development of the *Bernese GPS Software*: it guarantees that state-of-the-art modeling techniques are used and that the software tool is very efficient. We believe that it is this combination of correct modeling and high efficiency which makes our software highly attractive.

Owing to the IGS the orbit error, which was the dominant contributor to the error budget for large networks until 1992, became less and less important afterwards. After 1993 the IGS orbits allowed (and allow) to achieve sub-centimeter accuracy in the horizontal position and about 1 cm accuracy vertically even for regional networks with a diameter of several thousand kilometers, provided a good software system like the *Bernese GPS Software* Version 4.2 is used.

The EUREF solutions as produced by the Federal Office for Geodesy and Cartography (BKG, Frankfurt a. M., Germany) since 1999 and by the CODE Analysis Center from 1996 to 1999 are actually based on normal equation contributions from 12 European EUREF Analysis Centers which are combined with the program ADDNEQ.

The IGEX solutions are based on a global network of 20–30 combined GPS/GLONASS receivers and on GPS orbits, Earth rotation parameters parameters, etc. taken over from the CODE/IGS solutions. The result of highest interest are precise GLONASS orbits (RMS of about 10–20 cm per satellite coordinate) in the ITRF (thus in the same reference frame as the orbits of GPS satellites).

IGS and EUREF solutions are produced in weekly batches.

Permanent GPS networks are playing an increasingly important role. It is a trend that such networks serve several purposes, e.g., reference frame purposes, crustal monitoring, atmosphere applications, reference stations for precise navigation, etc.

Admittedly the improvement of the orbit quality was not so important for campaigns of the Turtmann-type. Atmosphere modeling techniques (ionosphere and troposphere) and antenna phase center calibrations proved to be far more important, here. We refer to [*Beutler et al.*, 1995] for more information.

For an informative overview of the broad spectrum of problems that is addressed today using the GPS observation technique we refer to [*Beutler et al.*, 1999].

Table 1.3: Campaigns and permanent arrays processed with the *Bernese GPS Software*.

Campaign	Year	Responsible Agency	# Sites	Size (km)	Accuracy (m) formal	Accuracy (m) actual
Ottawa	83	Canad. Energy, Mines, Resources	4	10 x 60	.004	—
Quebec	84	Energie et Ressources, Quebec	16	2 x 3	.001	.001
California	84	JPL	2	140	.015	—
CERN	84	CERN	7	12 x 12	.002	.004
Alaska	84	U.S. NGS	8	800 x 1600	.050	.070
HPBL	85	JPL	9 2	2000 x 4200 240	.050 .020	.065 .030
Turtmann	85	Swiss Geodetic Commission	7	4 x 6	.002	.003
Iceland	86	UNAVCO	52	250 x 450	.020	—
Turtmann	86	Swiss Geodetic Commission	8	4 x 6	.002	.003
Alaska	86	U.S. NGS	8	800 x 1600	.030	.030
Switzerland	87	Swiss Geodetic Commission	12	180 x 180	.010	—
EUREF-89	89	EUREF Commission	93	4000 x 2000	.020	.040
Turtmann	89	Swiss Geodetic Commission	8	4 x 6	.002	.003
Turtmann	91	Swiss Geodetic Commission	8	4 x 6	.001	.003
Turtmann	92	Swiss Geodetic Commission	8	4 x 6	.001	.003
Turtmann	93	Swiss Geodetic Commission	8	4 x 6	.001	.001
Turtmann	94	Swiss Geodetic Commission	8	4 x 6	.001	.001
GIG'91 (European Part)	94	JPL	14	3000 x 1000	.010	.020
GIG'91 (Global)	94	JPL	14	Global	.020	.050
Swiss Network	86-95	Federal Office of Topography	300	180 x 180	.001	—
COSMOS Japan	94-96	Geographical Survey Institute	100	200 x 200	.001	—
BIGG Japan	96-. . .	Geographical Survey Institute	600-1000	1200 x 1500	.001	—
CODE	92-. . .	Center for Orbit Det. in Europe	100	Global	.001	.004
EUREF	96-. . .	EUREF Commission	75	4000 x 2000	.001	.004
IGEX	98-. . .	CODE / BKG	28	Global	.002	.010