12. Troposphere Modeling and Estimation

12.1 Motivation

In view of the fact that orbit errors must no longer be considered as an important error source (due to the availability of high accuracy orbits through the International GPS Service (IGS), see Chapter 8), propagation delays of the GPS code and phase signals due to the *neutral atmosphere*, i.e., the *troposphere*, probably are the *ultimate accuracy-limiting factor* for geodetic applications of the GPS. The zenith path delay due to tropospheric refraction is of the order of 2.3 m (or about 8 ns) for a station at sea level and for standard atmospheric conditions.

Let us distinguish two kinds of troposphere biases:

- Relative troposphere biases caused by errors of (mismodeled) tropospheric refraction at one of the endpoints 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]. It is remarkable that *relative troposphere biases* invoke primarily *biased station heights* whereas *absolute troposphere biases* produce *scale biases* of the estimated baseline lengths.

For local and smaller 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

$$\Delta h = \frac{\Delta \varrho_r^0}{\cos z_{max}} \tag{12.1}$$

where

Δh ... is the induced station height bias,
$\Delta \varrho_r^0$ ... is the relative tropospheric zenith delay error, and
z_{max} ... is the maximum zenith angle of the observation scenario.

In the above order of magnitude formula, it is assumed that the satellites are uniformly distributed over the sky above the observing sites. Due to the fact that the GPS orbits all have inclinations of

55^o with respect to the Earth's equator, this assumption is not true, actually. [*Santerre*, 1991] studies this effect in particular.

In any case, Eqn. (12.1) indicates that a bias of only 1 cm in the relative troposphere leads to an error of approximately 3 cm in the estimated relative station height!

According to [*Beutler et al.*, 1988] the corresponding formula for the impact of an absolute troposphere error reads as

$$\frac{\Delta\ell}{\ell} = \frac{\Delta\varrho_a^0}{R_e \ \cos z_{max}} \tag{12.2}$$

where

ℓ, $\Delta\ell$ ... are the baseline length and the associated bias,

$\Delta\varrho_a^0$ ... 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) says that an absolute troposphere bias of 10 cm induces a *scale bias* of 0.05 ppm, a relatively small effect compared to the height error caused by a relative troposphere bias. Nevertheless, the 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 Formula (12.2). The consequences of a non-uniform distribution were studied by [*Santerre*, 1991].

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 is produced in the lowest levels of the atmosphere (99% below 10 km) whereas the *ionospheric shell height* is about 400 km. Tropospheric refraction tends to be much more site-specific than ionospheric refraction for that reason.

In summary, we may state that troposphere biases are orders of magnitude above the noise level of the phase observable. Their influence thus must be reduced to make full use of the accuracy of the observable by either of the following two methods:

- Model tropospheric refraction *without* using the GPS observable (e.g., by using ground met measurements or water vapor radiometers).
- Estimate tropospheric zenith delays in the general GPS parameter estimation process.

Both methods are used today (depending on the circumstances); for both methods there are options in the *Bernese GPS Software* Version 4.2. Before discussing the options available, we briefly review some aspects of the theory.

12.2 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., [*Baueršíma*, 1983]). Tropospheric refraction is thus identical for both GPS carriers, L_1 and L_2 (and both phase and code measurements – see Eqn. (9.14)). The tropospheric path delay is defined by

$$\Delta\varrho = \int (n-1)\,\mathrm{d}\,s = 10^{-6} \int N^{trop}\,\mathrm{d}\,s\ , \tag{12.3}$$

where n is the refractive index and N^{trop} the so-called refractivity. The integration has to be performed along the actual path of the signal through the atmosphere. According to [*Hopfield*, 1969] it is possible to separate N^{trop} into a *dry* and a *wet* component

$$N^{trop} = N_d^{trop} + N_w^{trop}\ , \tag{12.4}$$

where the dry component is due to the dry atmosphere and the wet component due to the water vapor in the atmosphere. About 90 % of the path delay due to tropospheric refraction stems from the dry component [*Janes et al.*, 1989]. Using the previous equation we may write

$$\Delta\varrho = \Delta\varrho_d + \Delta\varrho_w = 10^{-6} \int N_d^{trop}\,\mathrm{d}\,s + 10^{-6} \int N_w^{trop}\,\mathrm{d}\,s\ . \tag{12.5}$$

According to [*Essen and Froome*, 1951] we have

$$N_{d,0}^{trop} = 77.64\ \frac{p}{T} \left[\frac{\mathrm{K}}{\mathrm{mb}}\right] \quad \text{and} \quad N_{w,0}^{trop} = -12.96\ \frac{e}{T} \left[\frac{\mathrm{K}}{\mathrm{mb}}\right] + 3.718 \cdot 10^5\, \frac{e}{T^2} \left[\frac{\mathrm{K}^2}{\mathrm{mb}}\right]\ , \tag{12.6}$$

where p is the atmospheric pressure in millibars, T the temperature in degrees Kelvin, and e is the partial pressure of water vapor. The coefficients were determined empirically.

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 $\Delta\varrho^0$ and the so-called *mapping function* $f(z)$:

$$\Delta\varrho = f(z)\ \Delta\varrho^0\ . \tag{12.7}$$

According to, e.g., [*Rothacher*, 1992] it is better to use different mapping functions for the dry and wet part of the tropospheric delay:

$$\Delta\varrho = f_d(z)\ \Delta\varrho_d^0 + f_w(z)\ \Delta\varrho_w^0\ . \tag{12.8}$$

Below, we will give a list of the *a priori models for tropospheric refraction* available in the *Bernese GPS Software* Version 4.2. Each model has its own mapping function(s). It is worth mentioning, however, that to a first order (*"flat Earth society"*) all mapping functions may be approximated by:

$$f_d(z) \simeq f_w(z) \simeq f(z) \simeq \frac{1}{\cos z}\ . \tag{12.9}$$

The following a priori models taking into account tropospheric refraction are available in the *Bernese GPS Software* Version 4.2:

- the **Saastamoinen model** [*Saastamoinen*, 1973],
- the **modified Hopfield model** [*Goad and Goodman*, 1974], and

- the **differential refraction model based on formulae by Essen and Froome** [*Rothacher et al.*, 1986].

There is also the possibility to just use an a priori model (Saastamoinen, modified Hopfield) for the *dry* component. Usually, we take the Saastamoinen model as *a priori model* to account for tropospheric refraction. This model is based on the laws associated with an ideal gas. [*Saastamoinen*, 1973] gives the equation

$$\Delta\varrho = \frac{0.002277}{\cos z} \left[p + \left(\frac{1255}{T} + 0.05 \right) e - \tan^2 z \right] , \tag{12.10}$$

where the atmospheric pressure p and the partial water vapor pressure e are given in millibars, the temperature T in degrees Kelvin; the result is given in meters. [*Baueršíma*, 1983] gives special correction terms B and δR:

$$\Delta\varrho = \frac{0.002277}{\cos z} \left[p + \left(\frac{1255}{T} + 0.05 \right) e - B \tan^2 z \right] + \delta R . \tag{12.11}$$

The correction term B is a function of the height of the observing site, the second term δR depends on the height and on the elevation of the satellite. Only the former term is implemented in the present version of our software.

In the model either *measured values for pressure, temperature, and humidity* or the *values derived from a standard atmosphere model* may be used. If you decide to use surface met values stemming from a model atmosphere, the following height-dependent values for pressure, temperature and humidity are assumed [*Berg*, 1948]:

$$\begin{aligned} p &= p_r \cdot (1 - 0.0000226 \cdot (h - h_r))^{5.225} \\ T &= T_r - 0.0065 \cdot (h - h_r) \\ H &= H_r \cdot e^{-0.0006396 \cdot (h - h_r)} \end{aligned} \tag{12.12}$$

where p, T, H are pressure, temperature (Kelvin), and humidity at height h of the site; p_r, T_r, H_r are the corresponding values at reference height h_r. The reference height h_r, and the reference values p_r, T_r, H_r are defined in the file `X:/GEN/CONST.` and we do *not* recommend to change these values:

$$\begin{aligned} h_r &= 0 \text{ m} \\ p_r &= 1013.25 \text{ mbar} \\ T_r &= 18^{\circ} \text{ Celsius} \\ H_r &= 50\ \% \end{aligned} \tag{12.13}$$

When estimating station-specific troposphere parameters (see Section 12.5), we recommend to use still another option, namely, to apply *no a priori model* at all. This has the advantage that the *total* troposphere zenith delay can be estimated using the more appropriate Niell mapping function [*Niell*, 1996] (to be selected in Panel 4.5–2.4.0) instead of the mapping implicitly implemented in the Saastamoinen or Hopfield models.

12.3 Using Ground Meteorological Data

Let us first discuss the implications of small biases in ground met data (pressure, temperature, humidity) on the estimated station heights.

Table 12.1, together with Formula (12.1), gives an impression of the sensitivity of the estimated station height (independent of the baseline length!) on biases in surface met measurements for different atmospheric conditions. We see, e.g., that in a hot and humid environment (last line in Table 12.1) an error of only 1% in the relative humidity will induce a bias of 4 mm in the tropospheric zenith delay, which will in turn produce (using Equation (12.1)) a height bias of *more than one centimeter*! It is common knowledge that it is virtually impossible to measure the relative humidity to that accuracy; moreover the measured humidity is usually *not* representative for the entire environment of a site. This is why *experience tells that the estimation of troposphere parameters is a necessity if highest accuracy is required and if only ground met 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 (0.1 mm) to render pressure-induced height errors harmless.

Table 12.1: Tropospheric zenith delay as a function of temperature T, pressure P, and relative humidity H.

T	P	H	$\left\|\frac{\partial\Delta\varrho}{\partial T}\right\|$	$\left\|\frac{\partial\Delta\varrho}{\partial P}\right\|$	$\left\|\frac{\partial\Delta\varrho}{\partial H}\right\|$
^{o}C	mbar	%	mm/^{o}C	mm/mbar	mm/1%
0^o	1000	50	3	2	0.6
30^o	1000	50	14	2	4
0^o	1000	100	5	2	0.6
30^o	1000	100	27	2	4

You should always keep in mind the orders of magnitude reflected in Table 12.1 when using ground met data. Our conclusion is, that *only if you are able to provide met values stemming from Water Vapor Radiometers you have a good chance to get around the estimation of tropospheric zenith delays*. There is one exception to that rule: if you are working in a small network (diameter $<$ 10 km) in a flat Earth environment with height differences $<$ 100 m (e.g., in the Netherlands), you may be best advised by *not* using surface met information (using the a priori atmosphere model defined in the software) and by *not* estimating troposphere parameters.

12.4 Introducing Troposphere Data Into the Processing

Three programs in the *Bernese GPS Software* model tropospheric refraction:

CODSPP (see Chapter 10) may model tropospheric refraction using either the Saastamoinen or the Hopfield model. The values for pressure, temperature, and humidity are taken from the standard atmosphere (see Section 12.2) using the reference values given in the file `X:/GEN/CONST`. It is not possible to introduce ground met data. Optionally, GPSEST zenith delay estimates may be introduced. If only poor a priori coordinates are available, it may be wise *not* to apply a tropospheric refraction model.

MAUPRP (see Chapter 10) uses the Saastamoinen model with the standard atmosphere values. It is not possible (and not necessary) to select a particular model in this program.

GPSEST, the main parameter estimation program, has many options to deal with the tropospheric refraction. The user has to decide:

(1) in Panel 4.5–2, the a priori model to be used for tropospheric refraction (see Section 12.2),

(2) the values for temperature, pressure, and humidity to be used (the values may stem either from the standard atmosphere or from ground met measurements, Panel 4.5, "METEO DATA"),

(3) whether troposphere zenith delays saved from a previous GPSEST run should be introduced (Panel 4.5 , "TROPO. ESTIMATES"),

(4) whether corrections with respect to the selected a priori model should be estimated (Panel 4.5–2.4),

(5) in Panel 4.5–2.4.0, the mapping function to be used to estimate troposphere zenith delay corrections.

We discussed the a priori models and the standard atmosphere in Section 12.2. In this section, we give an overview of the met data file types which may be introduced into the processing. The estimation of tropospheric parameters will be discussed in the last section of this chapter.

When preparing a GPSEST run, the user may specify the met files in Panel 4.5. It is possible to specify a list of met files. Each file has to contain the data for exactly one station covering the time span of the entire session(s). However, it is *not* necessary to specify the met file for each station (for stations without met data, the a priori troposphere correction will be computed using the standard atmosphere). The met files have the default extension `.MET` and they are located in the campaign-specific `ATM` directory. You may either prepare these files manually (using an ASCII editor), or they may be transformed from RINEX met files using program RXMBV3 (see Chapter 7). There are four types of met files (see also Chapter 24). The first type contains pressure, temperature, and humidity values:

```
DISTRIBU           BERNESE MET.FILES
STATION : ZIMMERWALD GPS87   UTC-LOCAL TIME(HOURS) =  0 TYP= 1
JJJJ MM DD HH MM SS  PPP.PP  TT.TT  HH.HH
1989 10 14 18  0  6  911.40  11.20  72.10
1989 10 14 18 30  5  911.90  10.40  69.30
...
1989 10 15  6  0  5  915.60   7.10  84.60
```

The second type contains pressure, and dry and wet temperature:

```
EXAMPLE FOR DRY AND WET TEMPERATURE (NOT REALISTIC !)
STATION : ZIMMERWALD         UTC-LOCAL TIME(HOURS) =  0 TYP= 2
JJJJ MM DD HH MM SS  PPP.PP  TDRY   TWET
1987  6 16 10 30  0  910.49  12.61  17.41
1987  6 16 10 32  0  907.60  12.94  22.29
...
1987  6 16 10 40  0  903.21  14.11  21.36
```

The third type contains directly the total tropospheric zenith delays:

```
EXAMPLE OF A ZENITH DELAY FILE
STATION : ZIMMERWALD         UTC-LOCAL TIME(HOURS) = -1 TYP= 3
JJJJ MM DD HH MM SS  ZENITH DELAY (M)
1987  6 16 10 00  0     2.100
1987  6 16 10 30  0     2.115
...
```

Be aware, that if a met file of type 3 is specified, no a priori troposphere model is used and the tropospheric delay in Eqns. 9.14 will be simply the value given in the file (interpolated for current epoch) divided by $\cos z$ as mapping function. The last type of met file contains *the zenith delay corrections* with respect to an a priori model:

```
ADDNEQ: 3-DAY 230, AMB. FIXED, POLE: 2 PAR/3 DAYS ABS            22-AUG-96 06:10
STATION : ZIMM 14001M004     UTC-LOCAL TIME(HOURS) =  0 TYP= 4  #VALUES=  1  MOD= -1
 JJJJ MM DD HH MM SS  DDDD.DDDD
 1996  8 16 23 59 56     0.0687
 1996  8 17  6  0  0     0.0687
 ...
 1996  8 18  0  0  3     0.0927
```

This fourth file type is still supported but no longer used today, because zenith delay corrections estimated in GPSEST or ADDNEQ (see next section) and saved in troposphere files (Panel 4.5–0 , with the default extension .TRP) may be directly introduced in Panel 4.5 to apply "a priori" troposphere corrections.

CODE daily estimates of the troposphere in the form of .TRP files are available through anonymous ftp (ftp://ftp.unibe.ch/aiub/BSWUSER/ATM/) for all the global sites processed by CODE. If you consider stations from the IGS network in your processing (aiming at a correct, ITRF-conform reference frame for your local network), it is a good idea to introduce CODE tropospheric delay estimates for these stations into your solutions. 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.

Warning

When specifying a .TRP input file in Panel 4.5 , it is *prohibited* to set up troposphere parameters for stations for which corrections are presented. Otherwise, you might get a .TRP output file with erroneous correction values. Note that there is an option (NO_TROPO) in Panel 4.5–2.4.0 (see Section 12.5.2) to prevent the program GPSEST from doing this.

12.5 Tropospheric Delay Estimation

We pointed out in Section 12.3 that, usually, the a priori model of the tropospheric delay is not sufficient if highest accuracy is required. Therefore, it is necessary to *estimate* the tropospheric delay in GPSEST (and ADDNEQ). In the documentation of Version 4.0, we recommended to use an a priori model and to estimate only the *corrections* with respect to this a priori model. This is still true if you are interested in estimating the parameters of a *local troposphere model* (see below). The mapping functions used in the a priori models (Saastamoinen, Hopfield) are no longer the best possible choice, however. We, therefore, recommend now to use *no* a priori model and to estimate the full delay using the dry Niell mapping function (to be specified in Panel 4.5–2.4.0), when you estimate troposphere parameters for individual stations.

12.5.1 Local Troposphere Models

You may estimate the parameters of a *local troposphere model*. This model assumes that the correction $\delta\Delta\varrho(h)$ with respect to the selected a priori model for a station at height h and a satellite at zenith angle z is given by

$$\delta\Delta\varrho(h) = \frac{1}{\cos z} \sum_{i=0}^{n} a_i \, (h - h_r)^i \; , \tag{12.14}$$

where the reference height h_r is taken from the constants file (`$X/GEN/CONST.`), and a_i are the estimated parameters. Local troposphere models are *not* supported by the menu system. It is necessary to edit the file `GPSESTI.INP` before starting the program GPSEST (see Chapter 3). The relevant part of the input file looks like

```
LOCAL TROPOSPHERE MODEL PARAMETERS:
----------------------------------

      MODEL  #PAR.       FROM              TO
                        (YEAR,MONTH,DAY,HOUR)
F      ***    **    **** ** ** **.*   **** ** ** **.*

--> :    1     3    1987 10 28 00.0   1987 10 28 23.9
--> :    2     3    1987 10 29 00.0   1987 10 29 23.9
--> :    3     3    1987 10 30 00.0   1987 10 30 23.9

      TERM   A PRIORI SIGMA

F      **     ******.*****

--> :   1          0.00001
        2      10000.00000
        3      10000.00000
```

In this example, three local troposphere models (with polynomial degree $n = 2$) are estimated for three 24-hour sessions. The zero-degree term has to be constrained to zero for a local network (since the estimation of an absolute tropospheric correction is not possible in this case). We recommend using local troposphere models only in *local* campaigns (distances between stations of several kilometers at most) with *big* height differences. A perfect example of such a campaign is discussed in [*Beutler et al.*, 1995]. Needless to say that the estimation of local troposphere model parameters, the coefficients a_i of (12.14), does not make sense unless a reasonable number of stations is considered.

12.5.2 Troposphere Parameters for Individual Stations

The estimation of troposphere parameters for *individual stations* is much more common than the estimation of local troposphere models. The total tropospheric delay correction $\Delta\varrho_k^i$ in Eqns. (9.14) is given by

$$\Delta\varrho_k^i = f_{apr}(z_k^i) \; \Delta\varrho_{apr,k} + f(z_k^i) \; \Delta\varrho_k(t) \; , \tag{12.15}$$

where

$\Delta\varrho_{apr,k}$ ... is the tropospheric zenith delay according to the a priori model specified. If a standard atmosphere is used (no met files), this delay is time-invariant (depends on the station height only). $\Delta\varrho_{apr,k}$ may be zero.

z_k^i ... is the zenith distance (satellite i, station k),
f_{apr} ... is the mapping function of the a priori model (each a priori model has its mapping function),
$\Delta\varrho_k(t)$ ... is the (time-dependent) zenith troposphere parameter for station k, and
$f(z_k^i)$ ... is the mapping function used for the parameter estimation. This mapping function may be different from f_{apr}. The user has to select this mapping function in Panel 4.5–2.4.0. To use the function $f(z_k^i)$ to map the *total* zenith delay, you should set $\Delta\varrho_{apr,k} = 0$.

Let us give you several recommendations concerning the estimation of troposphere parameters for individual stations:

- For *regional* or *global* campaigns, it is recommended to estimate troposphere parameters for *all* stations.
- For *local* campaigns, it is recommended to estimate troposphere parameters for *all but one* stations (due to strong correlations between the troposphere parameters of the stations included). If you do not make use of any a priori troposphere model, however, mapping the full tropospheric delay with the (dry) Niell mapping function, it is a must to set up troposphere parameters for *all* stations involved in any case.
- If tropospheric delays from global solutions are available for some stations (e.g., from CODE, see previous section), it is recommended to introduce these values and to estimate troposphere parameters only for the remaining stations of the regional or local campaign.
- If water vapor radiometer measurements and high precision barometers and thermometers are available, you may generate a met file of type 3 by adding the dry and the wet components. Then you probably will not need to estimate troposphere parameters.
- For short time intervals (sessions < 1 hour) no troposphere parameters should be estimated.

As stated above, the troposphere parameters $\Delta\varrho_k(t)$ are time-dependent. In the *Bernese GPS Software*, a set of parameters $\Delta\varrho_k$ may be estimated for each site, each parameter being valid within a time interval $\langle t_i, t_{i+1}\rangle$. Manually (by editing the `GPSESTI.INP` file), you may select the intervals almost arbitrarily. The menu system divides the entire session into intervals of equal length. The user has to specify the corresponding options in the following panel:

```
4.5-2.4.0 |     PARAMETER ESTIMATION: SITE-SPECIFIC TROPOSPHERE PARAMETERS

    General Zenith Apriori Sigmas:      General Gradient Apriori Sigmas:
      ABSOLUTE     > 5.0000 <  m          ABSOLUTE      > 5.0000 <  m
      RELATIVE     > 5.0000 <  m          RELATIVE      > 5.0000 <  m

    Special Zenith Apriori Sigmas:      Special Gradient Apriori Sigmas:
      ABSOLUTE     > 0.0000 <  m          ABSOLUTE      > 0.0000 <  m
      RELATIVE     > 0.0000 <  m          RELATIVE      > 0.0000 <  m

    Special Station Selection (no estimation if special sigmas set to 0.0):
      STATIONS     > NONE            < (blank for selection list, NONE,
                                       NO_TROPO, SPECIAL_FILE.. $FIRST, $LAST)
    Set-up of Parameters:
      MAPPING FUNCTION           > DRY_NIELL <  (COSZ, HOPFIELD, DRY_NIELL,
                                                 or WET_NIELL)
      GRADIENT ESTIMATION MODEL  > NO        <  (NO, TILTING, or LINEAR)
      MODE OF PARAMETER SET-UP   > NUM <        (NUM: num/sess; MIN: minutes)
      # ZEN PAR/SESS OR INTERVAL > 12  <        (num/sess or minutes)
      # GRD PAR/SESS OR INTERVAL > 1   <        (num/sess or minutes)
```

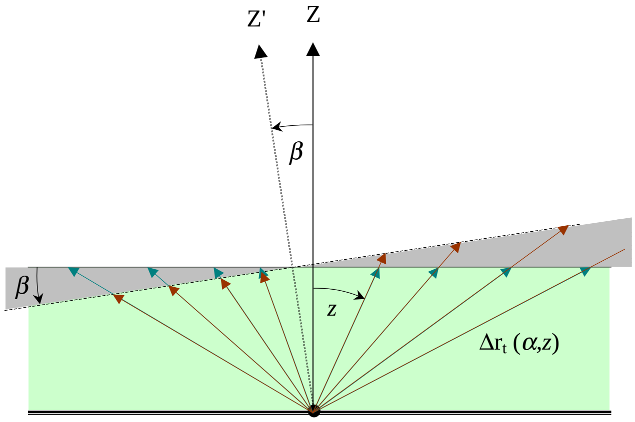


Figure 12.1: Tilting of the "tropospheric" zenith by the angle β.

We refer to the help panel for details on all options. Please note that it is possible to constrain not only individual parameters to the a priori model value (= *absolute* constraints) but also the *difference* between two subsequent parameters of the same station to an expectation value of zero (= *relative* constraints). For details we refer to [*Rothacher*, 1992]. Estimating a large number of parameters $\Delta\varrho_k$ with tight relative constraints produces results similar to Kalman filter techniques. For long sessions and troposphere estimation intervals longer than, let us say, 1 hour, relative constraints are *not* necessary.

12.5.3 Estimation of Troposphere Gradients

Estimation of troposphere gradients is a new feature introduced into the *Bernese GPS Software* Version 4.2. Estimation of gradients may considerably improve the repeatability of the estimated horizontal station components [*Rothacher et al.*, 1997*b*]. Lowering the elevation cut-off together with an elevation-dependent weighting of the observations (see next section) also improves the repeatability of the height component.

Troposphere gradient parameters are estimated to take into account *azimuthal asymmetries* in the tropospheric delay. 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

$$\Delta\varrho_k^i(t) = \Delta\varrho_{apr,k}\, f_{apr}(\tilde{z}_k^i) + \Delta\varrho_k(t)\, f(\tilde{z}_k^i)\ . \tag{12.16}$$

However, due to the fact that we usually do not have any a priori information on the tropospheric zenith, the geometrical zenith is used in the a priori part of the Equation (12.16):

$$\Delta\varrho_k^i(t) = \Delta\varrho_{apr,k}\, f_{apr}(z_k^i) + \Delta\varrho_k(t)\, f(\tilde{z}_k^i)\ . \tag{12.17}$$

Assuming a small angle between the tropospheric and geometrical zenith, the two zenith angles are related to each other by the equation

$$\tilde{z}_k^i = z_k^i + \beta = z_k^i + x_k \ \cos(A_k^i) + y_k \ \sin(A_k^i) \ , \tag{12.18}$$

where A_k^i is the azimuth of the direction station–satellite and x_k, y_k are two station-dependent parameters. Introducing this equation into Equation (12.17), we may write

$$\begin{aligned} \Delta\varrho_k(t) \ f(\tilde{z}_k^i) &= \Delta\varrho_k(t) \ f(z_k^i + x_k \ \cos(A_k^i) + y_k \ \sin(A_k^i)) \\ &= \Delta\varrho_k(t) \ f(z_k^i) + \Delta\varrho_k(t) \ \frac{\partial f}{\partial z} \ x_k \ \cos(A_k^i) + \Delta\varrho_k(t) \ \frac{\partial f}{\partial z} \ y_k \ \sin(A_k^i) \ . \end{aligned} \tag{12.19}$$

Introducing the notation

$\Delta^h\varrho_k(t) = \Delta\varrho_k(t)$ ... the zenith delay parameter,
$\Delta^n\varrho_k(t) = \Delta\varrho_k(t) \ x_k$ ... the gradient parameter in north-south direction, and
$\Delta^e\varrho_k(t) = \Delta\varrho_k(t) \ y_k$ ... the gradient parameter in east-west direction,

we end up with the equation

$$\begin{aligned} \Delta\varrho_k(t) &= \Delta\varrho_{apr,k} \ f_{apr}(z_k^i) + \\ &+\Delta^h\varrho_k(t) \ f(z_k^i) + \Delta^n\varrho_k(t) \ \frac{\partial f}{\partial z} \ \cos(A_k^i) + \Delta^e\varrho_k(t) \ \frac{\partial f}{\partial z} \ \sin(A_k^i) \ , \end{aligned} \tag{12.20}$$

which represents our adopted, refined tropospheric model. This model may be selected in Panel 4.5–2.4.0 by specifying "`TILTING`" for the gradient estimation model. The other possibility, "`LINEAR`", is not recommended. The user input options related to the troposphere gradient parameters are similar to those of the zenith delay parameters. They are all accessible through Panel 4.5–2.4.0. The number of gradient parameters estimated per session is usually much lower than the number of zenith delay parameters. Typically, one set of gradient parameters is estimated for a 24-hour session. The gradient parameters together with their rms errors are written into the last columns of the `.TRP` file (see Section 24.8.20). For a significant estimation of troposphere gradients, the cut-off elevation angle should be as low as possible, at most 15 degrees. Last but not least, let us advise *against* estimating troposphere gradient parameters in case of *small-area* networks or individually processed baselines.

Restriction Concerning Estimation of Troposphere Gradients

The programs ADDNEQ and ADDNEQ2 of Version 4.2 do **not** support the (explicit) estimation of troposphere gradient parameters. The user may get around this restriction by saving normal equation (`.NEQ` and `.NQO`) files with *pre-eliminated* troposphere parameters. It is recommended to do the corresponding parameter pre-elimination "after inversion" in order to have the possibility to get a `.TRP` file written by the program GPSEST. When manipulating such normal equation files, the troposphere gradient (and zenith) parameters are treated (implicitly) in a correct way, but the user has no longer access to their resulting estimates.

12.6 Elevation-Dependent Weighting of Observations

Observations at low elevations are generally much more corrupted by tropospheric refraction and multipath effects than those at high elevations. The unmodeled systematic errors decrease the quality of results. Therefore, prior to Version 4.2, we used to set the satellite elevation mask to 15 or even 20 degrees. Using low-elevation observations, however, may also improve the estimation of the tropospheric zenith delays and, consequently, the vertical component of the station position [*Rothacher et al.*, 1997*b*]. In order to optimize the usage of low-elevation observations, the option for elevation-dependent weighting of the observations was introduced into the software. After a few tests with different models, a weighting function $w(z)$ was adopted where the noise increases with elevation in the same way as the tropospheric delay, namely:

$$w(z) = \cos^2(z) \ , \tag{12.21}$$

where z is the zenith angle of the satellite. Thus, an observation at zenith is assumed to have a unit weight. The user has the possibility to enable the elevation-dependent weighting of observations in Panel 4.5–2. Incidentally, other weighting models $w(z)$ might be easily complemented by the interested user (see help panel of Panel 4.5–2). Whichever model you test, $w(0) = 1$ should still hold.

When enabling the elevation-dependent weighting, we recommend to reduce the "`A PRIORI SIGMA`" in Panel 4.5–2 from 0.002 m to 0.001 m. The a priori sigma of unit weight corresponds to the weight of the zero-difference L1 phase observable at the zenith, if elevation-dependent weighting is enabled, whereas it corresponds to the weight of the observable averaged over all zenith angles if no elevation-dependent weighting is enabled. The adaptation of the unit weight is necessary in order not to bias the weights of a priori constraints.

12.7 How to Retrieve Best Possible Zenith Delay Estimates

If a user is particularly interested in tropospheric zenith delay estimates—or a derivative of them, like wet delay or PWV values, he may ask for the optimal analysis strategy to retrieve best possible delay estimates. It is commonly known that tropospheric zenith delay parameters are very highly correlated with the *vertical* component of station coordinates simultaneously solved for. As a consequence of this, the user is obliged to take suitable measures that may defuse this circumstance as best as possible. There are two main measures which aim at a *de-correlation* of zenith delay and station height parameters, namely:

(1) imposing an elevation cut-off angle of 15, 10, or even 5 degrees on the analysis and

(2) averaging the station coordinate parameters over a longer period of time.

It is clear that the first measure does only make sense if (a) an appropriate mapping function is used in conjunction with an elevation-dependent weighting of observations (see Sections 12.2 and 12.6), (b) the user is sure that his data is not excessively contaminated with multipath effects, and (c) if low-elevation observations are actually at the user's disposal, of course. By the way, the latter point should be taken to heart by the reader. It is nowadays quite usual to get GPS tracking data recorded down to 5 (or at best 0) degrees. The primary reason for that is certainly the better retrieval of GPS-based tropospheric information, which leads in the end to an improved station coordinate determination. Solely a poor receiver performance, an insufficient number of channels which makes it impossible to the receiver to simultaneously track all satellites in view, or a receiver environment known from experience to be sensitive to multipath signals are points against lowering the elevation cut-off angle pre-set at the receiver.

The second measure can be achieved using the tool ADDNEQ. Let us discuss in the following a possible procedure starting from the assumption that the user is interested in analyzing one week of data. We further assume that the basic analysis is performed in daily batches and that each final GPSEST run, "classically" executed, yields a normal equation (`.NEQ`) file (containing at least station coordinate parameters) based on a correct, hopefully ambiguity-fixed network solution. In this case, a (weekly) station coordinate set may be derived by stacking the 7 (daily) normal equation systems (and saving a `.CRD` file). At this stage, the final tropospheric results may be produced after all by analyzing individually each daily `.NEQ` file—or by re-doing the GPSEST runs—and fixing the coordinate parameters on the values of the 7-day combination previously computed. If you look with favor on the ADDNEQ-based approach, indeed the more cultivated approach, you have to reckon with a possibly huge number of tropospheric parameters which urgently needs a pre-elimination of these parameters (in the program run deriving the long-time station coordinate results).

Whereas a time resolution of 1 or 2 hours for the zenith delay parameters is sufficient as part of the computation of station coordinates, the user may go to 30 or even 15 minutes for his troposphere-dedicated analysis . Exactly for this reason, one may reduce the number of tropospheric parameters per session (and their time resolution, respectively) in ADDNEQ. We recommend to refrain from going to a higher time resolution than 15 minutes since so-called "relative" constraints to be defined by the analyst (see Section 12.5.2) are of importance already in case of a moderate sub-hourly resolution. It is then the user's task to find (empirically) an "optimal" value for the corresponding a priori sigma (synonymous with standard deviation). The degree of freedom in this matter is considerable, and so we restrict our support to the closing statement that a "relative" (just as an "absolute") constraint does not take effect until its value is in the order of the parameters' formal errors.

12.8 Tropospheric SINEX Format

This is the place where another tropospheric format, the tropospheric SINEX format, should be introduced. This format is internationally adopted and may be used to exchange station-related total zenith delay estimates—and, optionally, the station coordinates the delay values are based on. This option is a clear indicator for the high correlation between both parameter types. The corresponding format specifications are available at `ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex_tropo.txt` (see also [*Kouba et al.*, 1996]). A tropospheric SINEX output is available in the programs GPSEST, ADDNEQ, and ADDNEQ2. Such files are generally indicated with the extension `.TRO`.

13. Ionosphere Modeling and Estimation

13.1 Subdivision of the Atmosphere

The *atmosphere* is usually subdivided into two main shells, the *troposphere* and the *ionosphere*, since the signal propagation conditions are quite different in these two shells.

- The *troposphere*, also called the *neutral* atmosphere, is the lower part of the Earth's atmosphere which extends from the Earth's surface up to an altitude of about 20 kilometers. The signal propagation depends mainly on the temperature, the pressure, and the water vapor content of the atmospheric layers (see Chapter 12).
- The *ionosphere* is the upper part of the Earth's atmosphere. It is located approximately between 70 and 1000 kilometers above the Earth. The signal propagation is mainly affected by free charged particles.

13.2 Motivation and Introductory Remarks

You have to deal with *ionospheric* refraction, more specifically, with the term I of the observation equation (9.14), in the following processing steps:

(1) *single-point positioning* (program CODSPP), if you do *not* use the ionosphere-free (L3) linear combination,

(2) *pre-processing* (program MAUPRP),

(3) *ambiguity resolution* (program GPSEST), if you do *not* make use of the Melbourne-Wübbena (L6) linear combination (see Section 9.6.4),

(4) *parameter estimation* (program GPSEST), if you do *not* use the ionosphere-free (L3) linear combination, and

(5) *ionosphere mapping* (programs GPSEST and IONEST).

Note that *ambiguity resolution* is a special case of *parameter estimation*.

13.2.1 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 ADDNEQ or ADDNEQ2 analyses. The same is by the way also valid in terms of elevation cut-off angle, weighting of observations, tropospheric mapping function, antenna phase center corrections, and so on.

If you have solely single-frequency (L1) data at your disposal, there is no point in talking about it any longer. If you consider dual-frequency (L1/L2) data, however, you cannot avoid making a decision. On one hand, in case of long baselines, you will certainly use the ionosphere-free (L3) 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," L1/L2-based solutions perform significantly better. As a consequence of this, there must be somewhere between a trade-off between L3 and L1/L2 solutions. Unfortunately, because of the pronounced variability of the *ionosphere*, it is quite impossible to generally give 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, however, is transferable exclusively to mid-latitude regions. Finally, if you decide to use the basic carriers in their original form, it is then better from our experience to ignore L2 and to use L1 only (see also Section 13.2.3).

13.2.2 Impact of Unmodeled Ionosphere on Single-Frequency GPS 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 GPS network by *unmodeled* ionospheric refraction is given in Table 13.1 (according to [*Beutler et al.*, 1988]) as a function of the linear combination (LC) 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 L1 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).

Table 13.1: Ionosphere-induced scale factor (per TECU) when neglecting the ionosphere.

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

13.2.3 How to Treat Small-Area High-Precision Arrays

If only single-frequency data is available, GPS-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—L1-only data in combination with a GPS-derived ionosphere model (see, e. g., [*Beutler et al.*, 1995]). Such ionosphere models are also useful for other applications, like ambiguity resolution (see Chapter 15).

The user of the *Bernese GPS Software* has a free hand 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 (see Section 7.4.1). The use of these GIMs may be recommended for *local* applications, too (see, e. g., [*Schaer et al.*, 1999]).

13.3 Theory

13.3.1 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.

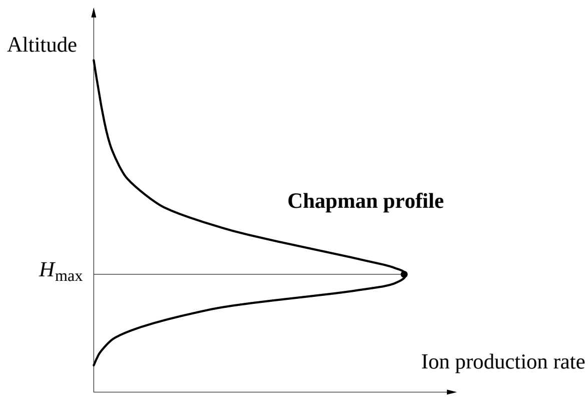


Figure 13.1: Chapman curve of ionization rate.

The degree of ionization shows large variations which are correlated with the solar activity; geomagnetic influences play 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 monthly-smoothed sunspot numbers from 1950 to 2000 (as obtained from `http://sidc.oma.be`). We see that the most recent ionospheric maximum must have happened in 1989/1990 and that currently (2001) we are approaching again a maximum. The situation will relax again afterwards, with decreasing sunspot cycle phase.

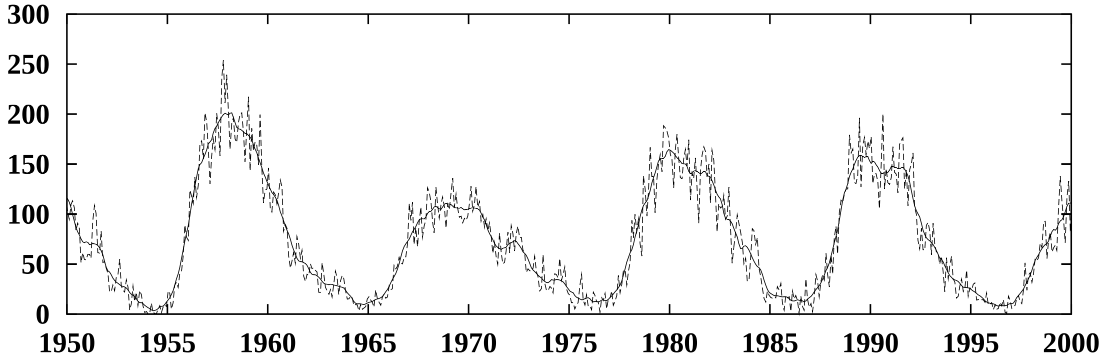


Figure 13.2: Monthly and monthly-smoothed sunspot numbers.

13.3.2 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 Total Electron Content E:

$$E = \int_R^S n_\mathrm{e}(s)\, ds. \tag{13.1}$$

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 R and satellite S. In geodetic applications, the TEC E is measured in so-called TEC Units (TECU), where one TECU corresponds to 10^{16} electrons per square meter ($10^{16}/\mathrm{m}^2$). For comparisons, the *vertical* TEC E_v is formed as

$$E_\mathrm{v} = E\, \cos z', \tag{13.2}$$

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, we may write the ionospheric refraction coefficient for carrier phase measurements as

$$n_I = 1 - \frac{a\, n_\mathrm{e}}{f^2}, \tag{13.3}$$

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

$$\Delta\varrho_I = \int_s (n_I - 1)\, ds = -\frac{a\, E}{f^2} \qquad \text{with} \quad a = 4.03 \cdot 10^{17}\ \mathrm{m\, s^{-2}\, TECU^{-1}}, \tag{13.4}$$

where E is the slant TEC.

Formulae (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* (L3) linear combination according to Eqns. (9.19) and (9.20).

In the observation equation (9.14), we defined a term I that is synonymous with the ionospheric delay on L1:

$$I = \frac{a\,E}{f_1^2} \qquad \text{with} \quad f_1 = 1.57542 \cdot 10^9 \text{ s}^{-1}. \tag{13.5}$$

Hence, the ionospheric delay may be written as

$$\Delta\varrho_I = \mp \frac{f_1^2}{f^2}\, I, \tag{13.6}$$

where we have to use the *negative* sign for *phase* observations and the *positive* sign for *code* observations. The resulting one-way range error $\Delta\varrho_I$, for GPS frequencies, 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 LC eliminating the first-order term is an excellent approximation, especially on the double-difference level, where the Residual Range Error (RRE), the difference between the ionosphere-free LC and the true range, is smaller than a few millimeters even for long baselines.

13.3.3 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 (LCs): the basic carriers (L1 and L2), the ionosphere-free LC (L3), the geometry-free LC (L4), and the wide-lane LC (L5). We may distinguish between *systematic* and *random* errors. Systematic errors may be further divided up into *geometrical* errors caused, e. g., by the limited accuracy of troposphere and orbit representation (“geometry”) and into *ionosphere-induced* errors (“ionosphere”). The “noise” of the measurements falls obviously into the category of random errors.

LCs labeled with a dash (e. g., L2′) are formed when data from a squaring-type receiver is processed, where L2 is available with half the wavelength λ_2 only. In this case, the wide-lane (L5) ambiguities N_5 are formed according to

$$N_5' = 2\,N_1 - N_2' \qquad \text{with} \quad \lambda_5' = \lambda_5/2 = 0.431 \text{ m}. \tag{13.7}$$

Note that the above linear combination is superior to, e. g., $N_5'' = N_1 - N_2'$ (with $\lambda_5'' = 0.341$ m) regarding the ionospheric influence. “L3 with N_5” denotes the so-called *narrow-lane* LC, where we introduce the previously resolved ambiguities N_5 (or N_5'). κ_1 and κ_2 are the factors to form the particular LCs based on L1 and L2. All errors are given in *meters* and *cycles*, scaled to the error on the first carrier L1. The information concerning the “noise” is based on two assumptions: the measurement noise of L1 and L2 expressed in *meters* is of the same order, and L1 and L2 are *not* correlated.

Table 13.2: Influences of the most important error sources on various linear combinations.

LC	λ	κ_1	κ_2	Geometry		Ionosphere [TECU] 6.05	1.15	Noise	
	[m]	[m/m]	[m/m]	[m]	[cycles]	[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

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 (L5) linear combination is much less ionosphere-sensitive for ambiguity resolution than L1 and L2 (see also Chapter 15). The relation between an ionospheric error on a particular LC and TEC (in TECU) is also given in this Table. Example: an ionospheric bias of one cycle in L5 corresponds to $1.15/0.28 = 4.14$ TECU.

13.3.4 Ionospheric Effects on GPS 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 corrupts 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 result of this, it makes sense to classify ionospheric refraction for our purposes into

- a *stochastic* part and
- a *deterministic* part.

13.4 Ionosphere Modeling

13.4.1 Deterministic Component

GPS-derived ionosphere models describing the *deterministic component* of the ionosphere usually are 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

$$F_I(z) = \frac{E}{E_\mathrm{v}} = \frac{1}{\cos z'} \qquad \text{with} \quad \sin z' = \frac{R}{R+H}\,\sin z, \tag{13.8}$$

where

z, z' are the zenith distances at the height of the station and 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.

With the help of Figure 13.3, it can be easily verified that the geocentric angle α equals $z - z'$.

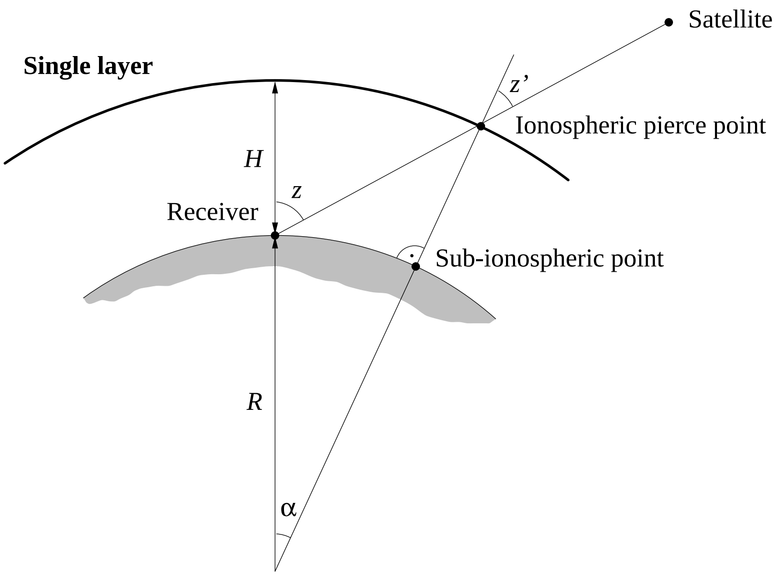


Figure 13.3: Single-layer model.

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.

To map TEC, the so-called *geometry-free* (L4) linear combination (9.24), which principally contains ionospheric information, is analyzed. 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),

$a = 4.03 \cdot 10^{17}\ \mathrm{m\,s^{-2}\,TECU^{-1}}$ is a constant,

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.

13.4.1.1 Differential Code Biases (DCBs)

On the basis of Eqns. (9.14), you might argue that the term b_4 equals to zero. This is actually *not* correct. The term b_4 (usually given in units of nanoseconds) stands for a so-called differential ($P_1 - P_2$) code bias (DCB). In practice, one is forced to consider satellite-specific as well as receiver-specific code biases [*Schaer*, 1999]. Figure 13.4 shows 30 days of accumulated P1-P2 DCB solutions as computed by CODE. A corresponding figure, daily updated, may be found at `http://www.aiub.unibe.ch/ionosphere.html` [*Schaer*, 1998]. The individual PRN-specific DCB values are rather stable, but they considerably vary from PRN to PRN.

Extrapolating from our IGS ionosphere analysis, values for the receiver-specific DCB should not exceed the level of few tens of nanoseconds. Corresponding estimates for all IGS/EUREF stations processed at CODE may be gathered from [*Schaer*, 1998]. In case of GPS/GLONASS-combined receivers, *two* receiver-specific bias values must be considered, one related to GPS and one related to GLONASS.

It is important to mention that P1-P2 code biases are not only relevant with respect to the geometry-free LC but may also be significant for "non-ionosphere-free" LCs. A detailed discussion would here be out of proportion, therefore we refer the interested reader to [*Schaer*, 1999].

P1-C1 Code Biases

Nowadays, also a further type of code bias, namely for P1-C1, is considered by the IGS. CODE is monitoring P1-C1 bias values for all PRNs of the GPS constellation [*Schaer*, 1998]. You might find corresponding DCB files in Bernese format in our data archives. It is *prohibited* to introduce such

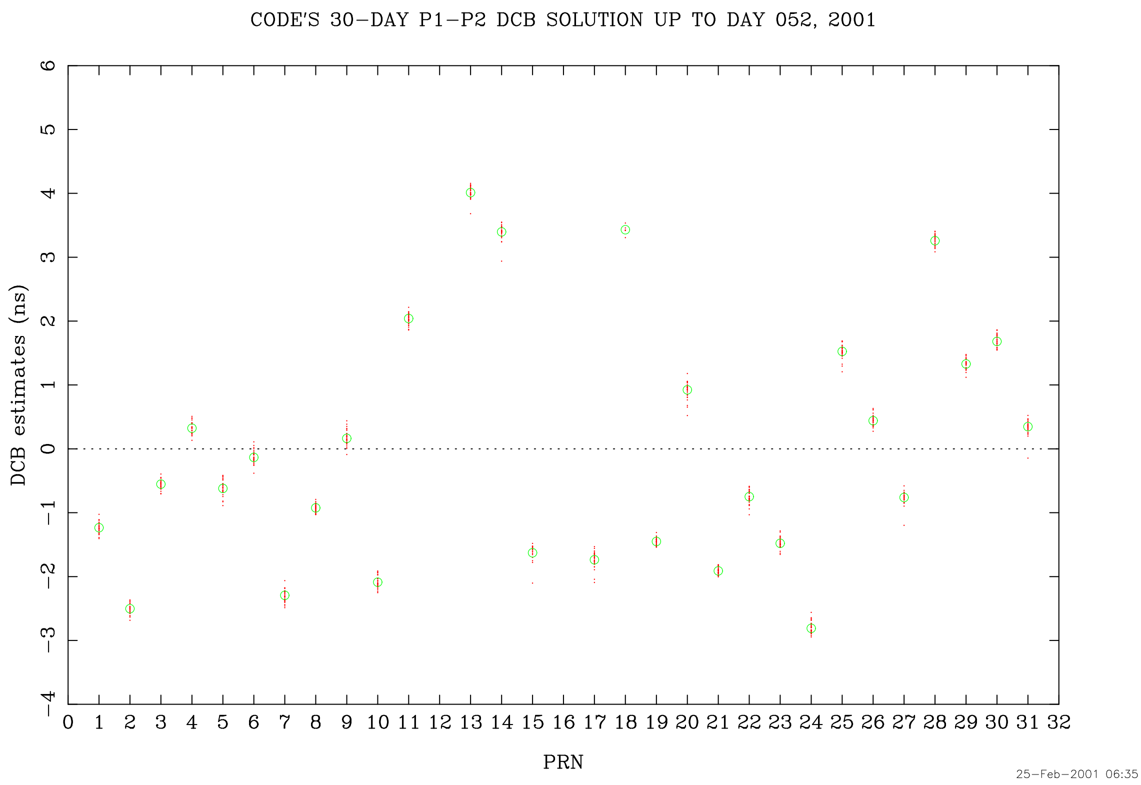


Figure 13.4: PRN-specific P1-P2 DCB estimates as computed by CODE.

DCB files into the software, however, since this type of code bias is *not* supported by the *Bernese GPS Software* Version 4.2.

The use of P1-C1 bias values is recommended for all IGS analysis centers and users of IGS clock products. "CC2NONCC" is an easy-to-use tool to handle P1-C1 biases. This tool works properly on the condition that (a) receiver names are used following the IGS naming conventions and (b) current RINEX data is converted. The mentioned RINEX converter utility program may be downloaded from `ftp://maia.usno.navy.mil/pub/biases/cc2noncc.f`. To avoid any confusion, it should be said that P1-C1 code biases are irrelevant to Eqns. (13.9), but they were introduced here for the sake of completeness. The interested user may have a look at `http://www.aiub.unibe.ch/ionosphere.html#p1c1`.

13.4.1.2 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 GPS Software* Version 4.2 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 13.6 and 13.8).

13.4.1.3 Local TEC Model

The *local* TEC model—applicable in the vicinity of one or more dual-frequency station(s)—is represented by

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} E_{nm} \, (\beta - \beta_0)^n \, (s - s_0)^m, \tag{13.10}$$

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

$$s = \mathrm{LT} - \pi \approx \mathrm{UT} + \lambda - \pi. \tag{13.11}$$

UT is Universal Time and λ denotes the geographical longitude of the sub-ionospheric point. For satellites at elevation angles of $15/20^\circ$ 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].

13.4.1.4 Global TEC Model

The *global* TEC model—which may be used for regional applications also—may be written as

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \widetilde{P}_{nm}(\sin \beta) \; (a_{nm} \, \cos ms + b_{nm} \, \sin ms) \, , \tag{13.12}$$

where

$n_{\max}$ is the maximum degree of the spherical harmonic expansion,

$\widetilde{P}_{nm} = \Lambda(n,m)\, P_{nm}$ 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].

13.4.1.5 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.

13.4.2 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 set up the ionospheric term I of the double-difference observation equation (9.17)—rewritten in a simpler way—

$$L_1 = \varrho - I + \ldots + \lambda_1 N_1 \quad (13.13a)$$

$$L_2 = \varrho - \frac{f_1^2}{f_2^2} I + \ldots + \lambda_2 N_2 \quad (13.13b)$$

as an *unknown* parameter. This type of parameter, called *Stochastic Ionosphere Parameter (SIP)*, represents the double-difference ionospheric delay on L1 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 SIP parameters, an *epoch-wise* parameter pre-elimination has to be performed.

This parameter type is particularly useful for “dual-band” ambiguity resolution when using strategies like the General-Search or the Quasi-Ionosphere-Free (QIF) strategy, which directly solve for L1/L2 ambiguities (see also Chapter 15). In the ambiguity-unresolved case, where neither L1 and L2 ambiguities (N_1 and N_2) nor L5 ambiguities ($N_5 = N_1 - N_2$) are known, you have to impose a priori constraints on the SIP parameters to retain the integer nature of the L1/L2 ambiguities, otherwise you will implicitly get real-valued ambiguity parameters B_3 according to Eqns. (9.21) and (9.22).

In addition, SIP parameters allow to smoothly switch between a pure L1/L2 solution and an ionosphere-free (L3) solution. This is demonstrated in Figure 13.5 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. We may recognize in Figure 13.5 that (a) 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) and that (b) for a very big a priori sigma, the 8 dotted curves showing the formal accuracy of the L1/L2 ambiguities go to infinity. Note that this particular scenario is based on a 5-satellite constellation.

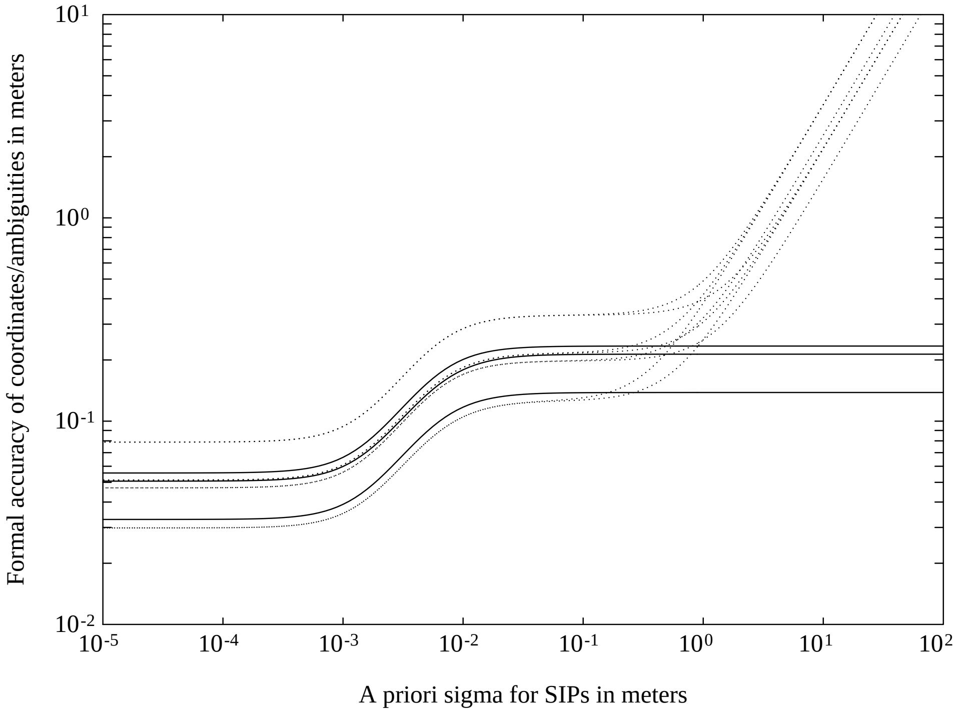


Figure 13.5: Coordinate and ambiguity parameters as function of SIP constraining.

13.5 Estimation of Deterministic Ionosphere Models

13.5.1 Local Ionosphere Models

Local ionosphere models (type-1 models) according to Eqn. (13.10) may be estimated with the program IONEST by activating Menu 4.7 . The processing steps RXOBV3 and CODSPP are presupposed.

```
 4.7   |                 PROCESSING: IONOSPHERE MODEL

   CAMPAIGN         >          <     (blank for selection list)

 Input Files:
   MEASUREMENT TYPE > PHASE    <     (CODE, PHASE)
   OBSERVATIONS     >          <     (blank for selection list)
   COORDINATES      >          <     (blank for selection list)
   ECCENTRICITIES   > NO       <     (NO, if not used; blank for sel.list)
   STANDARD ORBIT   >          <     (blank for selection list)

 Output Files:
   IONOSPHERE MODEL > IONTST   <     (NO, if not to be saved)
   RESIDUALS        > NO       <     (NO, if not to be saved)
```

In Panel 4.7 , 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

OBSERVATIONS, one or more zero-difference observation files may be selected. If you want to derive more than one ionosphere model per session, you have to concatenate/split up the observation file(s) either on the RINEX or the Bernese-binary-format level into the sub-sessions requested (see Menu 2.5.6.1 or Menu 5.1), because the program IONEST always takes *all* available observations. Furthermore, you have to combine the individual ionosphere model files created into one common file (see example in Figure 13.6). For longer sessions (e. g., 24-hour sessions), it is much easier to generate a *regional* ionosphere model than a *local* model. Please note that the estimation of local ionosphere models using the program GPSEST is *not* recommended, since this possibility is *not* menu-supported. In addition, you would have to prepare in a previous step the header of the ionosphere file to be introduced in GPSEST (see also Section 24.8.22).

The estimated ionosphere models may be used in further processing steps, therefore it makes sense to specify at IONOSPHERE MODEL a file name (e. g., IONTST). The ionosphere (ION) files are stored in the campaign-specific ATM directory. It is recommended to create a residual (RES) file containing L4 residuals, if you wish to study short-term TEC variations, like scintillations or Traveling Ionospheric Disturbances (TIDs). Use Menu 5.3.1 to browse through these files.

In Panel 4.7–1 , 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 (13.9)) for each cycle slip detected when processing phase measurements. The model-specific options include (1) MIN. ELEVATION, the minimum elevation to be processed, (2) HEIGHT OF THE LAYER, the single-layer height H (see mapping function (13.8) and Figure 13.3), (3) DEGREE OF DEVELOPMENT IN LATITUDE and DEGREE OF DEVELOPMENT IN HOUR ANGLE, $n_{\max}$ and $m_{\max}$ of the TEC representation (13.10), and (4) MAXIMUM DEGREE IN MIXED COEFFICIENTS, the maximally 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.

```
4.7-1                     IONOSPHERE MODEL: INPUT

  TITLE    >                                                        <

  Preprocessing:
    PRINT MESSAGES                      > NO  <    (YES or NO)
    CARRIER FOR BREAK DETECTION         > L4  <    (L3 or L4)
    POLYNOMIAL DEGREE                   > 1   <    (0,1,2,3)
    MAX.INTERVAL FOR TEST               > 4   <    minutes
    RMS OF ONE OBSERVATION             > 0.010 <   meters

  Processing Options:
    PRINT RESIDUALS                     > NO  <    (YES or NO)
    MIN. ELEVATION                      > 15  <    degrees
    HEIGHT OF THE LAYER                 > 400 <    kilometers
    DEGREE OF DEVELOPMENT IN LATITUDE   > 1   <
    DEGREE OF DEVELOPMENT IN HOUR ANGLE > 2   <
    MAXIMUM DEGREE IN MIXED COEFFICIENTS > 2  <
```

Figure 13.6 gives an example of an ION file containing a two-session model. When joining individual models, you have to guarantee that all models end with "-1" and that additional models directly start with "IONOSPHERE MODEL NUMBER," i. e., *without* title lines.

A series of zero-degree TEC parameters E_{00} extracted from local ionosphere models is plotted in Figure 13.7. 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

```
IONOSPHERE MODELS FOR TURTMANN                                       8-FEB-93 10:59
-------------------------------------------------------------------------------
IONOSPHERE MODEL NUMBER                               :    1
TYPE OF IONOSPHERE MODEL                              :    1
ORIGIN OF DELEVOPMENT: 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 DELEVOPMENT: 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
```

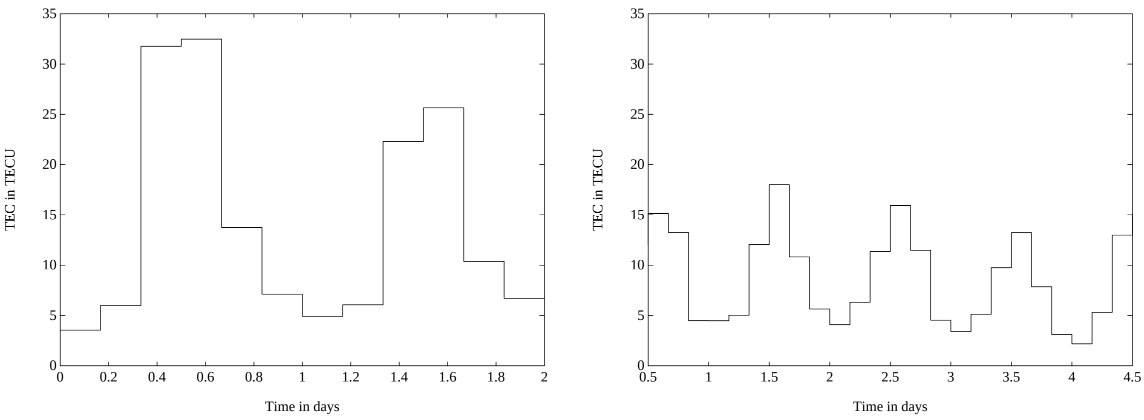
Figure 13.6: Example of an ionosphere file containing (two) local TEC models.

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 (compare also Figure 13.2).

13.5.2 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, which may be started with Menu 4.5 . It is then the user's decision to do the ionosphere analysis on either the zero- or the double-difference level. We may make two recommendations to you:

- If you favor the zero-difference approach, the following processing steps are presupposed: RNXSMT (see Chapter 16), RXOBV3, and CODSPP. The use of *smoothed* code observations in program GPSEST is suggested.



(a) 1992 Turtmann campaign

(b) 1993 Turtmann campaign

Figure 13.7: Zero-degree TEC parameter E_{00} extracted from local ionosphere models.

- If you follow the "traditional" double-difference approach, taking the steps RXOBV3, CODSPP, SNGDIF, MAUPRP, GPSEST, the use of phase observations is strongly recommended. Ionosphere mapping on double-difference level, however, is *not* recommended until your ground network is of large size.

The advanced user, eventually interested in doing "parallel" analyses on both differencing levels, might take the following processing steps: RNXSMT, RXOBV3, CODSPP, SNGDIF, MAUPRP, and finally GPSEST, selecting then either zero- or single-difference observation files.

In the following, we discuss the most important options to be specified to estimate global or regional ionosphere model parameters on the basis of zero-difference (ZD) smoothed code observations. We will highlight aspects which are relevant if double-difference (DD) phase observations were processed.

In Panel 4.5 , you have to select zero-difference smoothed code file(s) at `CODE Z.DIFF.`, or in the DD case, single-difference phase file(s) at `PHASE S.DIFF.`. In the ZD case, the specification of a `DCB` input file containing DCB values for all satellites of the constellation is highly recommended. Corresponding files, like `P1P2.DCB` (moving 30-day average), may be downloaded from our data archives (see Section 7.4.1).

```
 4.5                     PROCESSING: PARAMETER ESTIMATION

   CAMPAIGN          >         <    (blank for selection list)

 Job Identification:
   JOB CHARACTER       >   <        (blank, or A..Z, 0..9)

 Input Files:
   PHASE Z.DIFF.     > NO      <    (NO, if not used; blank for sel.list)
   CODE  Z.DIFF.     >         <    (NO, if not used; blank for sel.list)
   PHASE S.DIFF.     > NO      <    (NO, if not used; blank for sel.list)
   CODE  S.DIFF.     > NO      <    (NO, if not used; blank for sel.list)
   COORDINATES       >         <    (blank for selection list)
   STANDARD ORBIT    >         <    (blank for selection list)
   RAD.PRESS.COE.    > NO      <    (NO, if not used; blank for sel.list)
   IONOSP. MODELS    > NO      <    (NO, if not used; blank for sel.list)
   TROPO. ESTIMATES  > NO      <    (NO, if not used; blank for sel.list)
   METEO DATA        > NO      <    (NO, if not used; blank for sel.list)
   ECCENTRICITIES    > NO      <    (NO, if not used; blank for sel.list)
   OCEAN LOADING     > NO      <    (NO, if not used; blank for sel.list)
   SATELL. CLOCKS    > NO      <    (NO, if not used; blank for sel.list)
   CODE BIASES       > P1P2    <    (NO, if not used; blank for sel.list)
   ANT. ORIENTATION  > NO      <    (NO, if not used; blank for sel.list)
```

To save the estimated ionosphere models for further processing steps, you have to specify in Panel 4.5–0 at `IONOSPHERE MODELS` an ionosphere file name. If you specify at `IONOSPHERE MAPS` a file name, you get a file that contains a set of ionosphere maps in the so-called IONopshere map EXchange (IONEX) format, a format internationally adopted. The interested user is advised to have a closer look at Section 24.4.10, where the "IONEX control file" to be specified in Menu 0.3.1 is introduced and explained in detail. This file must be adjusted and completed in advance. Both ionosphere-related files (`ION` and `INX`) are stored in the campaign-specific `ATM` directory. In the DD case, do refrain from specifying a `DCB` output file name.

```
 4.5-0                     PAR. ESTIMATION: OUTPUT FILES

   Output Files:
     COORDINATES          > NO      <    (NO, if not to be saved)
     ORBITAL ELEMENTS     > NO      <    (NO, if not to be saved)
     TROPOSPHERE PARAM.   > NO      <    (NO, if not to be saved)
     TROPOSPHERE GRADI.   > NO      <    (NO, if not to be saved)
     TROPOSPHERE SINEX    > NO      <    (NO, if not to be saved)
     IONOSPHERE MODELS    > IONTST  <    (NO, if not to be saved)
     IONOSPHERE MAPS      > IONTST  <    (NO, if not to be saved)
     RESIDUALS            > NO      <    (NO, if not to be saved)
     COVARIANCES (COORD)  > NO      <    (NO, if not to be saved)
     COVARIANCES (ALL)    > NO      <    (NO, if not to be saved)
     NORMAL EQUATIONS     > NO      <    (NO, if not to be saved)
     EARTH ROTATION PARA. > NO      <    (NO, if not to be saved)
     POLE IN IERS FORMAT  > NO      <    (NO, if not to be saved)
     SATELLITE CLOCK FILE > NO      <    (NO, if not to be saved)
     CLOCK RINEX FILE     > NO      <    (NO, if not to be saved)
     CODE BIASES          > IONTST  <    (NO, if not to be saved)
     ANTENNA PCV (GRID)   > NO      <    (NO, if not to be saved)
     ANTENNA PCV (HARM)   > NO      <    (NO, if not to be saved)
     GENERAL OUTPUT       > IONTST  <    (NO, if standard name to be used)
```

In Panel 4.5–1 , two parameters are essential: (1) the frequency to be analyzed (option `FREQUENCY`), `L4` is recommended there; (2) in the input field `STATION`, `ALL` is mandatory. In the DD case, it is probably a good idea to set `ELIMIN` at `RESOLUTION STRATEGY`. In the ambiguity-fixed case, you will say `YES` for `INTRODUCE L1 AND L2`.

```
4.5-1                     PARAMETER ESTIMATION: INPUT 1

  TITLE  >                                                              <

  Frequency:
    FREQUENCY           > L4    <    (L1,L2,L3,L4,L5,L1&L2,L3&L4,MIXED,
                                      WUEBBena/Melbourne, or DTEC)
  Fixed Station(s):
    STATION      > ALL              <    (blank for sel.list, ALL or NONE,
  Kin.  Station(s):                       SPECIAL_FILE.. $FIRST, $LAST)
    STATION      > NONE             <    (blank for sel.list, ALL or NONE,
                                          SPECIAL_FILE.. $FIRST, $LAST)
  Ambiguities:
    RESOLUTION STRATEGY > NO     <   (ELIMIN..NO,ROUND,SEARCH..SIGMA..QIF..)
    INTRODUCE WIDELANE  > NO  <      (YES or NO)
    INTRODUCE L1 AND L2 > NO  <      (YES or NO)
    SAVE AMBIGUITIES    > NO  <      (YES or NO)
  Observation selection:
    MIN. ELEVATION      > 10    <    degrees
    SAMPLING RATE       > 180   <    sec (0: all observations)
    OBSERV. WINDOW      > NO    <    (YES.. NO or ASIS)
```

In Panel 4.5–2 , at CORRELATIONS, BASELINE is recommended in the ZD case, CORRECT in the DD case. The setting-up of "special" parameter types (coordinates, ambiguities, and orbit parameters do *not* fall into this category) has to be initiated in Panel 4.5–2 with YES for SPECIAL REQUESTS. As a demonstration, we request a nice printing option.

```
4.5-2                     PARAMETER ESTIMATION: INPUT 2


  Atmosphere Models:
    METEO DATA          > EXTRAPOLATED <  (EXTRAPOLATED, OBSERVED
                                           or ESTIMATED)
    TROPOSPH. MODEL     > NO           <  (SAASTAMOINEN,HOPFIELD,
                                           ESSEN-FROOME,MARINI-MUR,
                                           DRY_SAAST,DRY_HOPFIELD, or NO)
  Statistics:
    CORRELATIONS        > BASELINE     <  (CORRECT, FREQUENCY, or BASELINE)
    CORREL. INTERVAL       > 1      <     sec
    A PRIORI SIGMA         > 0.001  <     m
    ELEV.-DEP. WEIGHTING    > YES  <      (NO, COSZ, or model number)

  Further Options:
    PRINTING                > YES  <      (YES.. NO or ASIS)
    HELMERT                 > NO   <      (YES.. NO or ASIS)
    ORBIT ADJUSTMENT        > NO   <      (YES.. NO or ASIS)
    SPECIAL REQUESTS        > YES  <      (YES.. or NO)
    ZERO DIFFERENCE EST.    > NO   <      (YES.. or NO)
```

```
4.5-2.1                   PARAMETER ESTIMATION: PRINTING


  Print:
    NUMBER OF OBSERV. IN FILES          > NO  <      (YES or NO)
    POS.ECCENT./RECEIVER INFO           > NO  <      (YES or NO)
    CLOCK POLYNOMIAL COEFF.             > NO  <      (YES or NO)
    AMBIGUITIES IN FILES                > NO  <      (YES or NO)
    PARAMETER CHARACTERIZATION          > NO  <      (YES or NO)
    CONSTANTS, ANT. OFFSETS, ION. COEFF. > NO  <      (YES or NO)
    SATELLITE ELEVATIONS                > NO  <      (YES or NO)
    SYNCHRONIZATION ERRORS              > NO  <      (YES or NO)
    NUMBER OF DBL.DIFF.OBSERV.          > NO  <      (YES or NO)
    AMBIGUITIES FOR EACH ITERATION STEP > NO  <      (YES or NO)
    5-DEGREE BIN OBSERVATION STATISTICS > YES <      (YES or NO)
```

Finally, you will get Panel 4.5–2.4, where you have to select `COE` for `GLOBAL IONOSPHERE MODEL PARAMETERS` to set up GIM parameters, and, exclusively in the ZD case, `YES` for `DIFFERENTIAL CODE BIASES` to set up receiver-specific DCB parameters.

```
4.5-2.4              PARAMETER ESTIMATION: SPECIAL REQUESTS

 Special Requests:

   A PRIORI SIGMAS FOR SITE COORDINATES        > NO   <   (YES.. NO)

   SITE-SPECIFIC TROPOSPHERE PARAMETERS        > NO   <   (YES.. NO)
   STOCHASTIC IONOSPHERE PARAMETERS            > NO   <   (YES.. NO)
   GLOBAL IONOSPHERE MODEL PARAMETERS          > COE  <   (COE.. HGT.. NO)
   DIFFERENTIAL CODE BIASES                    > NO   <   (YES.. NO)
   EARTH ROTATION PARAMETERS                   > NO   <   (YES.. NO)
   COORDINATES OF CENTER OF MASS               > NO   <   (YES.. NO, ASIS)
   SATELLITE ANTENNA OFFSETS                   > NO   <   (YES.. NO)
   RECEIVER ANTENNA OFFSETS                    > NO   <   (YES.. NO)
   RECEIVER ANTENNA PATTERNS                   > NO   <   (YES.. NO)
   RECEIVER CLOCK ERRORS                       > NO   <   (YES.. NO)

   PARAMETER PRE-ELIMINATION                   > NO   <   (YES.. NO, ASIS)

   SATELLITE-SPECIFIC A PRIORI SIGMAS          > NO   <   (YES.. NO)
```

In Panel 4.5–2.4.C, you may enter your requests specific to the TEC modeling. The `NUMBER OF COEFFICIENT SETS PER SESSION` should be set to `1` for *regional*—or *station-specific*—models assuming a (maximum) session length of 24 hours. A larger number of coefficient sets (models) may be appropriate for the *global* application.

```
4.5-2.4.C      PARAMETER ESTIMATION: GLOBAL IONOSPHERE MODEL PARAMETERS

  Number of Ionosphere Models and Coefficients:
    NUMBER OF COEFFICIENT SETS PER SESSION  >    1 <
    STATION-SPECIFIC MODELS                 > NO   <  (YES, NO)
    MAXIMUM DEGREE OF SPHERICAL HARMONICS   >   12 <
    MAXIMUM ORDER  OF SPHERICAL HARMONICS   >    8 <

  Modeling Characteristics:
    TIME-DEPENDENCY            > STATIC  <      (STATIC or DYNAMIC)
    SUN-FIXED REFERENCE FRAME  > GEOMAGNETIC <  (GEOGRAPHIC or GEOMAGNETIC)
    LONGITUDE OF THE SUN       > MEAN <         (MEAN or TRUE)
    MAPPING FUNCTION           > COSZ <         (NONE or COSZ)

  Additional Information:
    A PRIORI HEIGHT OF SINGLE LAYER  >  450.00 <  km
    LATITUDE  OF GEOMAGNETIC POLE    >   79.00 <  degrees
    LONGITUDE OF GEOMAGNETIC POLE    >  -71.00 <  degrees
    ABSOLUTE SIGMA FOR COEFFICIENTS  >    0.00 <  TECU     (0: no sigma)
    RELATIVE SIGMA FOR COEFFICIENTS  >    0.00 <  TECU     (0: no sigma)
```

`MAXIMUM DEGREE OF SPHERICAL HARMONICS` and `MAXIMUM ORDER OF SPHERICAL HARMONICS` correspond to $n_{\max}$ and $m_{\max}(\leq n_{\max})$ of the TEC model (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 with $(n_{\max} + 1)^2$ GIM parameters per session.

For `TIME-DEPENDENCY`, you may select either `STATIC` to create ionosphere models representing *static* (or "frozen") TEC structures in the sun-fixed frame which are referred to specific time intervals, or `DYNAMIC` to model the TEC coefficients as piece-wise 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 `SUN-FIXED REFERENCE FRAME`, 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 `LONGITUDE OF THE SUN`, the argument s is computed according to the right-hand or left-hand side of Eqn. (13.11). The `MAPPING FUNCTION` should be `COSZ` to be in accordance with Eqn. (13.8).

It is recommended to set the `A PRIORI HEIGHT OF SINGLE LAYER` to $H = 450$ km. In the fields `LATITUDE OF GEOMAGNETIC POLE` and `LONGITUDE OF GEOMAGNETIC POLE`, you have to enter the coordinates of the Earth-centered dipole axis, if you select `GEOMAGNETIC` for the option `SUN-FIXED REFERNCE FRAME`. Finally, you have the possibility to define "absolute" as well as "relative" a priori sigmas. An absolute sigma of, e. g,, 10 TECU is recommended to be applied when producing *regional* or *station-specific* models.

In Panel 4.5–2.4.F , *one* set of DCB parameters may be set up. Since we consider a priori DCB values for the satellites, only DCB parameters for the receivers has to be determined.

```
4.5-2.4.F     PARAMETER ESTIMATION: DIFFERENTIAL CODE BIASES

  Differential Code Biases:

    ESTIMATE DIFFERENTIAL CODE BIASES FOR SATELLITES    > NO  <  (YES, NO)
    ESTIMATE DIFFERENTIAL CODE BIASES FOR RECEIVERS     > YES <  (YES, NO)

    REFERENCE SATELLITE NUMBER                          > SUM <  (SUM, ALL,
                                                                  or number)
    PROCESS NIGHT-TIME DATA ONLY                        > NO  <  (YES, NO)

    A PRIORI SIGMA OF REFERENCE SATELLITE               > 0.01    < nanosec
```

By selecting `HGT` in the field `GLOBAL IONOSPHERE MODEL PARAMETERS` in Panel 4.5–2.4 , you might set up in addition single-layer height parameters as *unknown* parameters. In that case, GPSEST would require an a priori GIM file—stemming from an initial program run—to be specified in Panel 4.5 (field `IONOSP. MODELS`), because the parameter estimation problem is no longer *linear*. Panel 4.5–2.4.C would be automatically skipped and you would immediately get Panel 4.5–2.4.D presented. Please note that this option has been designed for test purposes only!

```
4.5-2.4.D            PARAMETER ESTIMATION: HEIGHT OF SINGLE LAYER

   Number of Single-Layer Height Parameters:
     NUMBER OF HEIGHT PARAMETERS   > ALL  <  (one for ALL  ionosphere models,
                                              one for EACH ionosphere model)

   A Priori Sigma for Height Parameters:
     ABSOLUTE SIGMA FOR HEIGHT PARAMETERS  >    0.00 <  km  (0: no sigma)
     RELATIVE SIGMA FOR HEIGHT PARAMETERS  >    0.00 <  km  (0: no sigma)
```

Using Menu 5.6.5 , you may extract—among other items—GIM-related information from GPSEST output files by entering a file name for `GIM SUMMARY` in Panel 5.6.5 . Resulting `SUM` files are stored in the `OUT` directory.

```
CODE'S GLOBAL IONOSPHERE INFO FOR DAY 043, 2001                  15-FEB-01 22:21
--------------------------------------------------------------------------------
MODEL NUMBER / STATION NAME                     : 0430-01
MODEL TYPE (1=LOCAL,2=GLOBAL,3=STATION)         :    2
MAXIMUM DEGREE OF SPHERICAL HARMONICS           :   12
MAXIMUM ORDER                                   :    8
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=1/COS)               :    1
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) :   79.52
  EAST LONGITUDE (DEGREES)                      :  -71.85
PERIOD OF VALIDITY
  FROM EPOCH / REFERENCE EPOCH (Y,M,D,H,M,S)   : 2001 02 12 00 00 00
  TO EPOCH                                      : 2001 02 12 02 00 00
LATITUDE BAND COVERED
  MINIMUM LATITUDE (DEGREES)                    :  -88.94
  MAXIMUM LATITUDE (DEGREES)                    :   86.60
ADDITIONAL INFORMATION
  NUMBER OF CONTRIBUTING STATIONS               :  149
  NUMBER OF CONTRIBUTING SATELLITES             :   28
  ELEVATION CUT-OFF ANGLE (DEGREES)             :   10
  MAXIMUM TEC AND ITS RMS ERROR (TECU)          :  115.44     0.68
COMMENT / WARNING                               :
COEFFICIENTS
DEGREE  ORDER    VALUE (TECU)   RMS (TECU)
   0      0       33.84953164     0.0952
   1      0       -1.78804169     0.0870
   1      1       12.79193956     0.0801
...
  12     -7       -0.18703092     0.0476
  12      8        0.04490084     0.0462
  12     -8        0.11537741     0.0461

...
```

Figure 13.8: Example for an ionosphere file containing a series of global TEC models.

Figure 13.8 shows an example of an `ION` file containing 12 2-hour global models. To join a series of global/regional models (type-2 models) stored in individual `ION` files into a "multi-session" model, you may simply copy these files together in *chronological* order.

The GIMs, of which the coefficients are listed in Figure 13.8, are visualized in Figure 13.9. TEC snapshots taken at 01:00, 03:00, 05:00, ..., 23:00 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 (GIMs) as an additional product. Apart from that, GIMs for the entire year 1995 have been computed in a re-processing step [*Schaer et al.*, 1996]. The corresponding `ION` files starting with day 001 of 1995 are available via anonymous ftp (see also Chapter 7). Regional ionosphere models for *Europe*, routinely generated since December 1995, are available as well.

Figure 13.10 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 (compare also Figure 13.2).

13.5.3 Application of Deterministic TEC Models

Deterministic TEC models may be used by two programs:

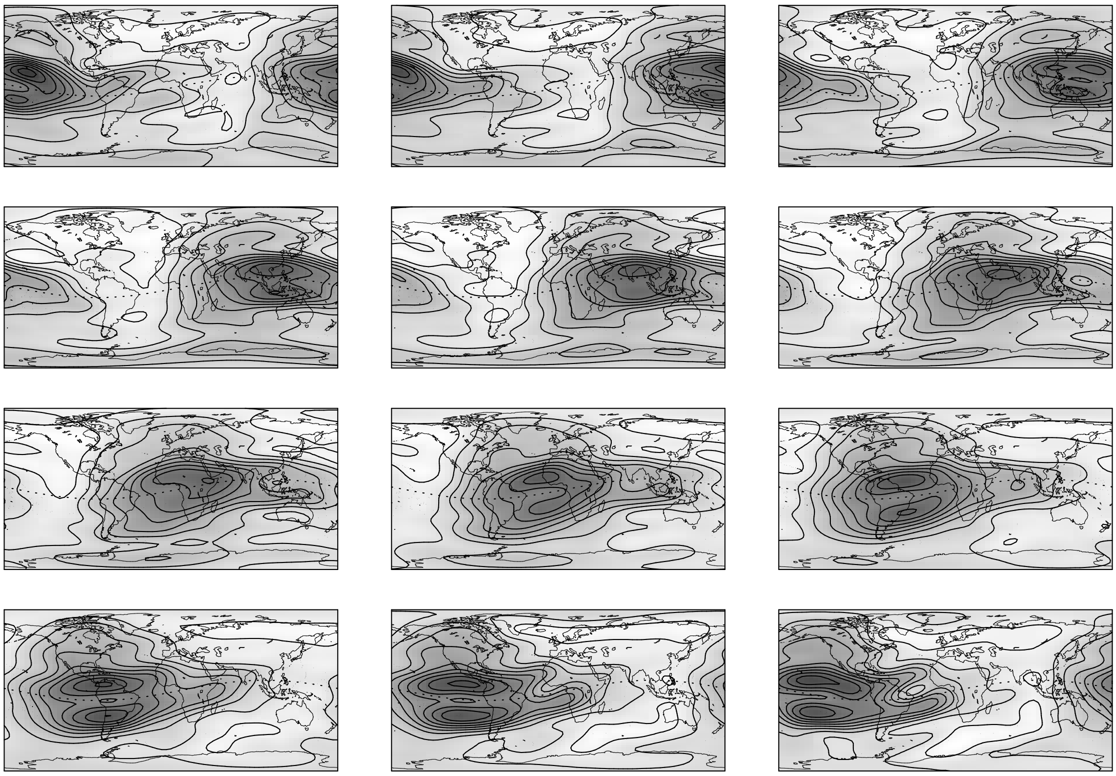


Figure 13.9: 2-hourly global TEC snapshots for February 12, 2001, as produced by CODE.

- the pre-processing program MAUPRP and
- the parameter estimation program GPSEST.

The requested ION file has to be specified in the option field `IONOSP. MODELS` in Panel 4.4.2 and Panel 4.5, 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 CODSPP 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 GPS/GLONASS data processing?

- In *pre-processing*, 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 pre-processing.
- For *ambiguity resolution*, to make the ambiguity fixing more reliable by reducing the fractional parts of (L1, L2, or especially L5) ambiguities, if you do *not* use (precise) dual-band code measurements by analyzing the Melbourne-Wübbena linear combination (9.28).
- In *parameter estimation* steps, to reduce the ionosphere-induced scale bias in GPS network solutions (see Table 13.1), if you process L1 and/or L2 observations—and *not* the *ionosphere-free* (L3) linear combination.

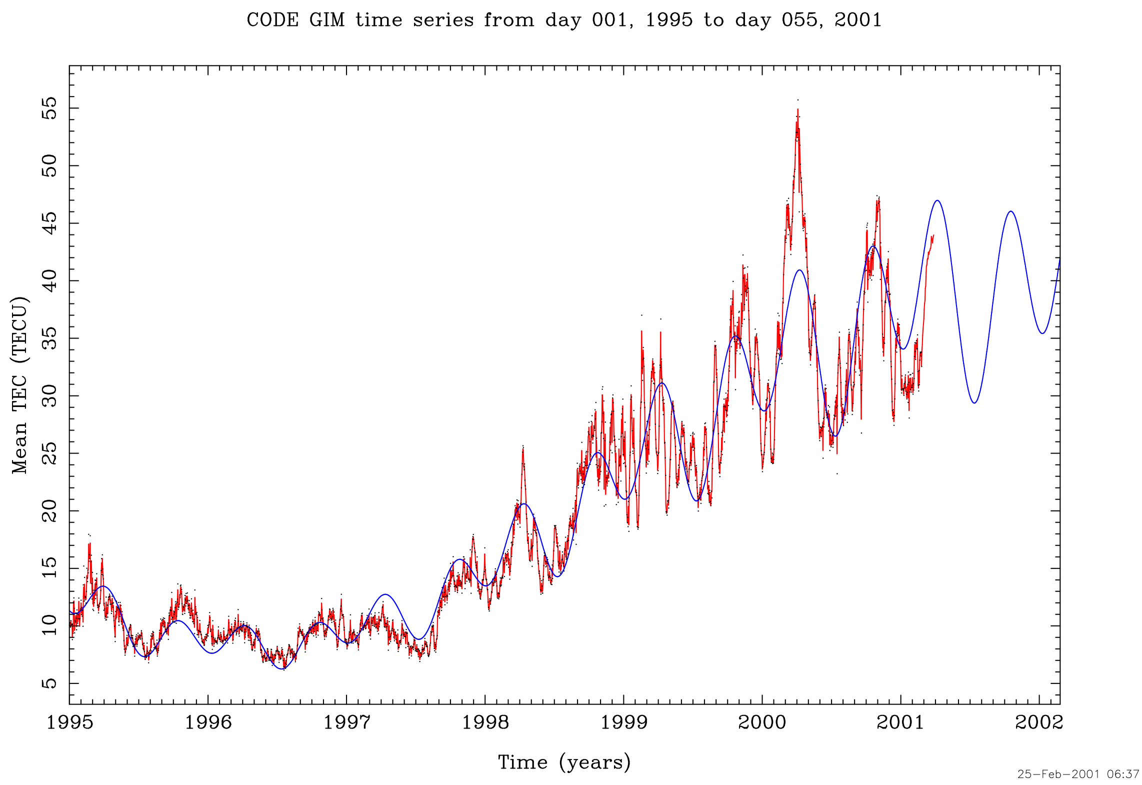


Figure 13.10: Mean TEC from January 1, 1995, extracted from CODE GIMs.

13.6 Stochastic Ionosphere Modeling Technique

13.6.1 Estimation of Stochastic Ionosphere Parameters

Stochastic Ionosphere Parameters (SIPs), representing the term I in Eqn. (13.13), may be set up in Panel 4.5–2.4 (see STOCHASTIC IONOSPHERE PARAMETERS). In Panel 4.5–2.4.7 , you may specify then several options concerning SIPs.

```
4.5-2.4.7 | PARAMETER ESTIMATION: STOCHASTIC IONOSPHERE PARAMETERS

 Stochastic Ionosphere Parameters:

   EPOCH-WISE PRE-ELIMINATION                          > YES <    (YES,NO)
   ELIMINATION OF REFERENCE IONOSPHERE PARAMETERS      > YES <    (YES,NO)
   ELEVATION-DEPENDENT PARAMETER CONSTRAINING          > NO  <    (YES,NO)

   ABSOLUTE A PRIORI SIGMA ON SINGLE DIFFERENCE LEVEL  > 0.25   < m
   RELATIVE A PRIORI SIGMA OF IONOSPHERIC RANDOM WALK  > 0.00   < m/min**1/2
```

With EPOCH-WISE PRE-ELIMINATION, a special parameter pre-elimination algorithm working epoch by epoch may be activated. This is a recommended procedure because of the huge number of SIPs usually involved. Note that the epoch-wise parameter pre-elimination may be enforced in Panel 4.5–2.4.8 with EP at DIFF. IONOSPHERE, too. ELIMINATION OF REFERENCE

IONOSPHERE PARAMETERS is the option where you may decide whether you want to estimate SIPs on the *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 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 ELEVATION-DEPENDENT PARAMETER CONSTRAINING is recommended in particular when processing low-elevation data.

An *absolute* a priori sigma must be specified in the field 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 Quasi-Ionosphere-Free (QIF) strategy (see also Figure 13.5). *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 ELIMINATION OF REFERENCE IONOSPHERE PARAMETERS). Such a "SIP smoothing" might be useful, e. g., for kinematic applications under moderate ionospheric conditions.

Figure 13.11 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 L1 have been estimated in several program runs by defining shifted time windows. Short-term variations like so-called *Medium-Scale Traveling Ionospheric Disturbances (MSTIDs)* with their typical periods of 10 to 60 minutes may be recognized.

13.6.2 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 L1/L2 ambiguities. There is another possible use as already demonstrated in Figure 13.5: by varying the a priori constraints imposed on the SIP parameters, you have the possibility to smoothly switch between a pure L1/L2 solution and an L3 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 SIP parameters to instantaneously separate—in a single processing run—the *stochastic* and the *deterministic* component of the ionosphere.

Figure 13.12 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 13.13, if (a) *no* deterministic TEC parameters are set up and if (b) GIM parameters are estimated.

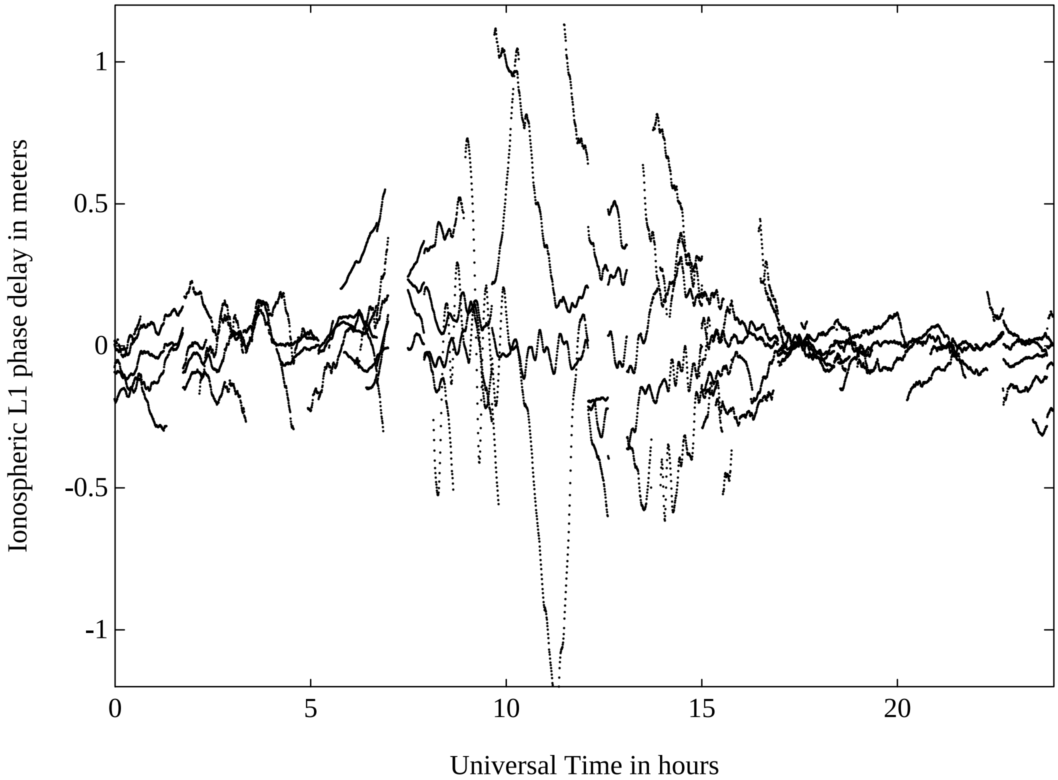
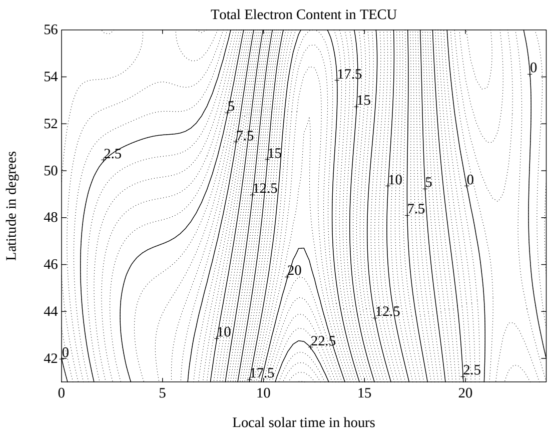
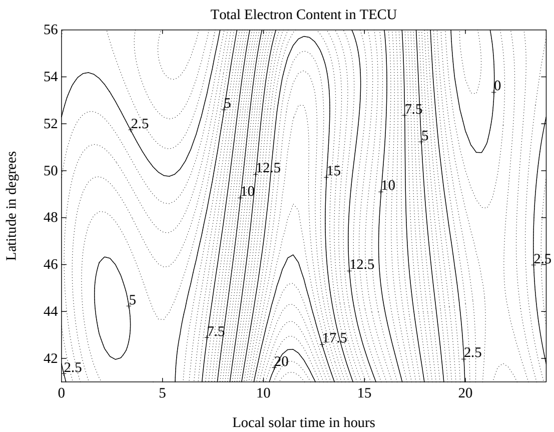


Figure 13.11: Stochastic ionosphere parameters (SIPs) describing the double-difference ionospheric delay on L1.

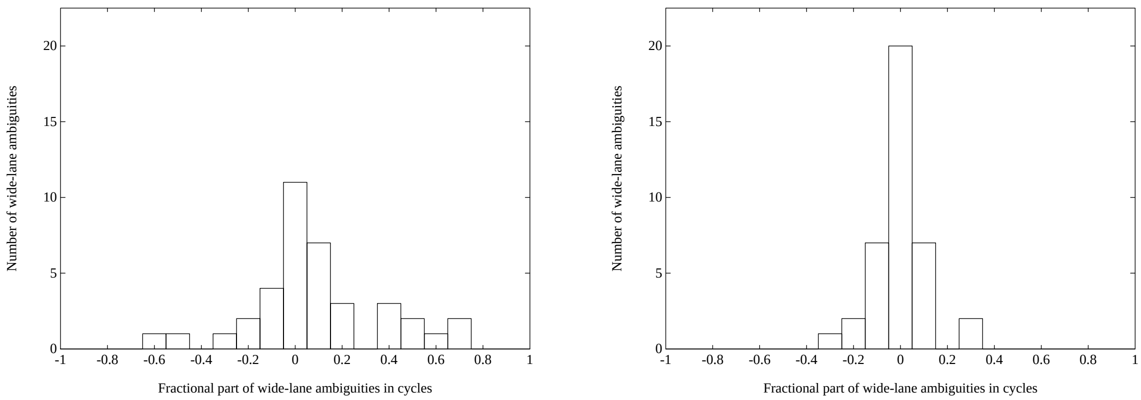


(a) *Before* ambiguity resolution



(b) *After* ambiguity resolution

Figure 13.12: Regional (or baseline-specific) ionosphere model.



(a) *Without* ionosphere model

(b) *With* ionosphere model

Figure 13.13: Fractional parts of wide-lane ambiguities indicating the (remaining) deterministic part of the ionosphere.