GLOBAL AND REGIONAL IONOSPHERE MODELS USING THE GPS DOUBLE DIFFERENCE PHASE OBSERVABLE

Stefan Schaer, Gerhard Beutler, Leos Mervart, Markus Rothacher
Astronomical Institute, University of Berne
CH-3012 Bern, Switzerland

Urs Wild
Federal Office of Topography
CH-3084 Wabern, Switzerland

ABSTRACT

The CODE[1] Analysis Center of the *International GPS Service for Geodynamics (IGS)* produces orbits, Earth orientation parameters, station coordinates, and other parameters of geophysical interest on a daily basis using the *ionosphere-free linear combination* of the double difference phase observables. Consequently, *clean* (i. e. *cycle-slip-free*) portions of the L1 and the L2 phases are readily available for every day. The difference L1–L2 in meters contains *only* differential ionospheric refraction effects *and* in the ambiguitiy-*un*resolved case a constant bias due to the initial carrier phase ambiguities in L1 and L2.

Here we use exactly this observable to extract ionospheric information from the IGS network. On one hand it is *not* ideal to use the difference L1–L2 on the *double difference level* — the differencing reduces the ionospheric signal considerably. On the other hand we have the advantage of a clean signal. Also, processing is simplified because satellite and receiver specific biases cancel out to the greatest extent in our approach.

As usual we model the ionospheric *Total Electron Content (TEC)* with a *single-layer model* which is based on the corresponding mapping function. As opposed to earlier attempts (*local* ionosphere models using Taylor series expansions in latitude and sun-fixed longitude) we develop the vertical TEC into a series of spherical harmonics. We may use the geocentric latitude and the sun-fixed longitude or an equivalent set in the solar-geomagnetic system as independent arguments. These models have the advantage — over Taylor series expansions — to be well suited for *regional and* for *global* models.

First results using one week of regional (European) and global data (entire IGS network) from the CODE Analysis Center seem to indicate that under *normal* ionospheric conditions the ionosphere models are very useful for single-frequency GPS users, i. e. ionospheric refraction effects are greatly reduced if these TEC models are taken into account.

---

[1] Center for Orbit Determination in Europe

Paper presented at the 1995 IGS Workshop, Potsdam, Germany, May 15–17, 1995

INTRODUCTION

Ionospheric refraction was considered as an important aspect within the GPS group of the *Astronomical Institute of the University of Berne (AIUB)* for a long time. In the time period when usually only *single-band* (L1) receivers were available it was important to get insight into the biases introduced in a GPS network by *unmodeled* ionospheric refraction (Beutler et al., 1988). Later on, it became obvious that short period variations in ionospheric refraction could harm GPS analyses even if *dual-band* receivers were available (Beutler et al., 1989). In the latter paper there were also clues that valuable information about the ionosphere could be extracted from dual-band GPS data.

Modeling and monitoring the ionosphere was the main topic of the Ph. D. thesis (Wild, 1994). In this thesis it could be shown that local ionosphere models like those presented by (Georgiadiou and Kleusberg, 1988) are very efficient to remove — or greatly reduce — the *scale bias* for single-band receivers operating in the vicinity of dual-band receivers, the data of which were used to establish a local ionosphere model. (Wild, 1994) computed such local ionosphere models for a number of IGS sites over an extended time period. He also describes a procedure to assess the *stochastic* behaviour of the ionosphere in the vicinity of a GPS station. The principal conclusion was that essential information concerning the ionosphere might be extracted from the IGS network. Local ionosphere models have proved their usefulness on many occasions. However, the concept of having as many ionosphere models as stations in a network like that of the IGS is hardly operational. The modeling techniques used by (Wild, 1994) had to be modified in one important respect before it became possible to replace N *local models* by *one regional* or *global model* based on the data of N stations.

Let us briefly review the modeling features as used by (Wild, 1994) and as used below. Wild uses the so-called *single-layer model* where it is assumed that all free electrons are concentrated in a shell of infinitesimal thickness. This *thin shell* is located in a height H above a spherical Earth. The height H of this idealized layer is usually set to 350 or 400 kilometers, which corresponds approximately to the peak height of the electron density profile in the F-region of the ionosphere. The electron density E — the surface density of the layer — is assumed to be a function of the geocentric latitude β and the *sun-fixed* longitude s

$$E(\beta, s) = \sum_{i=0}^{n} \sum_{j=0}^{m} E_{ij} \cdot (\beta - \beta_0)^i \cdot (s - s_0)^j \tag{1}$$

where

n, m	are the maximum degrees of the two-dimensional Taylor series expansion in latitude and in sun-fixed longitude,
E_{ij}	are the (unknown) coefficients of the Taylor series, and
β_0, s_0	are the coordinates of the origin of the development.

The single-layer model defined by equation (1) does *not* provide a modeling of the time dependence in the *sun-fixed* reference frame because the "frozen" ionosphere is co-rotating with the Sun. Nevertheless, there is always a time dependence in the *earth-fixed* frame. Note that short-term variations of the ionospheric TEC are *not* modeled by equation (1). They will be interpreted as noise of the *geometry-free* GPS observable.

The representation (1) is *not* well suited for *regional* or *global* TEC models because of limitations in the (β, s)-space. Based on the above considerations we decided to use a new approach to model the ionosphere in the following way (details explained in the next section):

(i) The *single-layer model* is used as previously.

(ii) The *mapping function* is taken over without change.

(iii) The *zero-difference* observable was replaced by the *double-difference* observable due to operational considerations.

(iv) Instead of using a *Taylor series* development a development into *spherical harmonics* was used.

As already mentioned above we are fully aware of the fact that by using *double* instead of *zero* differences we lose parts of the ionospheric signal but we have the advantage of a *cleaned* observable. Moreover we are *not* affected by a degradation of the code observations under the AS-regime. This advantage may be "lost" when the next generation of precise P-code receivers will become available.

THE "NEW" IONOSPHERE MODELING TECHNIQUE

The *double-differenced observation equation* for the *geometry-free linear combination* ϕ_4 of the carrier phase measurements (ϕ_1 and ϕ_2) referring to a set of *two* receivers and *two* satellites may be written as

$$\mathrm{dd}(\phi_4) + v_4 = -\alpha \left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2} \right) \mathrm{dd}(F(z) \cdot E) + B_4 \tag{2}$$

where

$\mathrm{dd}(\ldots)$ is the *double-difference operator*,

$\phi_4 = \phi_1 - \phi_2$ is the *geometry-free* phase observable (in meters),

v_4 is the corresponding residual,

$\alpha = 4.03 \cdot 10^{17}\ \mathrm{m\,s^{-2}\ TECU^{-1}}$ is a constant (TECU stands for Total Electron Content Unit[2]),

ν_1, ν_2 are the frequencies associated with the carriers L1 and L2,

$F(z)$ is the mapping function evaluated at the zenith distance z,

E is the *vertical* Total Electron Content (in TECU), and

---

[2] One TEC Unit corresponds to 10^{16} free electrons per square meter.

$B_4 = \lambda_1 N_1 - \lambda_2 N_2$ is a *constant* bias (in meters) due to the initial phase ambiguities N_1 and N_2 with their corresponding wavelengths λ_1 and λ_2; if new ambiguities were set up for one satellite, a new parameter of this type has to be introduced.

In the *ambiguity-resolved* case the (integer) double-difference ambiguity parameters N_1 and N_2 as well as the (real-valued) parameter B_4 are known. All *unresolved* ambiguity parameters B_4 — auxiliary parameters only — and the ionosphere model parameters have to be estimated simultaneously.

The *single-layer* or *thin-shell* mapping function $F(z)$ simply may be written as

$$F(z) = \frac{1}{\cos z'} = \frac{1}{\sqrt{1 - \sin^2 z'}} \qquad \text{with} \quad \sin z' = \frac{R}{R+H} \sin z \tag{3}$$

where

z, z' are the (geocentric) zenith distances at the station and at the single layer,

R is the mean Earth radius, and

H is the height of the single layer above the Earth's surface.

We develop the surface density E of the ionospheric layer into a series of spherical harmonic functions of maximum degree $n_{\max}$ and maximum order $m_{\max} \leq n_{\max}$:

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \widetilde{P}_{nm}(\sin\beta) \cdot (a_{nm} \cos ms + b_{nm} \sin ms) \qquad \text{with} \quad t \in [t_i, t_{i+1}] \tag{4}$$

where

β is the geocentric latitude of the intersection point of the line receiver–satellite with the ionospheric layer,

$s = \lambda - \lambda_0$ is the *sun-fixed* longitude of the ionospheric pierce point, which corresponds to the *local solar time* neglecting an additive constant π (or 12 hours),

λ, λ_0 are the *geographic* longitude of the ionospheric pierce point and the *true* (or *mean*) longitude of the Sun,

t is the time argument,

$[t_i, t_{i+1}]$ is the specified period of validity (of the i-th model),

$\widetilde{P}_{nm} = \Lambda(n,m) \cdot P_{nm}$ are the *normalized* associated Legendre polynomials of degree n and order m based on the *normalization function* Λ and the *unnormalized* Legendre polynomials P_{nm}, and

a_{nm}, b_{nm} are the *unknown* coefficients of the spherical harmonic functions, i. e. the global (or regional) ionosphere model parameters.

We may use the geocentric latitude β and the sun-fixed longitude s in the *geographical* coordinate system or an equivalent set (β', s') in the *solar-geomagnetic* coordinate system as independent arguments. Using simply the *mean* longitude of the Sun, the sun-fixed *mean* longitude s of the ionospheric pierce point in the geographical system reads as

$$s = \lambda - \lambda_0 = \lambda - (\pi - t) = \lambda + t - \pi \tag{5}$$

where t is the *Universal Time UT* (in radians).

The *normalization function* Λ is defined as follows:

$$\Lambda(n,m) = \sqrt{2 \, \frac{2\,n+1}{1+\delta_{0m}} \, \frac{(n-m)!}{(n+m)!}} \qquad \text{with} \quad \Lambda(0,0) = 1 \tag{6}$$

where δ denotes the Kronecker Delta.

The zero-degree coefficient a_{00} may be interpreted on a *global* scale as the *mean* TEC E_0 by forming the surface integral of the TEC distribution (4)

$$E_0 = \frac{1}{4\,\pi} \int_S E \;\mathrm{d}S = \frac{1}{4\,\pi} \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{2\pi} E(\beta, s)\; \cos\beta \,\mathrm{d}\beta \,\mathrm{d}s = \Lambda(0,0)\, a_{00} = a_{00} \tag{7}$$

Multiplying the coefficient a_{00} (in TECU) by the surface area of the ionospheric layer (in m^2) we obtain the total number of free electrons n_E (in 10^{16}) within the ionospheric shell

$$n_\mathrm{E} = 4\,\pi\, {R'}^2\, a_{00} \qquad \text{with} \quad R' = R + H \tag{8}$$

where R' is the geocentric radius of the ionospheric layer.

The number n_P of ionosphere model parameters a_{nm} and b_{nm} (per parameter set) is given by the expression

$$n_\mathrm{P} = (n_\mathrm{max} + 1)^2 - (n_\mathrm{max} - m_\mathrm{max})\,(n_\mathrm{max} - m_\mathrm{max} + 1) \qquad \text{with} \quad m_\mathrm{max} \le n_\mathrm{max} \tag{9}$$

or by

$$n_\mathrm{P} = (n_\mathrm{max} + 1)^2 \qquad \text{if} \quad n_\mathrm{max} = m_\mathrm{max} \tag{10}$$

Both TEC models (1) and (4) represent a *static* (or “frozen”) ionosphere in the sun-fixed reference frame. However, the parametrization of the ionospheric coefficients a_{nm} and b_{nm} as time-dependent parameters — for instance as piece-wise linear functions in time ensuring the continuity — allow us theoretically to model a *(low-)dynamic* ionosphere $E(\beta, s, t)$. In summary, we are able to set up in our procedure a set of constant ionosphere parameters per specified time interval $[t_i, t_{i+1}]$ *or* a parameter set per specified reference epoch t_i while the ionosphere coefficients $a_{nm}(t)$ and $b_{nm}(t)$ are interpolated linearly in time between subsequent epochs t_i. This modeling technique was *not* followed up in detail. Attempts were made specifying each 24 hours reference epochs t_i to generate a sequence of *quasi-static* ionosphere models *continuously* varying in time.

Figure 1. GPS tracking network of the *International GPS Service for Geodynamics (IGS)* — operational and planned stations (May 1995)

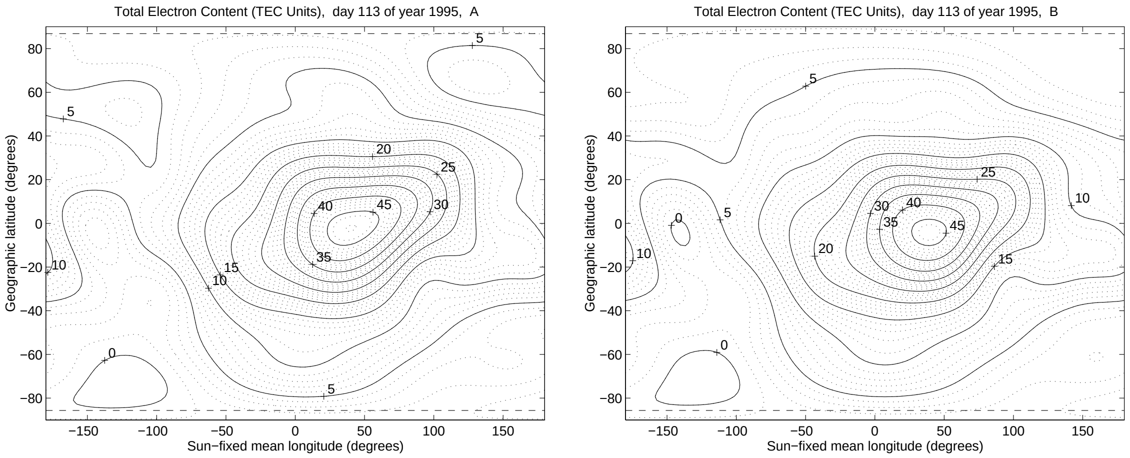
Looking at Figure 1 the *in*homogeneous distribution of the IGS sites and even the *sparse* coverage in the *southern* hemisphere can be clearly seen. Obviously, a high-temporal resolution of the TEC structure without any gaps over the *entire* globe will *not* be possible, because each GPS station "observes" the ionosphere within a radius of 1 000 (1 500) kilometers only when using an elevation angle cutoff at $20\,(15)^\circ$.

Global Ionosphere Models

Below we discuss results using a data set of April 23–29, 1995 (GPS week 798, DOY 113–119). Let us summarize some important aspects first. For all subsequent computations, a single-layer height H of 400 kilometers is assumed. Furthermore all ionosphere models (or maps) are derived from *double-differenced* GPS phase data using an elevation angle cutoff at 20° — as used for our routine processing — and a sampling rate of one epoch per 4 minutes[3].

An 8th-degree spherical harmonics expansion (4) is normally performed for a 24-hour *global ionosphere model*. Consequently, this 24-hour model represents a *time-averaged* TEC structure, which is a *static* (or "frozen") one in the *sun-fixed* reference frame. According to formula (10) the number of ionosphere parameters per such a TEC model is 81.

In order to illustrate *ionosphere maps*, the results for April 23, 1995 are included in this paper. Figure 2 shows the *global ionosphere map* based on the *geographical* coordinate system in the *ambiguity-free* and *ambiguity-fixed* case respectively. In both cases the *maximum* TEC is about 47 TECU (explicitly plotted in Figures 4a and 4b). The sun-fixed longitudes s of the ionospheric pierce points have been computed according to the simplified relation (5) as *mean* longitudes. In Figure 2 (and 3) the latitude band of the ionospheric pierce points is indicated by the two dashed lines.



(a) *Ambiguity-free* solution

(b) *Ambiguity-fixed* solution

Figure 2. *Global ionosphere map* for April 23, 1995 based on the *geographical* coordinate system (with 81 coefficients, i. e. $n_{\max} = m_{\max} = 8$)

On day 113 about 48 % of roughly 2 200 ambiguity parameters B_4 (see observation equation (2)) were resolved (i. e. known). Ambiguity resolution[4] *without* using the P-code measurements is performed up to baseline lengths of 2 000 kilometers (Mervart, 1995); where

---

[3] One epoch per 30 seconds would be available.

[4] We use the so-called *Quasi-Ionosphere-Free (QIF)* ambiguity resolution strategy.

typically about 85 (90) % of the ambiguities are resolved for baseline lengths $l < 500\,\text{km}$, 80 (85) % for $l < 1\,000\,\text{km}$, and 70 (75) % for $l < 2\,000\,\text{km}$ when *Anti-Spoofing (AS)* is turned on (off). By resolving the ambiguities we achieve primarily a drastic reduction of the number of *unknown* parameters as well as an improvement in accuracy of the remaining parameters. Since June 25, 1995 (GPS week 807, DOY 176) — after an experimental phase of several months — the *official* IGS products from the CODE Analysis Center are based on (partly) *ambiguity-fixed* solutions.

To study the effect of choosing the *geographical* and the *solar-geomagnetic* coordinate system respectively, we have compared global ionosphere models based on each coordinate system for all days of GPS week 798. However, we could *not* recognize any significant difference in terms of the root-mean-square (RMS) error of the unit weight. Figure 3 shows the ionosphere map for April 23, 1995 based on the *solar-geomagnetic* coordinate system in the *ambiguity-fixed* case.

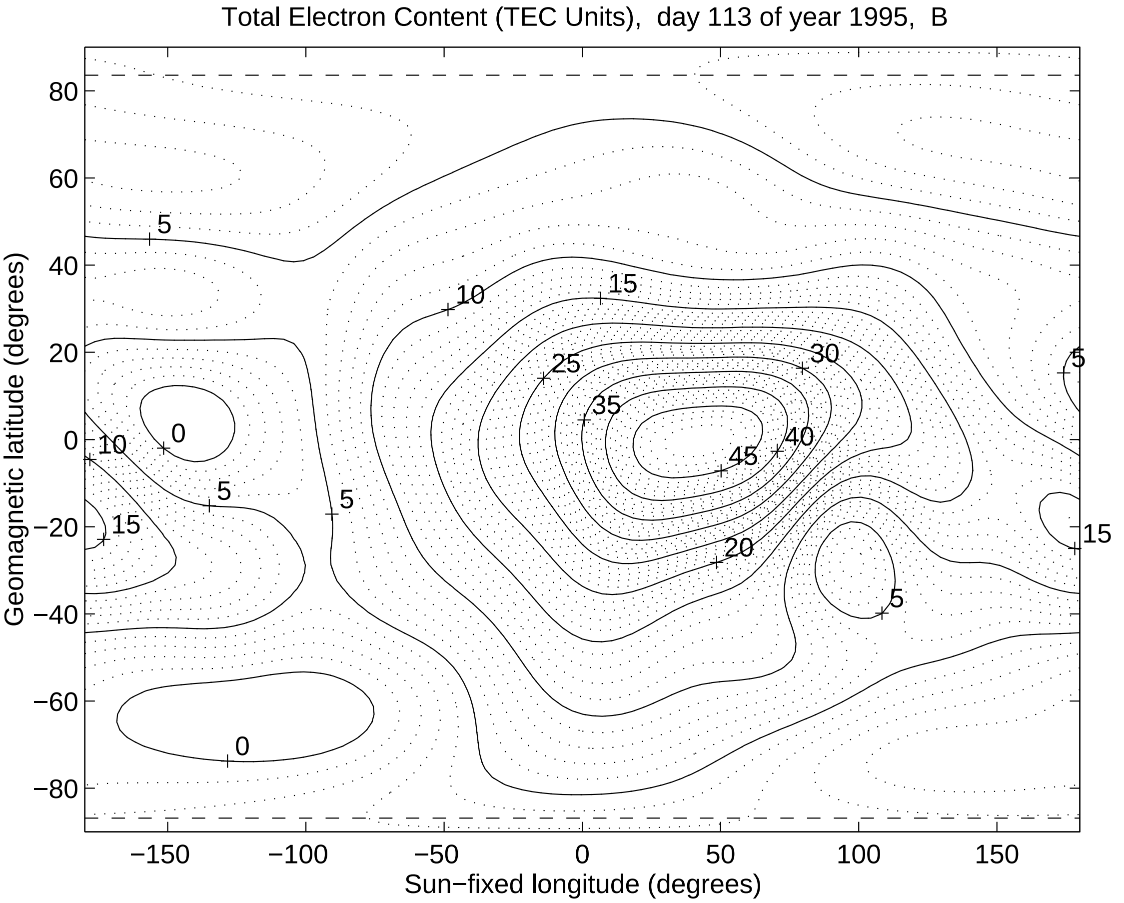
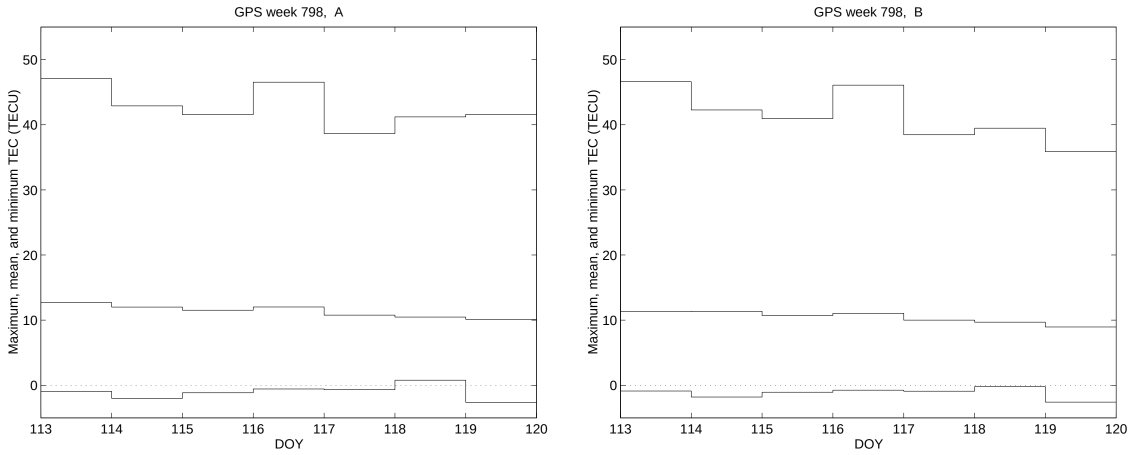


Figure 3. *Global ionosphere map* for April 23, 1995 based on the *solar-geomagnetic* coordinate system (with 81 coefficients, i. e. $n_{\max} = m_{\max} = 8$)

Comparing Figure 3 with Figure 2b both contour line maps look similar. Note that the *geomagnetic* latitude of the Sun varies considerably (ca. ±10.9°) as opposed to the *geo-*

graphical system, where the latitude of the Sun remains nearly constant over the time span of 24 hours.[5]

The development in time of three special quantities namely the *maximum*, *mean*, and *"minimum"* TEC is shown in Figure 4. The values coming from solutions based on both the *geographical* and the *geomagnetic* frame are very similar, hence the values of the first set only are plotted.



(a) *Ambiguity-free* solutions

(b) *Ambiguity-fixed* solutions

Figure 4. Development in time of the daily *maximum*, *mean*, and *"minimum"* TECs during GPS week 798

According to the surface integral (7) the *mean* TEC E_0 is represented by the zero-degree coefficient a_{00}. Using the simple relation (8) we can convert a_{00} (or E_0) into the total number n_E of free electrons within the ionospheric shell: e. g. $n_\mathrm{E} = 6.5 \cdot 10^{31}$ at day 113. The *mean* TEC (or the *time-averaged* total number of free electrons) steadily decreasing during GPS week 798 (see Figure 4) seems to be quite stable (small variations). After fitting the "observed" ionospheric coefficients a_{00} by a first-degree polynomial in time, we have got residuals with an RMS error of 0.3 TECU, which is a first criterion for the quality of the special ionosphere parameter a_{00} (or E_0). Theoretically the quantity E_0 should be a good indicator for the solar activity. One may expect that this ionospheric parameter is strongly correlated with the *Sun spot number*. We should mention that the solar activity was quite *weak* (*low* Sun spot number) during this test week.

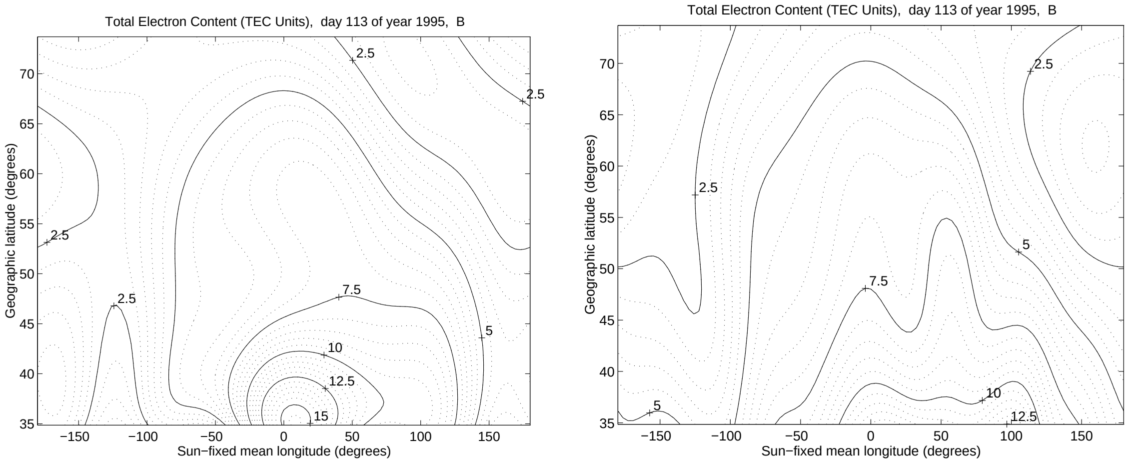
By definition the TEC must be greater than *zero*. Accordingly, the *"minimum"* TEC estimates are never significantly below *zero*, which is a sign of success, too (we have *never* applied any a priori constraints on the ionosphere model parameters).

---

[5] The current geographic latitude of the *geomagnetic pole* is about 79.1°.

Regional Ionosphere Models

When processing data from tracking stations located within a *narrow* longitude band, the ionosphere modeling technique (4) yields *regional* ionosphere models. An example of a *regional* ionosphere map is shown in Figure 5a compared with the corresponding detail (latitude band) of the *global* TEC map (see Figures 2b and 5b). Both maps are based on *ambiguity-fixed* GPS solutions using the *geographical* coordinate system.



(a) *Regional* TEC map (for Europe)

(b) *Global* TEC map (detail only)

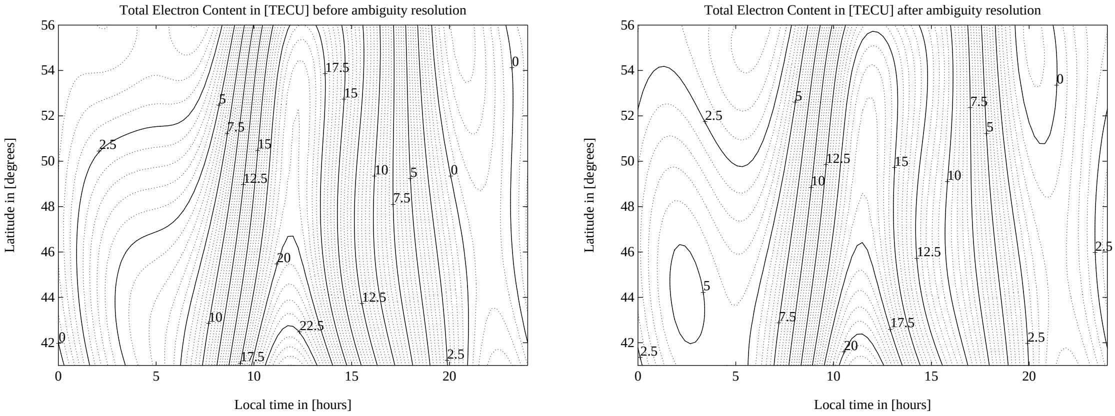
Figure 5. The *regional* TEC model (with $n_{\max} = 5$) for April 23, 1995 is based on data of 16 European IGS stations (listed in Tables 1 and 2), whereas the *global* TEC model (with $n_{\max} = 10$) is based on data of 50 globally distributed IGS stations (including the European ones).

The TEC model (4) — its specified period of validity assumed to be not longer than 24 hours (i. e. $t_{i+1} - t_i \leq 24\,\mathrm{h}$) — provides for a *regional* model a real modeling of the time dependence in the *sun-fixed* reference frame because by definition the longitude band $[\lambda_{\min}, \lambda_{\max}]$ of the monitor stations is small, i. e.

$$\lambda_{\max} - \lambda_{\min} \ll 2\,\pi \tag{11}$$

Therefore the monitor stations of a *regional* network "probe" at every time only a *narrow* longitude band of the ionosphere co-rotating with the Sun. A restriction of the latitude band would *not* be necessary, but is given by the station geometry. Considering these restrictions the *regional* ionosphere model (Figure 5a) is applicable only for GPS stations lying within the latitude band $[40^\circ\,\mathrm{N}, 70^\circ\,\mathrm{N}]$ *and* strictly speaking within the "narrow" longitude band $[4^\circ\,\mathrm{W}, 37^\circ\,\mathrm{E}]$, as opposed to the *global* model (Figure 5b), where we assume the TEC to be longitude-*in*dependent. Notice that Figure 5a shows the (wider) latitude band of the ionospheric pierce points.

The special case of processing individual baselines (two stations) only to generate so-called *baseline-specific* ionosphere models was already considered in (Schaer, 1994). The following Figures 6a, 6b, and 7b (from (Schaer, 1994)) are based on results of L1-L2-solutions containing station coordinates, ambiguities (N_1 and N_2), tropospheric zenith path delay parameters, *stochastic* ionosphere parameters, and last but not least *deterministic* ionosphere parameters according to TEC model (4) with $H = 350\,\text{km}$. Figure 6 illustrates the *baseline-specific* ionosphere model for the baseline Kootwijk–Wettzell (Europe) *before* and *after* ambiguity resolution respectively. The "bulge" at (local) early afternoon as well as a gradient in north-south direction are clearly recognizable. The ionospheric activity at that time seems to have been much stronger than 15 months later as seen in the TEC map for Europe (Figure 5a).


Total Electron Content in [TECU] before ambiguity resolution

Total Electron Content in [TECU] after ambiguity resolution

(a) *Before* ambiguity resolution

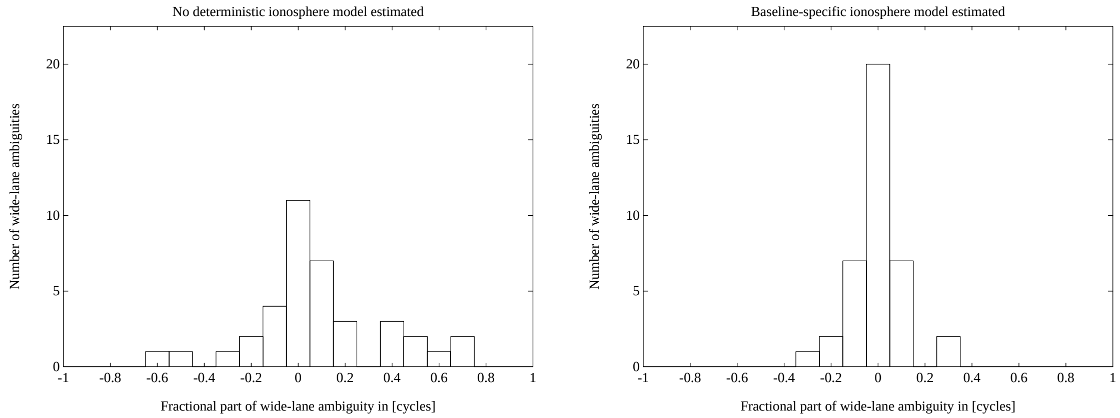
(b) *After* ambiguity resolution

Figure 6. *Baseline-specific* ionosphere model with 36 parameters ($n_{\max} = 5$) for baseline Kootwijk–Wettzell ($l \approx 600\,\text{km}$) at January 25, 1994

The fractional parts of the *wide-lane* ambiguities $N_5 = N_1 - N_2$ just before fixing are shown in Figure 7b. Note that our "fractional parts" are *not* generally the differences with respect to the next integer but the differences between *true* and *biased* ambiguity parameters; therefore they may be greater than *half* a cycle (see Figure 7a). Assuming that the station coordinates and the troposphere parameters (or the "geometrical" parameters) are well determined, these fractional parts are proportional to the biases due to the ionospheric refraction.[6] The dispersion of the fractional parts of the ambiguities N_5 is consequently an excellent indicator for the *un*modeled ionospheric influence *or* the quality of the ionosphere modeling of course — at least on differential level. Comparing Figures 7a and 7b the decreasing of this dispersion when TEC is modeled is clearly visible.

---

[6] One *wide-lane* cycle ($\lambda_5 = 86\,\text{cm}$) corresponds approximately to 4.1 TECU (at $z = 0$).



(a) *Without* TEC modeling

(b) *With* TEC modeling

Figure 7. Histogram of the fractional parts of the *wide-lane* ambiguities for one-day single-baseline solution — *without* or *with* TEC modeling (Figure 6a)

Quality Checks

Applying the ionosphere model (4) the *ionospheric range correction* (in meters) for the *zero-difference* GPS observation of the i-th frequency is given by

$$\Delta_i(\beta, s, z) = \mp \frac{\alpha}{\nu_i^2} \, F(z) \cdot E(\beta, s) \qquad \text{with} \quad i = 1, 2 \tag{12}$$

where one has to select the *negative* sign for *phase* observations and the *positive* for *code* observations (see also equations (2) and (3)). It is very important to use in relation (12) the same height H of the single layer the TEC model (4) is based on, whereas GPS results are nearly insensitive to the value itself of the height H (Wild, 1994). Nevertheless, the *absolute* calibration of the TEC E strongly depends on the assumed height H of the single layer.

In order to get a first impression of the quality of our large-scale ionosphere models we computed *regional* single-frequency (L1) solutions with European data with and without *regional* and *global* ionosphere models respectively applied according to the above formula (12). Note that the maximum extent of this IGS sub-network evaluated is about 3 500 kilometers in diameter. The baseline shortening introduced into GPS results by neglecting the ionospheric refraction is on the average 0.08 ppm/TECU when the L1 phase observable is processed with an elevation mask at 20° (Beutler et al., 1988). We expect an *apparent* network contraction of the same order.

Analyzing the scale biases estimated and the residuals of the coordinates coming from Helmert transformations with respect to ITRF[7] coordinates, we observed for every day of

---

[7] IERS (International Earth Rotation Service) Terrestrial Reference Frame

the test week that when applying our ionosphere models not only the scale bias has been reliably removed (on the 10-ppb level) but also the RMS variance of the residuals could be reduced significantly. *No* perceptible quality difference between *regional* and *global* ionosphere models could be detected by these criteria. Results of the seven parameter Helmert transformation between ITRF coordinates and the station coordinates of the *regional* single-frequency solution for the first day of the test week are shown in Table 1. The scale bias estimated is given at the bottom of the table: −0.25 ppm (without) and −0.02 ppm (with TEC model). The *global* TEC model illustrated in Figure 2b was used. The statistics of the corresponding six parameter Helmert transformation (*no* scale bias estimated) is given in Table 2. A dramatic increase of the standard deviation of the station coordinates when *no* TEC model is used has to be expected.

Table 1. Seven parameter Helmert transformation between ITRF coordinates and the coordinates of the *regional* L1 solution processing European IGS data from April 23, 1995

Global TEC model applied		No			Yes		
Station name		Residuals (cm)			Residuals (cm)		
		North	East	Up	North	East	Up
`JOZE`	Jozefoslaw	2.1	−0.4	6.6	1.8	−3.7	4.4
`BRUS`	Brussels	−4.6	−4.5	9.2	−2.7	−2.8	3.2
`BOR1`	Borowiec	1.0	0.7	7.3	1.0	−1.2	3.3
`GRAZ`	Graz	4.9	1.4	−3.3	4.6	−1.8	−4.1
`HERS`	Herstmonceux	−6.7	−3.4	−1.4	−5.4	−0.7	−1.5
`KOSG`	Kootwijk	0.5	−4.4	9.2	0.3	−3.6	5.6
`MADR`	Madrid	12.8	2.7	−9.8	15.2	8.8	−4.5
`MATE`	Matera	2.2	10.0	−19.6	1.1	4.3	−5.0
`TROM`	Tromso	2.4	11.3	−24.5	−2.0	13.4	−13.0
`WETT`	Wettzell	3.3	−1.9	7.2	3.2	−3.4	3.4
`ZIMM`	Zimmerwald	−8.4	−2.2	−6.7	−7.2	−1.6	−9.1
`ONSA`	Onsala	−8.1	0.4	13.7	−7.8	2.0	12.1
`METS`	Metsahovi	−3.3	1.0	−6.3	−2.9	4.2	−4.4
`POTS`	Potsdam	1.4	−0.9	7.1	0.8	−1.2	3.1
`LAMA`	Lamkowko	−1.7	1.9	10.8	−1.8	−0.7	6.8
`MDVO`	Mendeleevo	2.4	−11.7	0.6	1.7	−12.1	−0.3
RMS per component (cm)		5.4	5.4	11.1	5.4	5.8	6.4
RMS of transformation (cm)		8.2			6.2		
Degree of freedom		41			41		
Scale factor (mm/km)		−0.252 ± 0.020			−0.018 ± 0.015		

This method to perform quality checks indicates GPS-internal consistency of the ionosphere models. The same is true for the analysis of the fractional parts of wide-lane ambiguity parameters (Figure 7b). In order to check the *absolute* calibration of our TEC models, comparisons with models established by other groups using other techniques or even other than GPS observations will have to be made.

Table 2. Six parameter Helmert transformation (*no* scale factor permitted) between ITRF coordinates and the coordinates of the *regional* L1 solution processing European IGS data from April 23, 1995

Global TEC model applied		No			Yes		
Station name		Residuals (cm)			Residuals (cm)		
		North	East	Up	North	East	Up
`JOZE`	Jozefoslaw	2.2	13.0	5.1	1.8	−2.7	4.3
`BRUS`	Brussels	−1.1	−20.2	8.0	−2.4	−3.9	3.1
`BOR1`	Borowiec	1.2	7.3	5.4	1.0	−0.7	3.2
`GRAZ`	Graz	19.7	5.7	−4.5	5.6	−1.5	−4.1
`HERS`	Herstmonceux	−4.5	−26.1	−1.8	−5.2	−2.3	−1.5
`KOSG`	Kootwijk	0.4	−17.1	7.7	0.3	−4.5	5.5
`MADR`	Madrid	41.6	−34.1	−4.9	17.3	6.2	−4.2
`MATE`	Matera	34.7	17.4	−18.2	3.4	4.9	−4.9
`TROM`	Tromso	−45.6	16.9	−19.1	−5.4	13.8	−12.6
`WETT`	Wettzell	12.4	−2.5	5.4	3.9	−3.4	3.2
`ZIMM`	Zimmerwald	6.6	−13.2	−7.6	−6.1	−2.4	−9.2
`ONSA`	Onsala	−22.2	−1.6	12.3	−8.8	1.8	12.0
`METS`	Metsahovi	−26.4	16.5	−5.9	−4.6	5.3	−4.4
`POTS`	Potsdam	1.4	−1.1	5.0	0.8	−1.3	3.0
`LAMA`	Lamkowko	−6.5	14.2	9.4	−2.2	0.2	6.7
`MDVO`	Mendeleevo	−13.9	24.9	3.7	0.5	−9.5	−0.1
RMS per component (cm)		21.7	17.6	9.4	6.1	5.4	6.3
RMS of transformation (cm)		17.6			6.2		
Degree of freedom		42			42		

CONCLUSIONS AND OUTLOOK

The world-wide IGS network of permanent tracking dual-frequency GPS receivers provides a unique opportunity to *continuously* monitor the *Total Electron Content (TEC)* on a *global* scale. First results using one week of *GPS phase data* as used by the CODE Analysis Center seem to indicate that under *normal* ionospheric conditions we are able to estimate *plausible* ionosphere models using the *double-difference approach*. Results were illustrated by several *ionosphere maps* for April 23, 1995.

An 8th-degree spherical harmonics expansion seems to be adequate for a 24-hour global TEC model. This 24-hour model represents a *time-averaged* global TEC structure. To verify the GPS-internal consistency of our TEC models we computed *regional* single-frequency (L1) solutions with European data with and without using *regional* and *global* models, respectively. Comparisons by Helmert transformations between the station coordinates stemming from the different L1 solutions and the corresponding ITRF coordinates revealed that when applying our ionosphere models not only the *scale biases* could be reliably removed, a significant reduction of the residuals could be observed as well for every day of the test week. *No* quality difference between *regional* and *global* ionosphere models could be detected. In order to check in detail the quality as well as the *absolute* calibration of our TEC models, comparisons with models established by other groups will have to be made.

The assumptions of the thin-shell model — the height H of the shell in particular — are essential for *absolute* calibration. If a smaller (larger) height than the "effective" (or actual) height H_0 is adopted, larger (smaller) zenith distances at the ionospheric sub-points will cause the TEC values to be underestimated (overestimated). This means that in principle the determination of the single-layer height H as an additional *unknown* parameter would be possible.

The use of the *double-difference approach* will give us the capability to produce very "low-cost" one-day ionosphere models (and maps) on a routine basis — even under *Anti-Spoofing (AS)*. The ionosphere modeling technique presented in this paper will be implemented at the CODE Analysis Center in the very near future. An additional fully-automatic procedure will be set up to create ionosphere model files for every day. These daily *average ionosphere models* should potentially support our so-called *Quasi-Ionosphere-Free (QIF)* ambiguity resolution strategy (Mervart and Schaer, 1994). By statistically analyzing the *fractional parts* of the *wide-lane ambiguities* we will get another quality check indicator for our ionosphere models. After ambiguity resolution we will be able to generate ionosphere models which are based on (partly) *ambiguity-fixed* solutions.

The ionosphere model parameters (*global* ionosphere maps only) will *not* be sent to the *IGS Global Data Centers*, but will be made available in an *Anonymous FTP* account at the CODE processing center.[8] Such an *ionosphere service* providing day by day TEC models is of interest for all GPS users, which are analyzing and evaluating *small* high-precision control networks using the L1 observable only instead of the *ionosphere-free LC* for reasons of accuracy (see e. g. (Beutler et al., 1995)). Finally, let us not forget that we will obtain information related to the ionosphere (and the solar activity) like mean TEC, maximum TEC, etc. for long-term studies.

REFERENCES

Beutler, G., I. Bauersima, W. Gurtner, M. Rothacher, T. Schildknecht, 1988, *Atmospheric Refraction and Other Important Biases in GPS Carrier Phase Observations*, Monograph 12, School of Surveying, University of New South Wales, Australia.

Beutler, G., I. Bauersima, S. Botton, W. Gurtner, M. Rothacher, T. Schildknecht, 1989, Accuracy and biases in the geodetic application of the Global Positioning System, *Manuscripta Geodaetica*, Vol. 14, No. 1, pp. 28–35.

Beutler, G., I. I. Mueller, R. Neilan, 1994, The International GPS Service for Geodynamics (IGS): Development and Start of Official Service on 1 January 1994, *Bulletin Géodésique*, Vol. 68, No. 1, pp. 43–51.

Beutler, G., M. Cocard, A. Geiger, M. Müller, M. Rothacher, S. Schaer, D. Schneider, A. Wiget, 1995, Dreidimensionales Testnetz Turtmann 1985–1993: Teil II, *Geodätisch-geophysikalische Arbeiten in der Schweiz*, Band 51.

Georgiadiou, Y. and A. Kleusberg, 1988, On the effect of ionospheric delay on geodetic relative GPS positioning, *Manuscripta Geodaetica*, Vol. 13, pp. 1–8.

---

[8] The next version of the *Bernese GPS Software* will be able to process directly these *ionosphere files*.

Lanyi, G. E. and T. Roth, 1988, A comparison of mapped and measured total ionospheric electron content using global positioning system and beacon satellite observations, *Radio Science*, Vol. 23, No. 4, pp. 483–492.

Mannucci, A. J., B. D. Wilson, D.-N. Yuan, 1994, Monitoring Ionospheric Total Electron Content Using the GPS Global Network and TOPEX/POSEIDON Altimeter Data, *Proceedings of the Beacon Satellite Symposium*, Aberystwyth, Wales, July 1994.

Mervart, L., G. Beutler, M. Rothacher, U. Wild, 1993, Ambiguity Resolution Strategies Using the Results of the International GPS Geodynamics Service (IGS), *Bulletin Géodésique*, Vol. 68, No. 1, pp. 29–38.

Mervart, L. and S. Schaer, 1994, *Quasi-Ionosphere-Free (QIF) Ambiguity Resolution Strategy*, Internal report, Astronomical Institute, University of Berne, Switzerland.

Mervart, L., 1995, *Ambiguity Resolution Techniques in Geodetic and Geodynamic Applications of the Global Positioning System*, Ph. D. thesis, Astronomical Institute, University of Berne, Switzerland.

Rothacher, M., G. Beutler, W. Gurtner, E. Brockmann, L. Mervart, 1993, *The Bernese GPS Software Version 3.4: Documentation*, Astronomical Institute, University of Berne, Switzerland.

Rothacher, M., R. Weber, E. Brockmann, G. Beutler, L. Mervart, U. Wild, A. Wiget, C. Boucher, S. Botton, H. Seeger, 1994, *Annual Report 1994 of the CODE Processing Center of the IGS*.

Schaer, S., 1994, *Stochastische Ionosphärenmodellierung beim Rapid Static Positioning mit GPS*, Diplomarbeit, Astronomisches Institut, Universität Bern.

Wild, U., 1993, Ionosphere and Ambiguity Resolution, *Proceedings of the 1993 IGS Workshop*, March 25–26, 1993, Berne, Switzerland, pp. 361–369.

Wild, U., 1994, Ionosphere and Satellite Systems: Permanent GPS Tracking Data for Modelling and Monitoring, *Geodätisch-geophysikalische Arbeiten in der Schweiz*, Band 48.

Wilson, B. D. and A. J. Mannucci, 1993, *Instrumental Biases in Ionospheric measurements Derived from GPS Data*, Paper presented at ION GPS 93, Salt Like City, September 22–24, 1993.