Generating Klobuchar-Style Ionospheric Coefficients for Single-Frequency Real-Time and Post-Processing Users

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Abstract. Approaching the next solar maximum, the knowledge of the state of the ionosphere becomes more and more important. The access to up-to-date TEC information is required for many applications. The CODE analysis center of the IGS is routinely predicting global ionosphere maps in IONEX format making use of an uninterrupted ionospheric time series of several years. A first attempt is made in deriving Klobuchar model coefficients best fitting our predicted IONEX information. We validate our predicted IONEX and improved Klobuchar model information taking the Klobuchar model information broadcast by the Global Positioning System (GPS) as reference.

1 Introduction and Motivation

CODE, the Center for Orbit Determination in Europe (see, e. g., [*Hugentobler et al.*, 2000]), acts as one of currently five so-called ionosphere associate analysis centers of the International GPS Service (IGS) which produce global total electron content (TEC) maps on a regular basis [*Feltens and Schaer*, 1998; *Schaer*, 1998*b*]. These maps—as well as all other IGS analysis products—are derived from data of the IGS tracking network, the primary product of the IGS [*Beutler et al.*, 1999]. The data format adopted by the IGS analysis centers (ACs) to provide the TEC information is the Ionosphere Map Exchange (IONEX) format [*Schaer*, 1998*a*]. IGS IONEX files may also contain estimates for P1–P2 code biases of the current GPS satellite constellation, which are obtained as a by-product of the TEC determination.

At CODE, a final, a rapid, and a predicted ionosphere product are generated [*Schaer et al.*, 1998*b*; *Schaer*, 1999]. All these products are made available in two different data formats: the IONEX and the ionosphere file format of the Bernese GPS Software [*Hugentobler et al.*, 2001*a*]. IONEX is an exchange format which is not specific to GPS, it is technique-independent. It is therefore not surprising that GPS-derived IONEX data is also considered by non-GPS people, like altimetry groups, interested in global TEC information.

For some applications, however, especially if a user is solely interested in getting a first-order ionospheric correction, one may call it into question whether it is worthwhile to follow the IONEX interface. The considerable size of IGS IONEX files is actually not irrelevant in this context. It is a fact that most GPS software packages have an interface with respect to the GPS broadcast ionosphere model [*Rockwell International Corporation*, 1993]. This model was originally developed by *Klobuchar* [1987], the reason why it is often called just "Klobuchar model." The circumstance that the GPS broadcast—or Klobuchar—ionosphere model is very well established and widely used is the motivation for us to try to expand the use of CODE ionosphere products to a broader community by "converting," or better "reducing," our IONEX data into daily sets of ionospheric coefficients which are completely conform with the Klobuchar model. Incidentally, this idea was advanced for the first time in [*Schaer*, 1999]. Last but not least, the reader has to be aware of the fact that the model coefficients broadcast by the GPS are and remain predicted coefficients, whereas we are in a situation to provide besides—in addition to the predicted coefficients—sets of model coefficients which are based on actual TEC measurements. In particular for users who do their analysis in post-processing mode, this may be a weighty argument to consider our rapid or final "Klobuchar-style" ionosphere product. The data format adapted to make available this product is the RINEX format [*Gurtner*, 1994].

This article gives an overview of the ionosphere products generated at CODE and describes a way to extract Klobuchar-style ionospheric coefficients from IONEX data. Corresponding results of two months are compared and validated. Problems and various difficulties with respect to Klobuchar's TEC parameterization are highlighted as well. Finally, a unique data archive of daily RINEX files containing such improved CODE GIM ionospheric coefficients over several years is introduced.

2 Ionosphere Products Generated at CODE

2.1 Global Ionosphere Maps

IGS-based global ionosphere maps (GIMs) describing the Earth's vertically integrated total electron content (TEC) are our basic ionosphere product. Three kinds of GIM products are generated at CODE: a final, a rapid, and a predicted product. The final product is derived from the so-called geometry-free linear combination of phase-leveled-to-code measurements of about 140–150 globally distributed IGS ground stations and should be available approximately three days after observation; the rapid product is based on typically 90 stations and becomes accessible usually well before 12 hours UT of the following day. Both the final and the rapid GIM products are created as part of the fully automated CODE analysis using the Bernese Processing Engine (BPE) [*Hugentobler et al.*, 2001*a*]. The basic GPS data analysis is generally performed in 24-hour batches. CODE GIMs are represented by a spherical harmonics expansion of degree 12 and order 8 referring to a solar-geomagnetic frame, because the global TEC distribution is relatively stationary in that frame. The conversion of line-of-sight TEC to vertical TEC is done relying on a single-layer model. The time resolution considered is two hours.

The predicted GIM product, thought for real-time applications, is derived from the time series of accumulated final GIMs, completed with the rapid solutions of the last three days. It is computed by means of least-squares collocation as soon as the rapid TEC determination is finished [*Schaer et al.*, 1998*b*; *Schaer*, 1999]. Two GIM data sets are thus produced: one for the current day and one for the following day. They are addressed as "one-day predicted" and "two-day predicted," respectively.

The full CODE GIM information is accessible via the anonymous ftp server of the University of Berne, namely in IONEX and the Bernese ionosphere file format. The server address leading to the top directory of CODE's data archive is `ftp://ftp.unibe.ch/aiub/CODE/`. The final IONEX results, declared as our official IGS ionosphere contribution, are finally delivered to CDDIS (Crustal Dynamics Data Information System), an IGS global data center.

2.2 The IONEX Format

IONEX (Ionosphere Map Exchange) is a format for the exchange of two- or even three-dimensional ionosphere maps [*Schaer et al.*, 1998*a*]. It was developed by the IGS ionosphere working group and approved by the IGS community. The IONEX format has similar characteristics as the RINEX format [*Gurtner*, 1994].

Each IONEX file consists of a header section and a data section. The header section is placed at the beginning of the file and contains descriptive information which is valid for the entire file. The data section then contains the actual TEC information, tabulated TEC values which are referred to latitude-longitude(-height) grid points and to particular epochs. Figure 1 visualizes the content of a CODE IONEX file, namely of the one for February 12, 2001. 12 two-hourly snapshots of the global TEC distribution taken at 01:00, 03:00, 05:00, ..., 23:00 UT are shown underlaid with coastal lines. Contour lines are given every 10 TECU. (One TEC unit corresponds to 10^{16} free electrons contained in a column with a cross-section of one square meter.) The typical "bulge" (dark area), which may be bifurcated, is aligned to some extent with the longitude of the Sun and the geomagnetic equator (dotted line). Since the Sun's ultraviolet radiation and the Earth's geomagnetic field strongly influence the ionosphere, this is not really astonishing. On the night-time hemisphere, the TEC level is fairly low (light shading).

CODE IONEX files do also contain a set of associated rms-error maps, describing the formal accuracy of the TEC estimates. It is easy to understand that such rms maps reflect principally the coverage by the ground stations, that is, these maps should be more or less invariable with respect to the geographic frame.

2.3 Mean TEC of the Earth's Ionosphere

An essential parameter to simply characterize the state of the Earth's ionosphere is the mean (vertical) TEC, represented by the zero-degree coefficient C_{00} of our spherical harmonics expansion. The importance of this particular TEC parameter is evident from the linear relationship to the overall number of free electrons contained in the ionosphere.

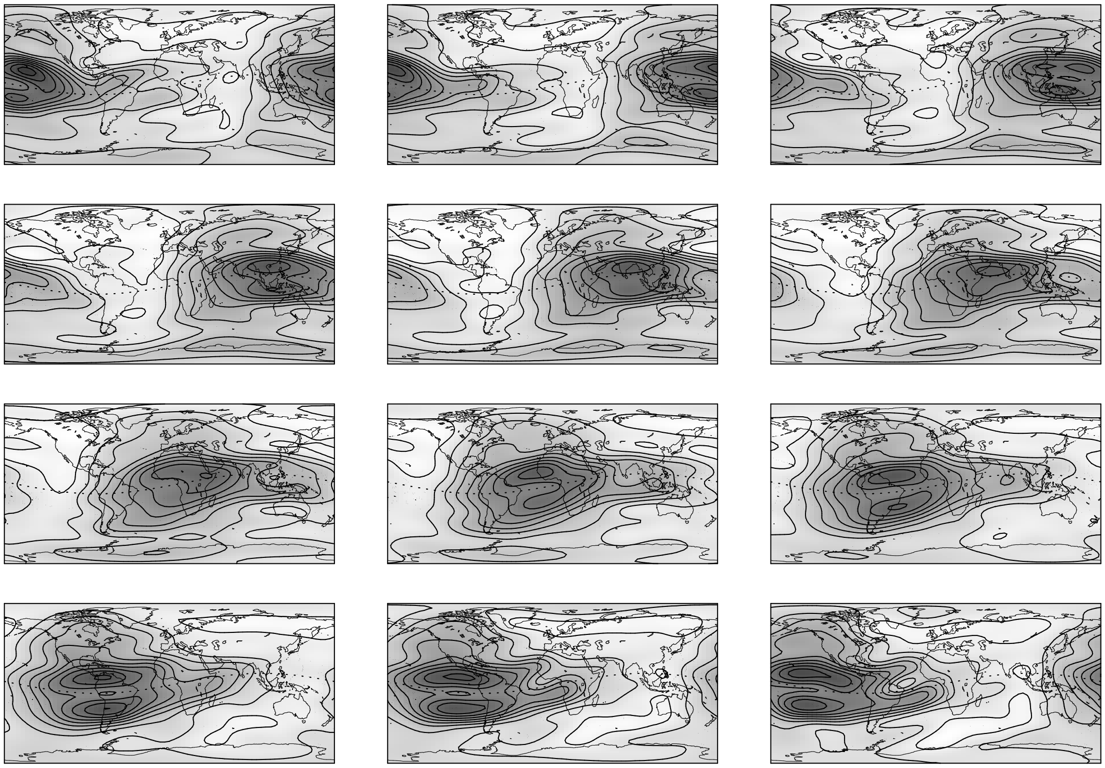


Figure 1: Two-hourly snapshots of the Earth's ionosphere for February 12, 2001, as produced by CODE.

The correlation of our C_{00} estimates with 10.7-cm solar flux data, with a value of almost 0.90, proved to be very significant [*Schaer*, 1999].

Figure 2 shows the evolution of the mean TEC as monitored by CODE from January 1995 onwards, during periods of both low and high solar activity. This figure documents the state of the Earth's ionosphere without any gaps over six and a half years. Dots indicate daily averaged estimates. The solid line, a slightly smoothed curve, has been added to get the behavior better visualized.

We notice a long-term trend coming from the 11-year solar activity cycle. The recent minimum of ionospheric activity could be observed, at least with regard to a global scale, in the summer of 1996. Our GIM time series reveals annual and semi-annual, or seasonal, variations in the mean TEC. Maxima occur at equinoxes and minima at solstices. The minima in summer, however, are more pronounced than those in winter. Furthermore, we may see pronounced short-term fluctuations caused by sunspots randomly developing and vanishing. These fluctuations show typically periods around 27 days, associated with the rotation of the Sun's surface. The striking ups and downs of the mean TEC during the years 1999–2001, a period of high heliographic activity, may be attributed to potential sunspot groups which are located in selective solar longitudes. In the end, Figure 2 demonstrates the impressive dynamics of the Earth's ionosphere, taking note of a mean TEC ranging from about 5 TECU up to more than 50 TECU. This range

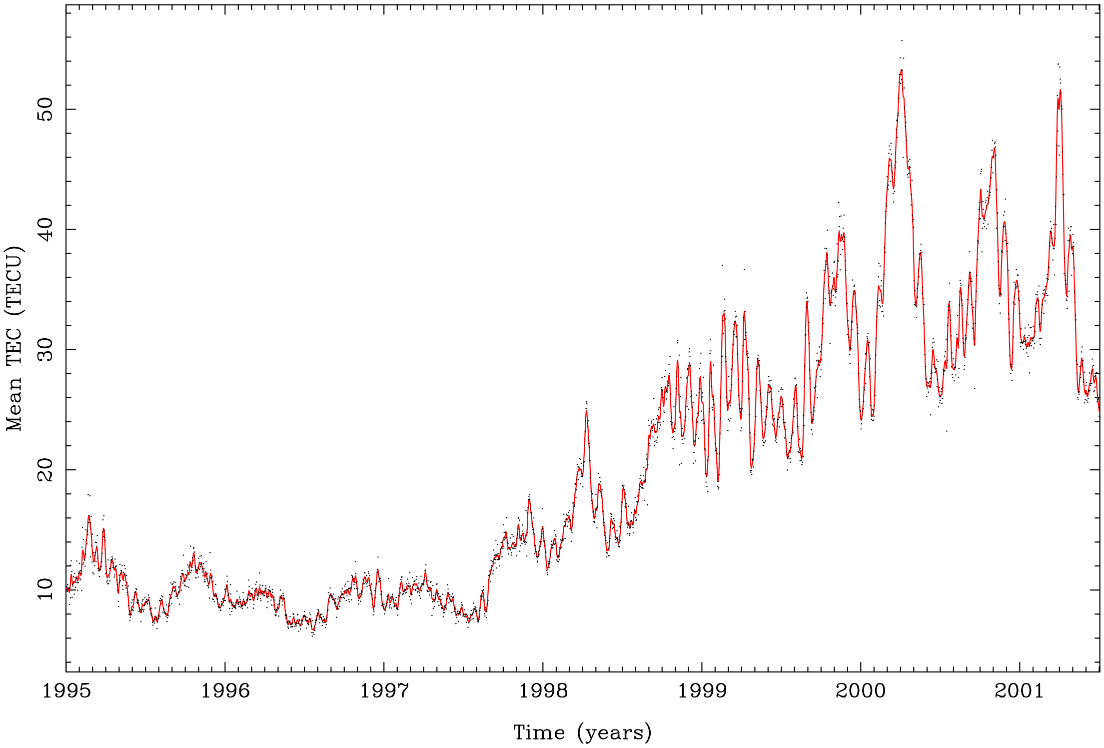


Figure 2: Mean TEC of the Earth's ionosphere computed by CODE, from January 1995 through June 2001.

corresponds to one order of magnitude!

2.4 P1–P2 Code Bias Values

In addition to the TEC parameters, the actual ionospheric parameters, differential P1–P2 code bias (DCB) parameters are solved for as part of the ionosphere mapping. They are related to the individual satellites as well as all receivers involved. One independent set of such parameters is taken into account each day.

Figure 3 shows the latest 30 sets of DCB values obtained for the current GPS satellite constellation (dots). The day-to-day reproducibility of these values is regularly confirmed to be of the order of 0.1 nanoseconds. Because all code biases may be shifted by a common bias, a zero-mean condition is imposed on the (satellite-related) DCB estimates.

The circles in Figure 3 indicate average DCB values of the 30-day comparison. Corresponding results of a moving 30-day average are daily updated and posted in the Bernese DCB file format to the Internet [*Schaer*, 1998*a*]. They also include estimates related to the IGS receiver network. The satellite DCB estimates daily obtained are provided with every CODE IONEX file.

It remains important to mention that P1–P2 code bias values multiplied by a factor of $-f_{\mathrm{L2}}^2/(f_{\mathrm{L1}}^2 - f_{\mathrm{L2}}^2) = -60^2/(77^2 - 60^2) \approx -1.55$ lead in principle to values similar to the interfrequency "group delays," T_{GD}, that are broadcast by the GPS. Note that

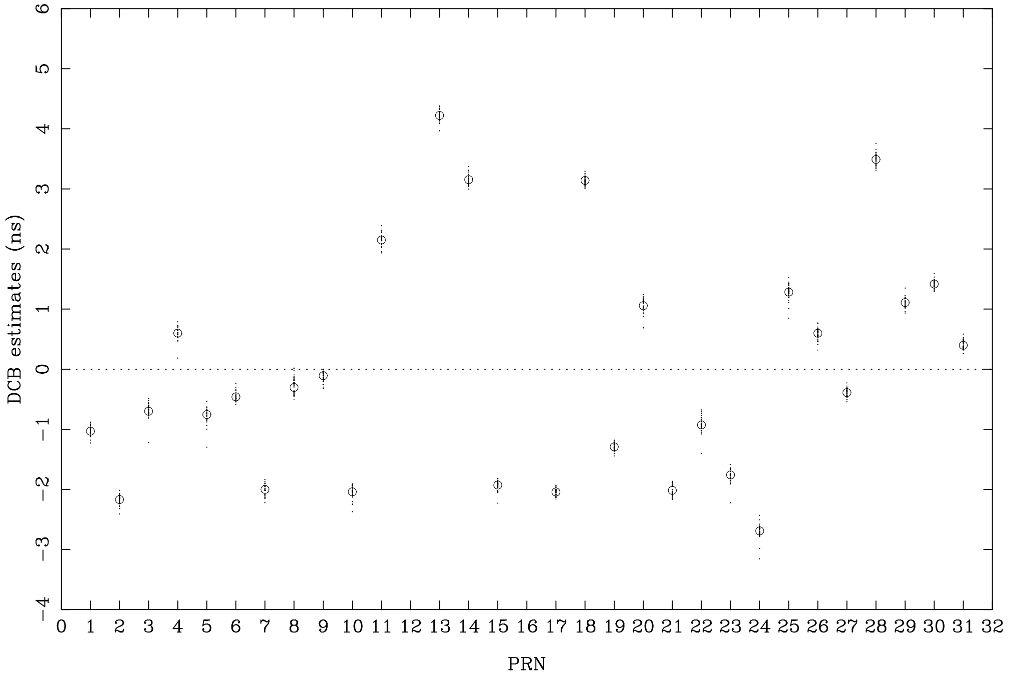


Figure 3: Daily P1–P2 code bias estimates for 29 GPS space vehicles, accumulated over 30 days and compared.

f_{L1} and f_{L2} denote the nominal center frequencies of L1 and L2, respectively. This piece of information is required by the single-frequency GPS user, either for positioning or time transfer, to make his measurements consistent to the (dual-frequency) satellite clock corrections broadcast by the GPS (or produced by the IGS), which definitively depend on the ionosphere-free linear combination of P1 and P2 measurements. Strictly speaking, P1–C1 DCB values should be taken into account as well, if only C1 (say C/A) measurements are at the user's disposal. This type of code bias is monitored at CODE since May 2000 (see [*Schaer*, 1998*a*]). As opposed to the P1–P2 DCB, the P1–C1 DCB is not considered by the GPS broadcast navigation data message.

2.5 Station-Specific Ionosphere Maps

In addition to the global ionosphere maps (GIMs), we are producing in parallel station-specific ionosphere maps. The TEC distribution above each ground station is treated there independently, modeled with 49 ionospheric parameters each over 24 hours. Assuming that we analyze data of 150 GPS tracking stations (and 29 satellites), 7535 unknown parameters have to be coped with, namely $150 \cdot 49 = 7350$ TEC parameters, 150 station and 29 satellite DCB parameters, and $2 \cdot 3 = 6$ L1–L2 satellite antenna offset parameters (one vector for each Block generation), which are set up for test purposes. We are able to manage this relatively big number of parameters by means of normal equation stacking manipulations.

In GIM analyses, the total number of unknown parameters to be adjusted is comparatively small. Following the above assumption, 1967 unknown parameters would result in total: constantly $12 \cdot 149 = 1788$ GIM parameters and again $150 + 29 = 179$ DCB parameters. Therefore we can do the GIM dedicated parameter adjustment without any problems "en bloc." This would be possible even with a much bigger number of stations.

3 Determination of Klobuchar-Style Ionospheric Coefficients

3.1 The GPS Broadcast Ionosphere Model

Let us recapitulate the ionosphere model as it is supported by the GPS system. This model was developed in the 1970s by *Klobuchar* [1987]. Eight ionospheric coefficients, called α_0, α_1, α_2, α_3, β_0, β_1, β_2, β_3, are transmitted by the GPS satellites. Each value of them is represented by an 8-bit data word in the navigation data message. (The scale factors are defined to be 2^{-30}, 2^{-27}, 2^{-24}, 2^{-24}, 2^{11}, 2^{14}, 2^{16}, and 2^{16}, respectively.) The four alpha and four beta coefficients are coefficients associated with two cubic polynomial representations for two parameters describing a cosine-shaped, approximate TEC distribution that co-rotates with the Sun.

Let us list the steps in chronological order as they are needed in the calculation of line-of-sight ionospheric delay. We try to keep in the following as far as possible to the notation as used in the GPS interface control document (ICD) [*Rockwell International Corporation*, 1993]. The receiver generated terms which are relevant in this context are: E and A, the elevation and azimuth angle between the receiver and satellite, ϕ_u and λ_u, the user geodetic latitude and longitude, and GPS time, the receiver computed system time. We may substitute UT for GPS time, as the difference, currently amounting to 13 seconds, is negligible here. All angle arguments—including those of the following equations—are assumed to be in semi-circles (one semi-circle corresponds to π radians); time arguments have to be in seconds. In a first step, the Earth's central angle Ψ between the user position and the Earth projection of the ionospheric intersection point of the line of sight has to be calculated:

$$\Psi = \frac{0.0137}{E + 0.11} - 0.022. \tag{1}$$

The geodetic latitude ϕ_i of the ionospheric pierce point, obtained as

$$\phi_\mathrm{i} = \begin{cases} \phi_\mathrm{u} + \Psi \cos A, & |\phi_\mathrm{i}| \leq 0.416 \\ \text{if } \phi_\mathrm{i} > +0.416, & \text{then } \phi_\mathrm{i} = +0.416 \\ \text{if } \phi_\mathrm{i} < -0.416, & \text{then } \phi_\mathrm{i} = -0.416 \end{cases}, \tag{2}$$

is required to compute the geodetic longitude

$$\lambda_\mathrm{i} = \lambda_\mathrm{u} + \frac{\Psi \sin A}{\cos \phi_\mathrm{i}} \tag{3}$$

and then the geomagnetic latitude

$$\phi_\mathrm{m} = \phi_\mathrm{i} + 0.064 \cos(\lambda_\mathrm{i} - 1.617) \tag{4}$$

of the ionospheric pierce point considered. The "amplitude" and "period" of the cosine representation are both functions of the geomagnetic latitude ϕ_{m}. They may be reconstructed from the four alpha coefficients α_n and four beta coefficients β_n, respectively:

$$\mathrm{AMP} = \begin{cases} \sum_{n=0}^{3} \alpha_n \, \phi_{\mathrm{m}}^n, & \mathrm{AMP} \geq 0 \\ \text{if AMP} < 0, & \mathrm{AMP} = 0 \end{cases}, \tag{5}$$

$$\mathrm{PER} = \begin{cases} \sum_{n=0}^{3} \beta_n \, \phi_{\mathrm{m}}^n, & \mathrm{PER} \geq 72000 \\ \text{if PER} < 72000, & \mathrm{PER} = 72000 \end{cases}. \tag{6}$$

The values of the ionospheric coefficients α_n and β_n are nominally given in units of seconds/semi-circles^n. This implies that AMP as well as PER are obtained in units of seconds. Using the local time

$$\mathrm{LT} = 4.32 \cdot 10^4 \, \lambda_{\mathrm{i}} + \mathrm{UT}, \tag{7}$$

the auxiliary phase argument x (radians) results in

$$x = \frac{2\,\pi\,(\mathrm{LT} - 50400)}{\mathrm{PER}}. \tag{8}$$

The line-of-sight time delay due to the ionosphere (expressed in seconds) then becomes

$$T_{\mathrm{iono}} = \begin{cases} F \left[5.0 \cdot 10^{-9} + \mathrm{AMP}\left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right], & |x| < 1.57 \\ F\,(5.0 \cdot 10^{-9}), & |x| \geq 1.57 \end{cases}, \tag{9}$$

where

$$F = 1.0 + 16.0(0.53 - E)^3 \tag{10}$$

is a unitless obliquity, or slant, factor. For Eqn. (10) as well as for Eqn. (1), a mean ionospheric shell height of 350 kilometers is implicitly assumed.

T_{iono} of Eqn. (9) is referred to the L1 frequency. If the user is operating on the L2 frequency, the correction term must be multiplied by the constant $(f_{\mathrm{L1}}/f_{\mathrm{L2}})^2 = (77/60)^2 \approx 1.65$. The attentive reader may recognize in Eqn. (8), that maximum TEC is predicted to be generally at 50400 seconds (or 14 hours) local time, and in Eqn. (9), that the night-time zenith delay is held constant at 5.0 nanoseconds, corresponding to about 9.2 TECU. The factor to convert ionospheric time delay on L1 into TEC is given by

$$\xi = \frac{c\,f_{\mathrm{L1}}^2}{40.3 \cdot 10^{16}} \approx 1.85 \cdot 10^9 \ \mathrm{TECU/seconds}\,, \tag{11}$$

where c denotes the speed of light and $f_{\mathrm{L1}} = 154 \cdot 10.23$ MHz $=$ 1575.42 MHz is the primary satellite system operating frequency.

Some mention should be made here of the fact that the algorithm as delineated by the GPS ICD [*Rockwell International Corporation*, 1993] stipulates that $0 \leq \mathrm{LT} < 86400$ seconds should hold for the resultant local time—addressed in Eqn. (7) and finally required in Eqn. (8). Specifically, the following guideline is drawn: if $\mathrm{LT} \geq 86400$ seconds, subtract 86400 seconds; if $\mathrm{LT} < 0$ seconds, add 86400 seconds. We will later give a reason why this instruction has to be regarded as questionable.

For further details of the derivation of these equations and a discussion of the approximations used and their accuracy, we can refer to [*Klobuchar*, 1987].

3.2 Ionospheric Coefficients Transmitted by the GPS System

The α_n and β_n coefficients are selected from 370 possible sets of constants by the GPS master control center (MCC) and placed in the satellite upload message for downlink to the user. The selection of a set is based on the following two parameters:

- day of the year and
- average solar 10.7-cm flux value for the previous five days.

Klobuchar generated ten sets of base coefficients for each of 37 ten-day periods of the year. Set 1 covers days 1–10, set 2 covers day 11–20, and so on, and with set number 37 covering days 361–365 (or through day 366 for leap years). Each of the ten sets was for a different range of five-day average solar 10.7-cm flux values. Therefore there should be a total of 37 times ten, or 370 sets of base coefficients. The only group that has the full set of base coefficients as they are transmitted is probably the GPS MCC, since it changed the unit of the original base coefficients, then scaled them by truncating, not rounding them, into their present transmitted form [*Klobuchar*, 2000].

One may start from the assumption that the GPS MCC is used to reconsider the ionospheric coefficients once each day. This means that the coefficients transmitted by the GPS satellites may change from day to day. It is not unusual, however, that they remain unchanged over two or more days, or, to be more precise, that only one or a subset of coefficients is altered. Because of the discretization of the model coefficients, such a behavior may be entirely expected.

By using the algorithm as recapitulated in Section 3.1 in conjunction with these ionospheric coefficients, the goal of a 50-percent rms correction should be met according to *Klobuchar* [1987] and *Feess and Stephens* [1987].

3.3 Parameter Adjustment Method

We are interested in finding improved sets of ionospheric coefficients best fitting our IONEX GIM data. For this purpose, we may view the IONEX vertical TEC data as pseudo-observations for the ionosphere-induced zenith time delay at specific epochs and positions. Our IONEX files give TEC values every 2 hours in time, every 2.5 degrees in latitude and every 5 degrees in longitude. Consequently, 12 times 71 times 72, or 61 344 of such observations are available for each day. Because these observations are zenith observations, an elevation angle E of 90 degrees (or 0.5 semi-circles) is valid, and thus the central angle Ψ becomes zero and the obliquity factor F becomes unity. Note that Eqns. (1) and (10) do not make exactly these values as they are approximate formulae. For our application, we may write $\phi_\mathrm{i} = \phi_\mathrm{u}$ and $\lambda_\mathrm{i} = \lambda_\mathrm{u}$. If $|\phi_\mathrm{i}| > 0.416$, ϕ_i has still to be truncated according to Eqn. (2). By multiplying the right-hand side of Eqn. (9) with the factor ξ as introduced in Eqn. (11), remembering that $F = 1$, we get our (pseudo-)observation equation in units of TECU as

$$\mathrm{TEC} = \begin{cases} \xi \left[5.0 \cdot 10^{-9} + \mathrm{AMP} \left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right], & |x| < 1.59 \\ \xi \left(5.0 \cdot 10^{-9}\right), & |x| \geq 1.59 \end{cases}, \tag{12}$$

denoting the (adjusted) IONEX GIM pseudo-observations as "TEC." The information from associated IONEX rms maps, if available, can be utilized as a-priori variance information. The value of 1.59 (instead of 1.57) defining the crossing-point in Eqn. (12) is no typographical error. Its use will be justified in Section 3.6.

Our task now is to find an unambiguous set of α_n and β_n parameters for which the best possible fit of IONEX-originated TEC observations is achieved. To get a solution, we will strive for somehow minimizing the residuals between the TEC observations and the TEC distribution fit. If the reader has a closer look at the equations the Klobuchar algorithm is based on, it immediately becomes obvious that this system of formulae is highly nonlinear with respect to these eight parameters. In face of this nonlinearity, the question may arise whether the problems behind this task are actually solvable or not using standard methods. The answer is basically yes, but there are a few restrictions where additional considerations are needed. We will mention related issues in Section 3.6.

Nevertheless, one vital aspect must be emphasized already in this section. Unlike the original Klobuchar ionosphere model which has a basis of 370 sets of α_n and β_n coefficients and which is therefore of discrete nature, our model coefficients are definitely not subject to a similar restriction. One may start from the assumption, however, that the users' algorithms do not realize this generalization of the model at all. Anyway, with the exception of this generalization, our model coefficients should be completely conform with the algorithm as specified by the GPS ICD [*Rockwell International Corporation*, 1993] and as repeated in Section 3.1.

A software tool, called INXFIT (IONEX fit), has been developed as a further component of the Bernese GPS Software [*Hugentobler et al.*, 2001*a*]. This tool will likely be included in the next release of the software, intended to be Version 5.0. The INXFIT program is capable to derive one or a series of sets of Klobuchar-style ionospheric coefficients from IONEX TEC data by means of a weighted least-squares adjustment. Due to the pronounced nonlinearity in the unknown parameters, adequate a-priori information in conjunction with an iterative adjustment are indispensable. The partial derivatives with respect to the unknown parameters are computed numerically. As the necessary mathematical operations proved to be not very time-consuming, we advise to ask for ten or more iterations. The following main features are offered by the INXFIT program:

- consider a-priori variance information in form of IONEX rms maps for individually weighting the TEC pseudo-observations,
- take over adjusted coefficient values from previous day as initial values for subsequent day (in order to enable an efficient time series generation),
- detect numerical instabilities in the adjustment process and take suitable measures to prevent them (see also Section 3.6),
- determine coefficients for n IONEX TEC maps each (in order to control their time resolution),
- restrict analysis to a user pre-defined geographical area (in order to generate optimum coefficients being valid for a certain region),
- reduce input TEC data with a specific scale factor and/or add constant term,
- ignore data at polar caps.

In any case, independent of whether a-priori variance information is considered or all pseudo-observations are equally treated, a latitude-dependent weighting scheme is employed to account for the circumstance that IONEX data is referred to a grid which is inhomogeneous in space.

From a theoretical point of view, it might be interesting to solve eventually also for additional parameters, such as a parameter responding to the night-time TEC level, a local time parameter indicating where maximum TEC is reached, etc. In principle, such a model refinement would be smoothly achievable, but we do very deliberately without any modifications and "improvements" of this kind in order to be with our model coefficients fully compatible to the Klobuchar model—and in the end to related users' algorithm implementations.

3.4 The RINEX Navigation Data Format Used as Interface

To provide our Klobuchar-style ionospheric information for the interested public, we make use of the RINEX (Receiver-Independent Exchange) format, or more specifically, of the RINEX navigation data format [*Gurtner*, 1994]. This format is internationally adopted and allows to exchange, among other things, such coefficients, internally addressed as "ionospheric alphas and betas." An example of a CODE GIM (CGIM) RINEX file is shown in Figure 4. CGIM RINEX files do not contain any satellite positions and clock corrections, which are actually the primary information usually included in RINEX navigation data files. Their content is limited to a header section containing exclusively these coefficients.

```
     2              NAVIGATION DATA     GPS                 RINEX VERSION / TYPE
INXFIT V4.3         AIUB                12-JUL-01 09:55     PGM / RUN BY / DATE
CODE'S 2-DAY PREDICTED IONOSPHERE INFO FOR DAY 194, 2001    COMMENT
WWW address: http://www.aiub.unibe.ch/ionosphere.html       COMMENT
FTP address: ftp://ftp.unibe.ch/aiub/CODE/                  COMMENT
WARNING: USE DATA AT NORTHERN POLAR REGION WITH CARE        COMMENT
    2.1445D-08  1.0698D-08 -3.9058D-07  6.1989D-07          ION ALPHA
    1.4653D+05  2.7111D+05 -6.6384D+05  2.7363D+06          ION BETA
                                                            END OF HEADER
```

Figure 4: Example of CODE GIM (CGIM) RINEX file containing ionospheric alpha and beta coefficients, as taken from ftp server.

3.5 Setting a Visualized Example

In this section, a series of figures is presented to make the various ionosphere products more real and to illustrate the ionosphere parameter adjustment method introduced in Section 3.3. The following example is not based on predicted data but on final data in order to be able to compare CODE IONEX data, at least in an exemplary fashion, to two further GIM products created by IGS ACs. Figure 5 shows a particular snapshot of the global TEC distribution for June 25, 2000. To be more precise, it is the seventh, or the 13:00-UT snapshot extracted from IONEX data as produced by CODE. Contour lines are given every 10 TECU. TEC reached on this day a maximum value above 80 TECU, producing in the worst case a zenith time delay of approximately 45 nanoseconds on the L1 frequency. The dotted line indicates the geomagnetic equator, the locus where ϕ_{m}

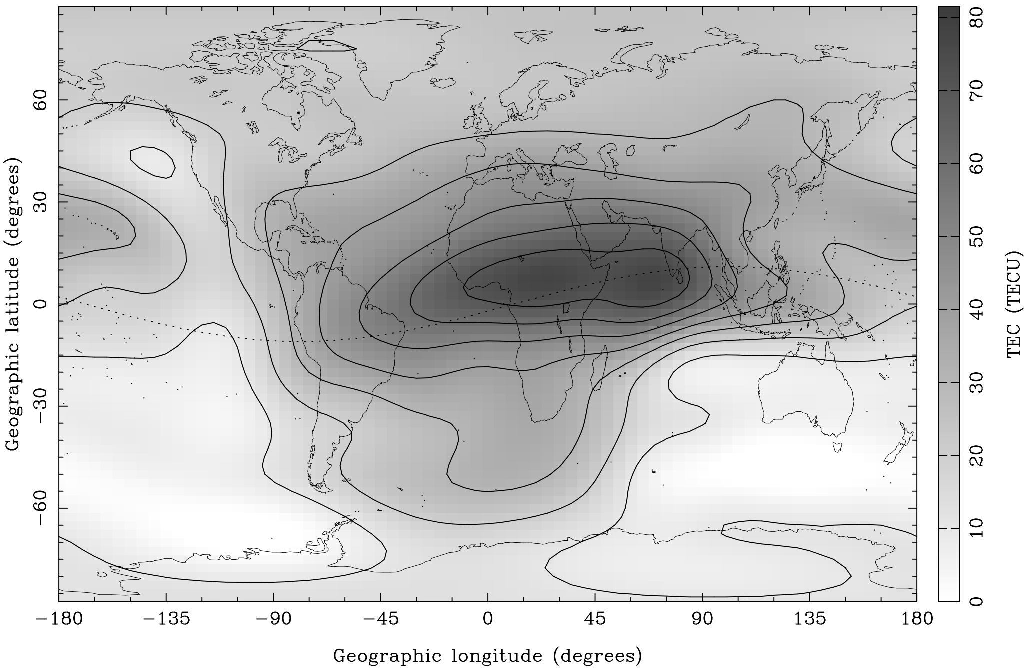


Figure 5: 13:00-UT snapshot of the global TEC distribution for June 25, 2000, extracted from IGS IONEX data as produced by CODE.

of Eqn. (4) equals zero. For comparison purposes, analogous snapshots are shown in Figures 6 and 7. Figure 6 shows the corresponding snapshot as produced by the JPL group [*Mannucci et al.*, 1998]. Figure 7 shows the corresponding result of a weighted average based on five IGS GIM contributions. This (preliminary) combined GIM product is generated in a weekly rhythm by the ionosphere combination center of the IGS, namely at ESA/ESOC in Darmstadt, Germany [*Feltens*, 1999]. Since the CODE GIM contribution flows in general with a significant weight into the IGS ionosphere combination, the combined GIM in Figure 7 is not quite independent of the CODE GIM shown in Figure 5. Figures 5, 6, and 7 all indicate a striking feature: the TEC level at this time is indicated to be generally much higher on the northern hemisphere than that one on the southern hemisphere.

Before presenting the resulting Klobuchar-type GIM, it should be called to mind again that optimum fit is sought not only with respect to a single IONEX map but to an ensemble of 12 maps as a whole, remembering that each IGS-conform IONEX file provides maps at 01:00, 03:00, 05:00, ..., 13:00, ..., 23:00 UT. This may explain possible, visually detectable deviations when comparing Figure 8, which shows the best fitting Klobuchar-type GIM as obtained for June 25, 2000, with Figure 5, which shows solely one of overall 12 CODE IONEX maps considered. Figure 9 finally shows the global TEC distribution as prognosticated by the GPS system for June 25, 2000. The snapshots in Figures 8 and 9 are once more referred to 13:00 UT. It is clear, however, that both the Klobuchar model and our model derivate might be used to create directly, without any interpolation, snapshots referring to any day times, as they describe—viewed from

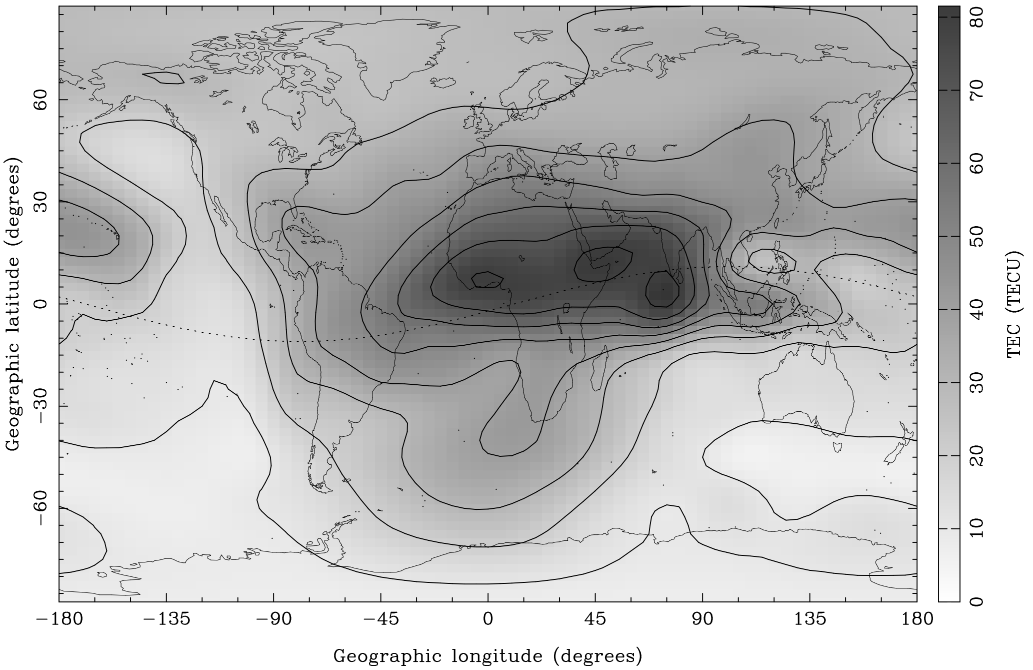


Figure 6: 13:00-UT snapshot of the global TEC distribution for June 25, 2000, extracted from IGS IONEX data as produced by the JPL group.

a solar-geomagnetic frame—a stationary TEC distribution. The north-south disproportion in the TEC distribution as observed in Figures 5 to 7 is still reflected in Figure 8. It is less pronounced in Figure 9. Comparing the maximum TEC values of about 60 TECU for our IONEX fitting model derivate and of about 45 TECU for the Klobuchar model, one may conclude that the Klobuchar model underestimates the prevailing TEC on this day. By the way, one may expect the differences between IONEX fit results considering CODE final or other IGS GIM data to be inconsiderable. It is appropriate to mention here that our predicted Klobuchar-type information does basically reflect, due to the establishment, the main features as they are implied by rapid GIM data. The mentioned TEC distribution anomaly, for instance, would be reproduced by the predicted information for this day.

3.6 Problems Related to the Klobuchar Ionosphere Model

It is worth dedicating a separate subsection to problems and issues which may become relevant when applying the Klobuchar ionosphere model, or especially when performing related model parameter adjustment. Two problems have been already addressed in Sections 3.1 and 3.3. Model-based corrections can never meet the truth completely, but that is not the point. One requirement, however, is basic, under certain circumstances even vital: based on a common set of model parameters, correction functions should be continuous in their arguments. In case the Klobuchar ionosphere model is applied strictly following the GPS ICD instructions as specified in [*Rockwell International Corporation*, 1993], this requirement is definitely not fulfilled. For a hand-held GPS C/A code receiver

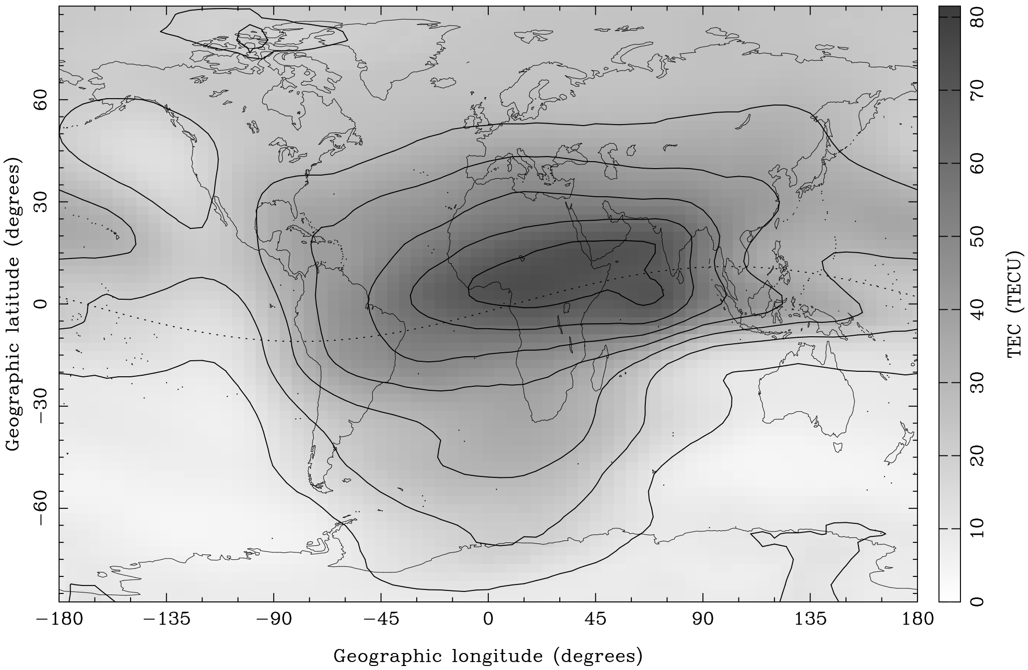


Figure 7: 13:00-UT snapshot of the global TEC distribution for June 25, 2000, extracted from (preliminary) IGS-combined ionosphere product as generated at ESA/ ESOC, Germany.

operating in a epoch-by-epoch mode, this may be irrelevant. For applications where L1 carrier phase measurements are complimentary used, in particular in applications where the GPS surveying technique is employed in an interferometric manner aiming at highest relative accuracy, any discontinuities may be a crucial factor and may in the worst case harm the data evaluation. Nevertheless, the use of adequate ionosphere models is particularly recommended for small-area high-precision GPS arrays, where differenced L1 carrier phase data in conjunction with such a model (eliminating the ionosphere-induced scale bias) often does a better job than ionosphere-free dual-band data (manifesting a roughly three times increased measurement noise characteristics).

It is easy to understand that the situation concerning discontinuity problems gets even worse for our IONEX fitting procedure, keeping in mind that partial derivatives have to be computed there numerically. We are therefore forced to avoid each discontinuity in the Klobuchar TEC distribution function system. We start the following listing with some basic problems and continue then with various difficulties which are connected to the ionosphere parameter adjustment procedure.

- The GPS ICD instruction stipulates that $0 \leq \mathrm{LT} < 86400$ seconds should hold for the resultant local time of Eqn. (7). We cannot agree to this specific rule. We postulate the condition $7200 \leq \mathrm{LT} < 93600$ seconds to get a LT argument the entered around 50400 seconds and to get finally from Eqn. (8) a phase argument x centered around zero. Specifically, we draw the following guideline being contrary to the GPS ICD document: if $\mathrm{LT} \geq 93600$ seconds, subtract 86400 seconds; if

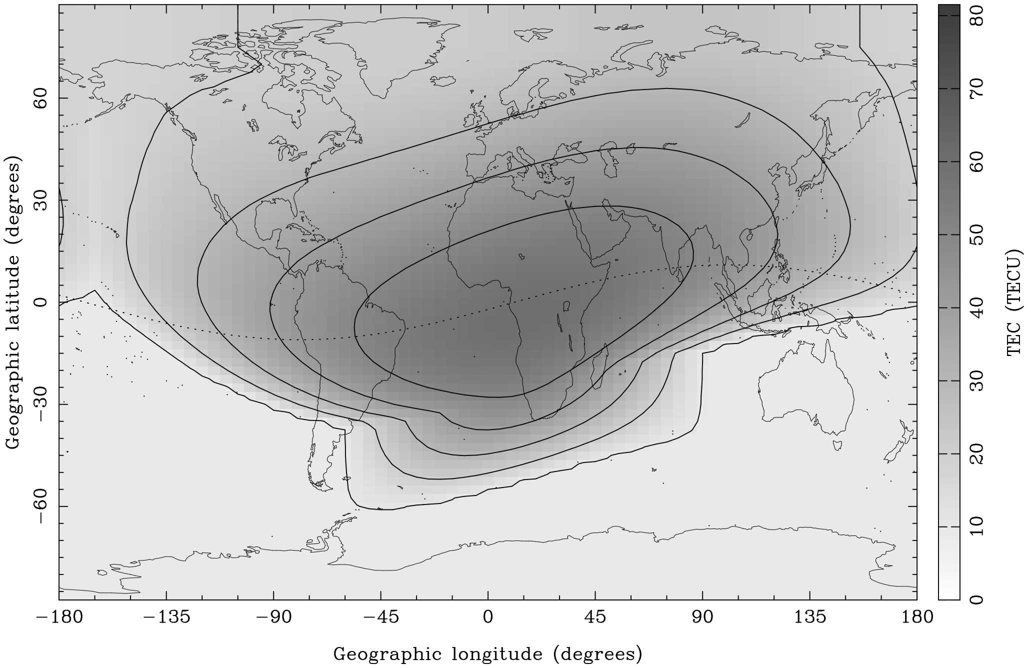


Figure 8: 13:00-UT snapshot of the global TEC distribution for June 25, 2000, reconstructed from ionospheric model coefficients generated by CODE.

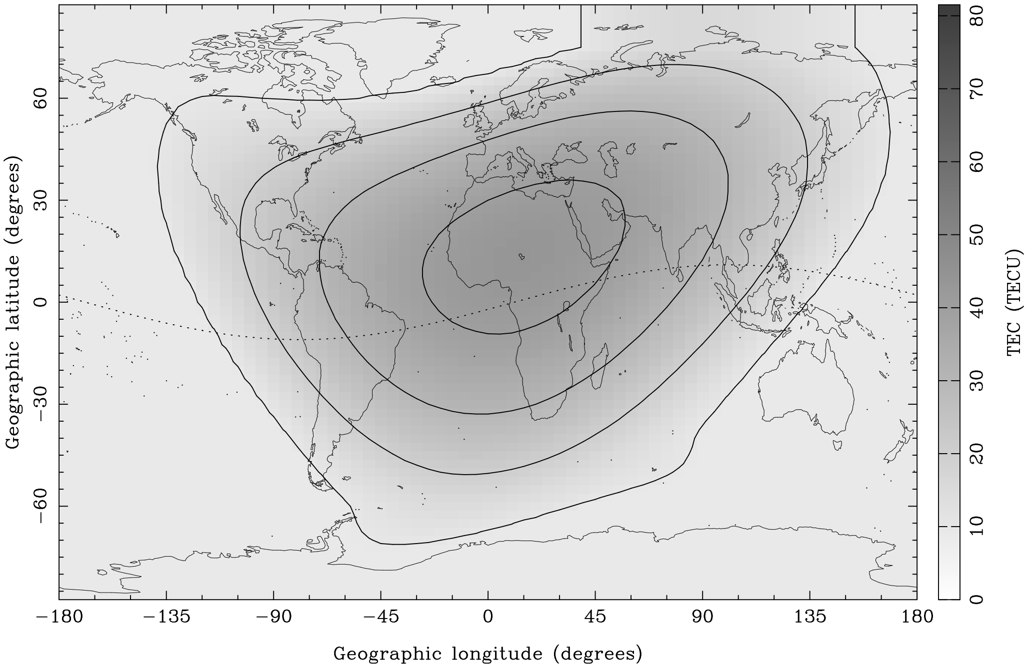


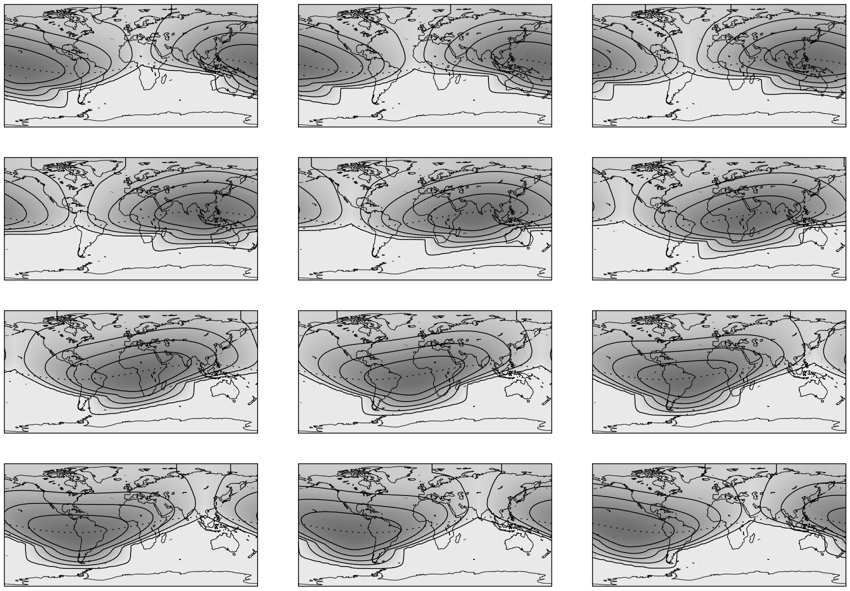
Figure 9: 13:00-UT snapshot of the global TEC distribution for June 25, 2000, reconstructed from ionospheric model coefficients broadcast by the GPS system.

LT < 7200 seconds, add 86400 seconds. Our suggestion is supported by Figure 10. This figure shows a series of two-hourly snapshots of the global TEC distribution reconstructed from CGIM model coefficients when truncating the LT argument in the two different ways. The snapshots of the top subfigure (a) indicate no discontinuities, whereas those of the bottom subfigure (b) exhibit a remarkable break at 00:00 (or 24:00) LT. The TEC distribution reconstructed following the GPS ICD actually differs at local times between 00:00 and 02:00. The reason is obvious: an incorrectly reduced x argument may be misinterpreted by Eqn. (9), namely if the PER variable exceeds 40 hours, or 144000 seconds. Such a big PER value may occur not only if adjusted, real-valued CGIM coefficients are used but also in the case a set of the 370 sets of the discrete base coefficients considered by the GPS MCC are taken into account. In fact, values even bigger than 48 hours, or 172800 seconds, the threshold value where the constant night-time TEC level does no longer take effect, are possible for both kinds of model coefficients. (Remark: The seventh snapshot of Figure 10a corresponds to the one depicted in Figure 8.)

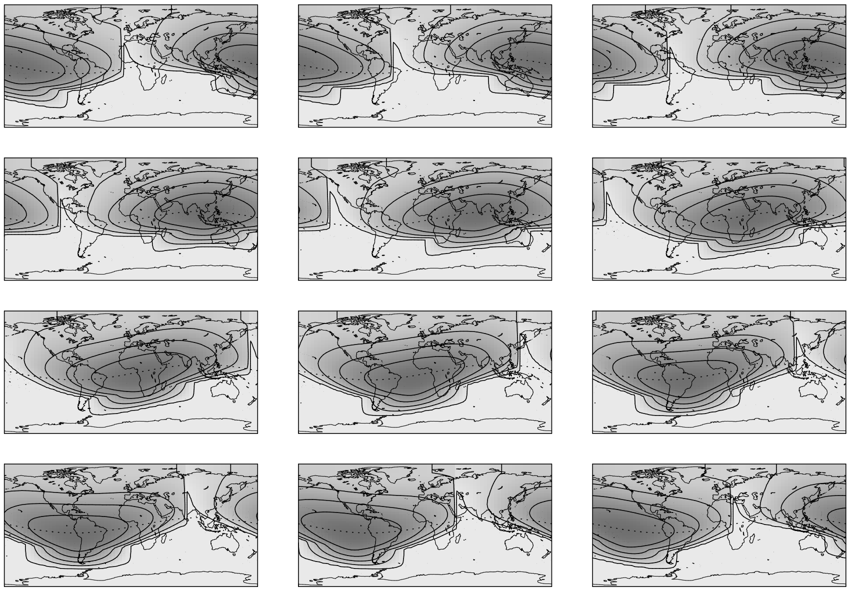
- Eqn. (9) has potential for a further discontinuity problem. In our opinion, it does not make sense to use in this equation a threshold value of $|x| = 1.57$, because this value does actually not agree with the roots of the truncated polynomial expansion set on the cosine function. The jump to be expected at $|x| = 1.57$ amounts to rather exactly two percent of the effective amplitude (AMP). As a consequence of this, we recommend to use either (a) the original fourth-order polynomial representation in combination with a threshold value of

$$|x| = \sqrt{6 - \sqrt{12}} \approx 1.59, \tag{13}$$

  the positive root value of this approximation, or alternatively (b) the true cosine function then in combination with the given threshold value of $\pi/2 \approx 1.57$. We follow solution (a). This is confirmed by Eqn. (12). However, solution (b) has to be regarded as “legal” too, since this solution seems to be very popular.
- Associated with the parameterization, the Klobuchar TEC representation may be unpleasant at high latitudes, namely if $|\phi_\mathrm{i}| > 0.416$ semi-circles (approximately 75 degrees). The reason for the strange truncation of ϕ_i as demanded in Eqn. (2) is not really obvious. Probably, the variable ϕ_m shall be kept within certain limits, as this truncation does guarantee that ϕ_m never exceeds $+/-0.480$ semi-circles. The related problem becomes definitely relevant at the geographic (not geomagnetic) poles, provided that AMP > 0 is valid there. This can be true for the original Klobuchar model, too (see Figure 9). In such a case, it is unavoidable that the amount of the correction evaluated at the concerned pole is ambiguous, depending on the longitude argument considered. For this reason, we display a corresponding warning in our CGIM RINEX files in case the adjusted TEC distribution above a latitude of 75 degrees does reach day-time level. How such a warning may look like can be gathered from Figure 4.
- The hard-wired night-time TEC level of the Klobuchar model gives reason for unnecessary difficulties connected to the ionosphere parameter adjustment. Looking at Figure 2, the reader can recognize that, during periods of low ionospheric activity, the mean global TEC level may fall considerably below the level of 9.2 TECU,



(a) LT argument truncated symmetrically to 14 hours LT



(b) LT argument truncated symmetrically to 12 hours LT

Figure 10: Two-hourly snapshots of the global TEC distribution for June 25, 2000, reconstructed from CGIM ionospheric model coefficients when truncating the local time (LT) argument in different ways: (a) as suggested by the author or (b) as stipulated by the GPS ICD [*Rockwell International Corporation*, 1993].

the constant night-time level of the model. The consequence of this is that the lower the mean TEC level lies the smaller gets the area where day-time TEC takes effect in the adjustment process. An "active" day-time TEC area becoming smaller and smaller may at any time provoke numerical instabilities in the iterative parameter adjustment. If this happens, the solution vector does not properly converge, or, the solution vector can oscillate without end. Solving for a ninth ionosphere parameter responding to the effective night-time TEC level might certainly defuse the situation, but we would be then no longer compatible with the Klobuchar model constantly referencing to. As the compatibility is a declared goal, this would be no acceptable solution of the problem. From experience, we may treat two problems in isolation: a first problem concerns the alpha coefficients α_n, a second problem concerns the beta coefficients β_n. Exceptional oscillations in the solution vector are a reliable indicator for problem (1); problem (2) becomes important as soon as the "equatorial" period, represented by the coefficient β_0, seems to fall below 72000 seconds (20 hours), corresponding to the minimum period allowed by Eqn. (6). We manage the two problem cases independently of each other. In case (1), the fourth, or third-order coefficient α_3 is kept in further iterations artificially on zero, finally solving for a reduced set of alpha coefficients (α_0 through α_2). The risk of a TEC fit tilting up and down (at high latitudes) is drastically minimized having only a quadratic polynomial representation for the amplitude (AMP). In case (2), the first, or zero-order beta coefficient β_0 is subsequently initialized to a value of 72000 seconds, and the remaining beta coefficients, β_1 through β_3, are all set to zero. In view of the "fateful" if-statement in Eqn. (6), it is actually plausible that it does not make sense to solve for beta coefficients in the latter case.

- We must start from the basic assumption that a user of our CGIM model coefficients does follow Eqn. (10) to convert zenith corrections into slant, or line-of-sight corrections. Eqn. (10) is based on a mean ionospheric shell height of 350 kilometers, whereas our correction values are referred to a mean shell height of 450 kilometers above the Earth's surface. Nevertheless, the effect caused by this inconsistency is surely a second-order effect, and consequently this problem can be argued away in this context. There would be in principle an option designed to account for a possible systematic trend by considering a specific scaling factor as part of the IONEX fitting procedure.

This listing is certainly not completing, but it includes the most important problems and issues to be aware of when dealing in detail with the parameterization and the given sequence of calculation steps the Klobuchar ionosphere model relies on.

4 Building Up a Time Series of Ionospheric Coefficients

4.1 Routine Generation of CODE GIM Ionospheric Coefficients

The regular generation of CODE GIM ionospheric coefficients became operational in July 2000. The related analysis steps are embedded in the ionosphere prediction procedure mentioned in Section 2.1. This procedure is passed through each day. It is executed immediately after completion of the standard rapid GIM product. This is normally the case with a delay of well below 12 hours after the daily observation scheme (each ending at 24:00 UT) complied by the IGS ground network. As part of this procedure, GIM data is predicted for two days, the current and the next day. To be more specific, complete sets of spherical harmonics coefficients describing the global TEC distribution are extrapolated by means of least-squares collocation for 24, or two times 12 following two-hour time intervals. The main result of this prediction analysis, two files in Bernese ionosphere format, is subsequently converted into IONEX form which is conform to IGS standards. In this way, it is guaranteed that ionospheric data is at our disposal to serve real-time users without interruption. Finally, the IONEX fitting (INXFIT) program is deployed to generate four daily set of Klobuchar-style ionospheric coefficients, namely based on

- the most recent final IONEX file,
- the last rapid IONEX file, and
- the latest one-day and two-day predicted IONEX files.

Following this concept, (one-day) predicted coefficients can be replaced in turn by rapid coefficients, and eventually rapid coefficients by final coefficients. In contrast to our rapid or final IONEX files, predicted IONEX files do not include rms-error maps, or variance information, of which, if available, we generally make use of in the course of the ionosphere parameter adjustment. In terms of initial values for the coefficients, we do not rely on GPS broadcast values but we use values stemming from the previous day's analysis.

The resulting predicted and rapid Klobuchar-style ionospheric coefficients are made available in form of content-reduced, uncompressed RINEX navigation data files at `ftp://ftp.unibe.ch/aiub/CODE/`. The files are named `CGIMddd0.yyN`, being in accordance with the RINEX file naming convention [*Gurtner*, 1994]. The four-character acronym `CGIM` stands for "CODE GIM" information. `ddd` indicates the three-digit day number of the year; `yy` is the corresponding two-digit year. A suffix "`_R`" is used to distinguish CODE rapid product files. Accordingly, "`_P`" or "`_P2`" denote one-day or two-day predicted files (e. g., `CGIM1940.01N_P2`). The same suffixes are used incidentally for all other CODE product file names, too. All file names are generally provided in uppercase. The final CGIM RINEX files are stored in year-specific subdirectories. For further details, it is referred to Section 4.4 where a complete data archive is introduced.

In addition to actual analysis steps, the mentioned ionosphere prediction procedure involves a series of auxiliary steps, such as creation of graphic output, which are designated to regularly update a web site concerning CODE ionosphere products. This site is accessible at the address `http://www.aiub.unibe.ch/ionosphere.html`. By connecting to `http://www.aiub.unibe.ch/ionosphere.html#cgim`, you get promptly presented a paragraph dedicated to the Klobuchar-style ionosphere product. This paragraph contains among other things a visual comparison of the rapid CGIM information with the ionospheric information originally transmitted by the GPS system for the same day, complemented by a declaration of mean and peak TEC values for both models. It remains important to mention here that a direct link to the latest set of CGIM RINEX files created is offered at this site as well.

4.2 Full Reprocessing of CODE Final IONEX Data

Remembering Figure 2 showing the mean TEC as it evolves on a global scale, an uninterrupted ionospheric time series of several years is at our disposal. The length of this time series, the start of which is at the beginning of 1995, is increased meanwhile to more than six and a half years. As the corresponding GIM data is available in IONEX form, too, the effort has been made to carry out a full reprocessing of the CODE final IONEX data. IONEX, however, was developed and established not until 1998. It should therefore be mentioned that the availability of older GIM data in IONEX comes from an earlier effort made in 1998 to produce IGS-conform IONEX counterparts from all accumulated Bernese-formatted CODE ionospheric files (containing global information).

Our reprocessing plan would depend in theory on only one set of Klobuchar model coefficients required to initialize the ionosphere parameter adjustment. We did without a reprocessing proceeding backwards. Because we have somehow or other an interest in old sets of Klobuchar model coefficients, we decided to perform the reprocessing in yearly batches executed in parallel (each asking for a-priori model coefficients with respect to the first day of the year). To find old GPS broadcast ionospheric data—that besides is proper—turned out to be a tricky thing, however. Because there is no "official" data archive concerning GPS broadcast information, we availed us of RINEX navigation data as recorded by the IGS ground network and finally collected by the IGS data centers. We first concentrated on using concatenated RINEX navigation data files that a few IGS data centers generate by merging the content of all available (station-specific) RINEX navigation data. Such concatenated RINEX navigation data files are provided, e. g., by CDDIS (Crustal Dynamics Data Information System, located at NASA GSFC, Greenbelt, Maryland, USA) and by BKG (Federal Office of Cartography and Geodesy, Frankfurt am Main, Germany). The current ftp addresses of these and further IGS data centers can be found through the information system maintained by the IGS central bureau (CB). (This information system can be accessed via `http://igscb.jpl.nasa.gov`.) The concatenated RINEX navigation data files created by CDDIS and BKG (formerly IfAG) are indicated with the four-character abbreviations `BRDC` and `IFAG`, respectively.

In the end, we must experience that the majority of station-specific IGS RINEX navigation data files did contain incorrect values for the ionospheric alpha and beta coefficients! We may state more precisely that, at that time, RINEX files from only a handful of stations were unaffected by this problem. The disagreements we complained about turned out afterwards to be an immediate consequence of a RINEX convert problem. Consequently, also concatenated RINEX files may contain defective ionospheric information, meaning that care is needed if you have in mind to revert to any GPS broadcast ionospheric information archived by IGS data centers. This is an unpleasant situation, but it may be understood since this piece of (broadcast) information was regarded within the scope of the IGS service as far as a "nuisance." Nevertheless, the IGS community drew attention to this unfortunate circumstance. The situation in terms of incorrect ionospheric alpha and beta coefficients nowadays seems to be much improved.

The time series of original Klobuchar model coefficients we make use of in this work consists for the most part of data provided by the Department of Radio Engineering of the Czech Technical University, Prague, Czech Republic. This group started to collect the values of these coefficients in April 1994.

4.3 Discussion of the Retrieved Time Series Results

Figure 11 gives an impression of the mean TEC of the ionosphere derived from three types of GIM representations: following the legend, GPS broadcast model coefficients (solid line), CODE generated model coefficients (gray line), and CODE IONEX reference (light line), from which the CODE generated model coefficients have been deduced (see also Figure 2). Although the time series indicated by the solid line is at times incomplete, in particular in the past, one may draw the conclusion that mean TEC based on GPS broadcast coefficients develops like a step function. This behavior can be attributed to the fact that these coefficients may remain unchanged over some days. The CODE-GIM curve can follow the CODE-IONEX (reference) curve not until the end of 1997, because of the hard-wired night-time TEC level of the (Klobuchar) model, indicated by

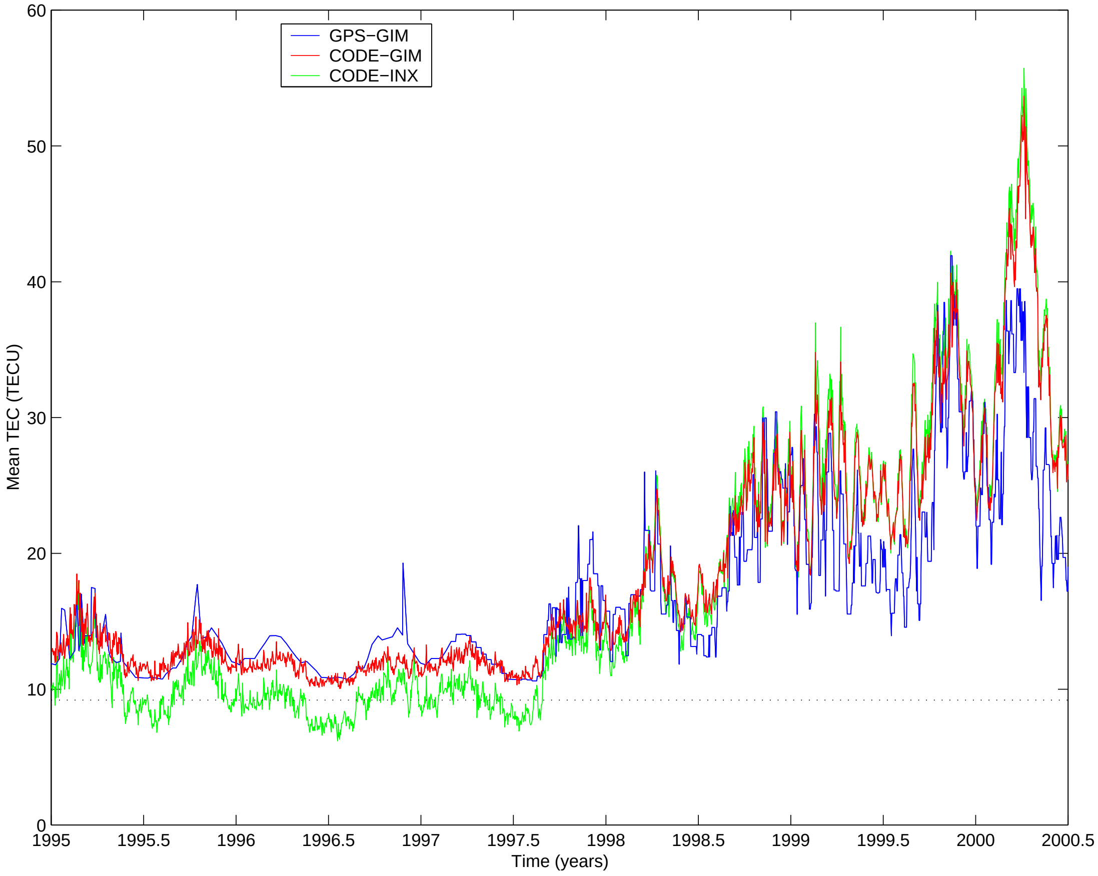


Figure 11: Mean TEC of the ionosphere derived from GPS broadcast model coefficients, CODE generated model coefficients, and CODE IONEX reference, compared from 1995.0 to 2000.5.

the dotted line at 9.2 TECU. This means that the CODE-GIM curve can, by definition, not undershoot the dotted line. And since we are looking for Klobuchar-style GIM representations best fitting not CODE-IONEX mean TEC but entire CODE-IONEX TEC maps, it is understandable that there is a tendency to overestimate the mean TEC level during a period of low ionospheric activity (because there is always a significant daytime maximum to be compensated). Here, we encounter one of the problems related to the Klobuchar model, the "low-activity" problem, which has been already highlighted in Section 3.6. It is therefore easy to comprehend that GPS broadcast ionospheric information also tends to globally overestimate the TEC level during low-activity periods. During high-activity periods, however, the situation seems to be rather opposite. There, the GPS-GIM curve reveals the tendency to underestimate the global TEC distribution. This weakness is particularly evident under extraordinary high-activity conditions, as they could be registered, e. g., in March 2000, where the GPS-GIM curve just is not able to follow the two other curves.

The controversial issue whether a better fit could be managed on the 370 possible sets of base coefficients remains unsettled. If that would be the case actually, revealing a "high-activity" problem, so to speak, that would be a substantial drawback of the Klobuchar ionosphere model, or intrinsically of the sets of base coefficients available to the GPS MCC. We would be capable to answer this question, of course, if we would possess all sets. Unfortunately, this end is not yet realized. Based on more than five years of GPS broadcast ionospheric data, we can recover approximately 70 percent of the 370 sets. The intermediate question may come up whether it is easily possible to retrieve the complete palette of base coefficients, based on 70 percent, which is indeed a remarkable percentage. For this purpose, we plotted the values concerning the various coefficients versus day of the year. Such plots showed, however, constant levels following logarithmic scales and a plainly visible "fuzziness," which make it impossible for us to intuitively identify a logic behind the generation of the 37 times ten groupings of constants (responding to seasonal effects and different solar flux classes, respectively). The whole matter in terms of these constants seems to be fairly veiled.

Nevertheless, globally viewed, we have to recognize how well the GPS broadcast ionospheric coefficients do mirror short-term variations in the global TEC distribution. This is principally due to the very high correlation between 10.7-cm solar flux and global TEC measurements (see, e. g., [*Schaer*, 1999]). Keeping in mind that the GPS-GIM curve originates in essence solely in 10.7-cm solar flux measurements, that is, no actual TEC measurements are involved, we have to appreciate the still remarkable model performance with respect to the "original" ionospheric coefficients as established by the GPS MCC.

The characteristics of the daily values/estimates concerning GPS broadcast and CODE generated ionospheric model coefficients are shown individually in Figures 12 and 13. The related plots show the two time series from epoch 1997.0 to epoch 2000.5 using the same color code as used in the one of Figure 11. The results are labeled in original units of seconds/semi-circles^n, depending on the coefficient index n. By visually assessing the correlation between the two types of model coefficients on the basis of these plots, we may establish a significant correlation with respect to the model coefficients α_0, α_1, β_0, as well as β_1, whereas no correlation is obvious for the higher-order coefficients

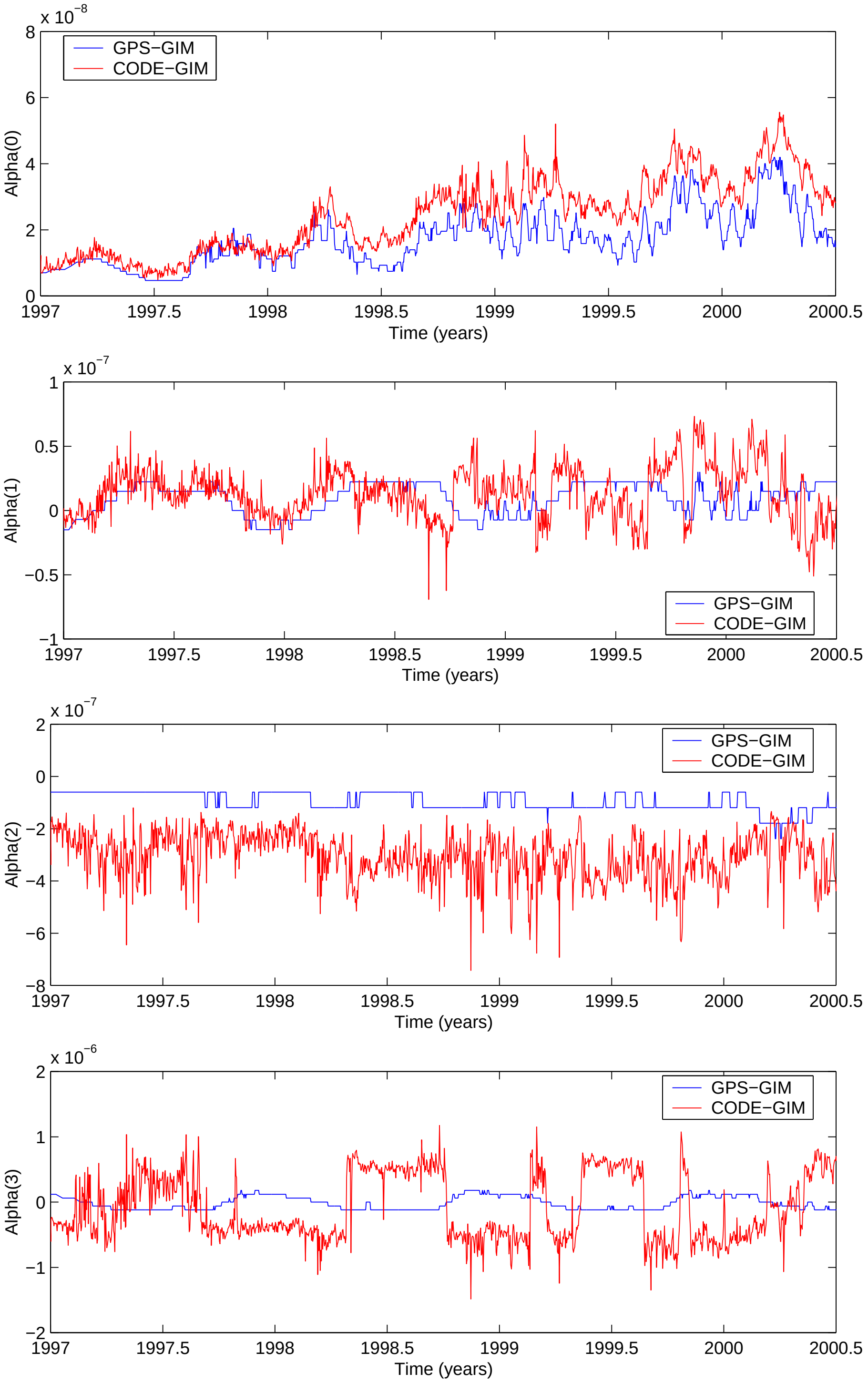


Figure 12: GPS broadcast and CODE generated ionospheric model coefficients α_0, α_1, α_2, and α_3, plotted from 1997.0 to 2000.5.

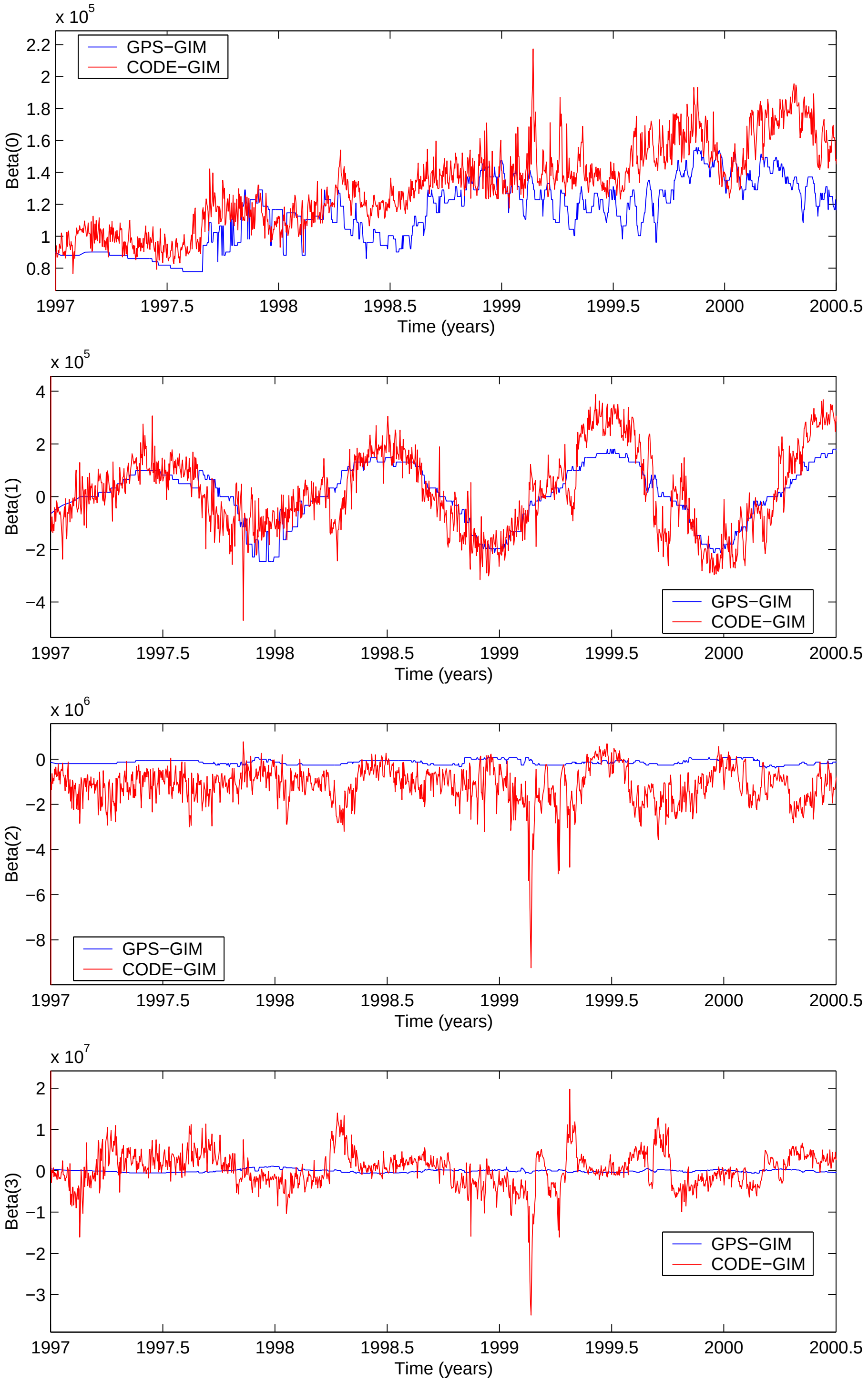


Figure 13: GPS broadcast and CODE generated ionospheric model coefficients β_0, β_1, β_2, and β_3, plotted from 1997.0 to 2000.5.

α_2, α_3, β_2, and β_3. The correlation with respect to α_1, however, seems to be present under low-activity conditions only.

The way of the GPS MCC is operating the eight "switches" is particularly obvious for α_1 through α_3 shown in Figure 12. On that score, the behavior of α_2, manifesting in our sample only four levels, is specially funny. In fact more important to us is the realization that our estimates do exceed the value range covered by Klobuchar's constant levels with respect to each model parameter. This realization indicates that a worse fit should be expected if we would intend to permit exclusively these constant levels in the model parameter adjustment.

Let us close this discussion with an annotation of the the resulting time series of each model parameter on the basis of Figures 12 and 13. Concerning α_0, the equator-related amplitude, a very high correlation between the two curves may be noticed. Annual, semi-annual, as well as 27-day variations are dominant. The GPS values, however, tend to be systematically smaller than the CODE estimates. α_1, describing a linear portion of north-south asymmetry of the amplitude, shows similar variation characteristics. The initially existing correlation seems to vanish, however, as soon as a certain activity level is reached. The CODE estimates for α_2 and α_3, describing higher-order portions of the asymmetry, deviate considerably from the GPS values. Whereas those for α_2 are systematically off, those for α_3 reveal a clear tendency to bounce following a half-yearly rhythm. Corresponding jumps usually happen around the equinoxes. This odd behavior must be associated with the "high-latitude" problem mentioned in Section 3.6. By the way, a negative correlation concerning α_3 can somehow not be denied. Let us lastly address the plots shown in Figure 13. The CODE estimates for β_0, the equator-related period, turn out to be generally longer, compared with the GPS values. The correlation is not as high as it could be noticed concerning α_0. The results for β_1, giving a linear trend of the north-south change of the period, are once again strongly correlated. Both curves follow each other amazingly well. The pronounced annual variation is the effect of the varying Sun's declination, causing minima and maxima at solstices. Accordingly, zero passages may be observed around equinoxes. Unlike the CODE estimates for β_1 that exhibit further signal shares, the GPS values are obviously more conservative. The situation concerning β_2 and β_3 is similar to the one portrayed in terms of α_2 and α_3. It remains to remark, that the corresponding CODE estimates are far away from complying with a random noise signal.

4.4 Data Archive

As a result of the full reprocessing that has been accomplished as part of this work, the CODE analysis center is able to offer a unique, continuous time series of (final) CGIM RINEX files containing improved Klobuchar-style ionospheric coefficients starting with January 1, 1995. The file naming for these files coincides with that complied for the rapid and predicted CGIM RINEX files (see Section 4.1), with the exception of the suffix, which is in this case "`.Z`," indicating binary-compressed files. The final product files are stored in year-specific subdirectories, one level below the top directory of CODE's anonymous ftp environment, more precisely at `ftp://ftp.unibe.ch/aiub/CODE/yyyy/`, denoting the four-digit year with `yyyy`. To give an example, we include the precise ftp address for downloading the CGIM information for June 25, 2000, as it has been visualized in Figure 8, or Figure 10. It reads `ftp://ftp.unibe.ch/aiub/CODE/2000/CGIM1770.00N.Z`. For the sake of completeness, we include Table 1 summarizing the various CGIM RINEX product files generated by the CODE analysis center. Real-time, or near-real-time users asking for "`CGIMddd0.yyN*`" should find at any time a corresponding file containing up-to-date ionospheric information. It must be pointed out that non-final product files are regularly removed from the ftp archive as soon as the final version gets available. For a complete overview of CODE's products made available through this data archive, the interested reader is referred to [*Hugentobler et al.*, 2001*a*, 2001*b*].

Table 1: CODE GIM (CGIM) RINEX product files available through `ftp://ftp.unibe.ch/aiub/CODE/`.

File name	Product description
`yyyy/CGIMddd0.yyN.Z`	Final CODE GIM results
`CGIMddd0.yyN_R`	Rapid CODE GIM results
`CGIMddd0.yyN_P`	One-day predicted CODE GIM results
`CGIMddd0.yyN_P2`	Two-day predicted CODE GIM results

In August 2000, we began to save GPS broadcast ionospheric information on a daily basis. For this purpose, RINEX navigation data files coming from a well-defined subset of stations is considered for the extraction in order to eliminate corrupted information as it has been advised against in the previous section. However, the restriction to such a subset of stations seems to be slowly but surely needless, associated with corresponding RINEX converter updates taken place within the IGS ground network. The midget RINEX files thus gained are stored separately in an internal data archive. They are available upon special request. The same is, by the way, also valid for older non-final CGIM RINEX product files.

5 Comparisons and Validation

The results of about 60 days, covering days from mid of May to mid of July in 2000, were used to assess the quality of the different types of ionosphere products. As a quality measure we use the overall root-mean-square (rms) difference evaluated with respect to corresponding CODE final IONEX results, supposed in this context to represent the "ground truth." This can be justified because CODE final ionospheric results proved to meet a high quality standard [*Schaer*, 1999]. This claim is also regularly supported by IGS-made comparisons and combinations [*Feltens*, 1999].

The comparisons we carried out were done on the basis of the IONEX interface, ultimately comparing TEC values at grid points. Again, a latitude-dependent weighting scheme is employed to deweight differences referring to densely populated high-latitude IONEX data (see also Section 3.3). Table 2 summarizes the results. Klobuchar, or Klobuchar-style TEC representations are indicated with the mnemonic code "GIM," IONEX representations with "IONEX." The entries are organized according to their

Table 2: Overall root-mean-square (rms) differences for different types of ionosphere products, evaluated with respect to CODE final IONEX results.

Type of product	rms (TECU)
Zero-value model	35.55
9.2-TECU model	28.49
GPS GIM	14.10
Two-day predicted CODE GIM	9.40
One-day predicted CODE GIM	9.28
Rapid CODE GIM	8.89
Final CODE GIM	8.54
Two-day predicted CODE IONEX	5.35
One-day predicted CODE IONEX	5.07
Rapid CODE IONEX	3.30

rms difference values, starting with the biggest value. Hypothetical "zero-value" and "9.2-TECU" model constructs, corresponding to "no" model and "minimum" Klobuchar TEC representation, complement the table to make the noteworthy performance of the "GPS GIM" model clear. Focusing on the GPS and the CODE eight-parameter TEC representations, a significant quality enhancement may be noticed in favor of the CODE products. We estimate the improvement at roughly 35 percent, taking the GPS product as reference. An improvement from the two-day predicted to the one-day predicted product, and from the one-day predicted to the rapid product is clearly detectable, but the corresponding improvement in time is actually marginal. The rms difference of 8.54 TECU associated with final CODE GIM information eventually manifests the limit of the Klobuchar-style TEC representation capability. This limitation may partly explain our observation concerning the relatively slowly decreasing rms. To be complete, the non-final CODE IONEX products are included in Table 2 too. We should once more emphasize that the rms difference values given in this table are overall values, referred to the entire Earth's surface. In particular, if CODE rapid IONEX results are compared with CODE final IONEX results, we should clarify that rms differences pertaining to well-probed areas, such as the areas over Europe or North America, are typically below the one-TECU level.

A related comparison study has been made to investigate the model performance in terms of "regional" Klobuchar-style ionospheric coefficients (optimally fitting the TEC distribution for a certain geographical area). Following a daily time resolution, the relative improvement turned out to be modest, compared with the globally treated counterparts.

6 Summary and Conclusions

We have described a method for generating ionospheric coefficients being compatible with the GPS broadcast, or Klobuchar ionosphere model and the related algorithm as delineated by the GPS ICD [*Rockwell International Corporation*, 1993]. This method takes advantage of high-quality global TEC map information in IONEX form that is routinely derived by the CODE analysis center as final, rapid, as well as predicted products. It is worth mentioning that the ionosphere mapping approach followed at CODE is self-calibrating because satellite and receiver instrumental biases, known as P1–P2 code biases, can be estimated simultaneously with the TEC maps.

Weighted least-squares fitting is used to perform the "compression" of IONEX data into daily sets of ionospheric coefficients supporting the Klobuchar model. The values for the eight ionospheric coefficients, α_0 through α_3 and β_0 through β_3, are provided in the commonly accepted RINEX format [*Gurtner*, 1994], to be more specific, they are output in form of content-reduced RINEX navigation data files. Contrary to GPS broadcast ionospheric coefficients, which are in a certain sense of integer nature, our ionospheric coefficients are not subject to a similar restriction. For this reason, the reservation must be made from our side that a subsequent rounding of the coefficients' values after reading them (for the thinkable purpose to recover their GPS internal 8-bit representation considering the scale factors as listed on page 7) is prohibited. Anyway, we do not have knowledge of such a case.

In addition to the issue concerning the mentioned generalization of our model derivate, which we generally assess as uncritical, several problems which may become relevant when applying Klobuchar's model have been discussed in detail. We advise the user of the model to review his algorithm implementation principally with respect to the two first problem items addressed in Section 3.6. Further problems, such as the "low-activity" problem, are handled directly by the software tool, INXFIT, developed to generate such ionospheric coefficients. This tool is in operation since July 2000 and seems to work very reliably, as no failure could be recorded so far.

Due to a comprehensive reprocessing of CODE final IONEX data that has been carried out as part of this work, we are able to supply the post-processing user with a unique, continuous time series of CODE GIM (CGIM) RINEX files containing improved Klobuchar-style ionospheric coefficients starting with January 1, 1995. The corresponding data archive can be accessed via `ftp://ftp.unibe.ch/aiub/CODE/` (see Sections 4.1 and 4.4 for details). Based on a 60-day comparison study analyzing rms differences with respect to our IGS (final) ionosphere product, their model performance is estimated to be better by roughly a factor of 1.5 than those of the "original" ionospheric coefficients (transmitted as integral part of the GPS broadcast navigation data message). The fact that this factor is not bigger is due to the actually quite noteworthy performance of the GPS broadcast product. The quality differences regarding the different CGIM product stages turned out to be small. Also, this comparison study has clearly shown the limitation of the eight-parameter TEC representation. Even though, we can conclude that under conditions of strong solar activity, the difference between considering a Klobuchar-type ionosphere model and going—in the extreme case—without any model is truly striking.

Let us finally bring the web site dedicated to CODE's ionosphere products to the reader's notice. At `http://www.aiub.unibe.ch/ionosphere.html#cgim`, he may find among other things direct links to the most recent CGIM RINEX files containing improved values for the alpha and beta coefficients, and moreover a brief description concerning the organization of the data archive maintained by CODE. This web site is automatically updated each day in terms of the latest ionosphere-related results coming from the CODE routine analysis.

First results of this work have been already presented in [*Schaer*, 2000*a*, 2000*b*].

7 Outlook

A sort of continuation paper is planned. The main focus of that paper will be directed to the determination and the application of differential code bias (DCB) values related to the GPS satellite constellation. It will be shown that two types of DCB values responding to the differences of P1–P2 and P1–C1 code measurements are sufficient to correct any linear combination (LC) of C1 (C/A), P1, and P2 code measurements, or, vice versa, to make GPS or IGS-produced precise satellite clock corrections, which usually rely on the ionosphere-free LC of P1 and P2, consistent with a specific code observable type. With the exception of the ionosphere-free LC, any other LC is affected by the ionosphere. We will take this circumstance as an opportunity to demonstrate—on the basis of comprehensive (code-based) precise-point-positioning (PPP) analyses—not only the impact of code biases but also the effect of an unmodeled ionosphere and the performance of various ionospheric model products we have presented in this paper. We intend to give our attention specifically to the use of C/A code measurements, being in the single-frequency users' interest.

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