DAILY GLOBAL IONOSPHERE MAPS BASED ON GPS CARRIER PHASE DATA ROUTINELY PRODUCED BY THE CODE ANALYSIS CENTER

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ABSTRACT

The Center for Orbit Determination in Europe (CODE) — one of the Analysis Centers 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 doubly differenced GPS carrier phase observations.

Since January 1, 1996, daily global ionosphere maps are routinely estimated as an *additional* product by analyzing the so-called *geometry-free* linear combination, which contains the information on the ionospheric refraction. The Total Electron Content (TEC) is developed into a series of spherical harmonics adopting a single-layer model in a sun-fixed reference frame. For each day a set of TEC coefficients is determined which approximates the average distribution of the vertical TEC on a global scale.

After re-processing all IGS data of the year 1995, a long-time series of TEC parameters is at our disposal indicating that reasonable *absolute* TEC determination is possible even when applying an *interferometric* processing technique. The global ionosphere maps produced are already used in the CODE processing scheme to improve the resolution of the initial carrier phase ambiguities. Spaceborne applications (e.g. altimetry) may benefit from these rapidly available TEC maps. For ionosphere physicists these maps are an alternative source of information about the *deterministic* and *stochastic* behaviour of the ionosphere, that may be correlated with solar and geomagnetic indices and compared to theoretical models.

CODE TEC MAPPING TECHNIQUE

Let us briefly review the TEC modeling features as developed by (Wild, 1994) and those currently used by the CODE Analysis Center for the global (and regional) applications. GPS-derived ionosphere maps are based on the so-called *single-layer* or *thin-shell* model with a simple mapping function. It is assumed that all free electrons are concentrated in a shell of infinitesimal thickness. The height of this idealized layer is usually set to the height of the maximum electron density expected. Furthermore the electron density E —

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the surface density of the layer — is assumed to be a function of geocentric latitude β and sun-fixed longitude s.

The *local* ionosphere models presented by (Wild, 1994) were described with a two-dimensional Taylor series expansion. Such local TEC models have proved their usefulness on many occasions. Nevertheless, this TEC representation is *not* well-suited for *global* models because of limitations in the (β, s)-space. Therefore we decided to develop the global TEC into spherical functions. We write the surface density $E(\beta, s)$ representing the TEC distribution on a global scale as

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

where

- $n_{\max}$ — is the maximum degree of the spherical harmonic expansion,
- β — is the geocentric latitude of the intersection point of the line receiver–satellite with the ionospheric layer,
- $s = t + \lambda - \pi$ — is the *mean* sun-fixed longitude of the ionospheric pierce point, which corresponds to the local mean solar time neglecting an additive constant π (or 12 hours),
- t — is the Universal Time UT (in radians),
- λ — is the geographic longitude of the ionospheric pierce point,
- $[t_i, t_{i+1}]$ — is the specified period of validity (of model number i),
- $\widetilde{P}_{nm} = \Lambda(n, m) \cdot P_{nm}$ — are the *normalized* associated Legendre functions of degree n and order m based on the normalization function $\Lambda(n, m)$ and the unnormalized Legendre functions P_{nm}, and
- a_{nm}, b_{nm} — are the *unknown* TEC coefficients of the spherical functions, i.e. the global ionosphere model parameters to be estimated.

Another essential modification of our TEC measurement technique has to be emphasized. The CODE Analysis Center of the IGS produces precise orbits and Earth orientation parameters on a daily basis by analyzing the *ionosphere-free* linear combination of doubly differenced phase observations. As a result of this, *cycle-slip-free* portions of L1 and L2 phase observations are readily available for every day. Consequently the *zero*-difference observable was replaced by the *double*-difference phase observable due to operational considerations. We are fully aware of the fact that by using *double*- instead of *zero*-differences we loose parts of the ionospheric signal, but we have the advantage of *clean* observations. Moreover, we are *not* affected by the degradation of the code measurements under the regime of Anti-Spoofing (AS). This advantage may be "lost" when the next generation of precise code receivers will become available. To get more information about the "new" TEC mapping technique we refer to (Schaer et al., 1995).

IMPLEMENTATION INTO THE CODE PROCESSING SCHEME

The computation of Global Ionosphere Model (GIM) parameters has been completely integrated into the Bernese GPS Software (Rothacher et al., 1996a). The scripts to automate the GIM production were prepared at the end of 1995.

Since January 1, 1996, the GIM estimation procedure is running in an operational mode. Several GIM products are derived every day (Rothacher et al., 1996b):

(i) Ambiguity-free one-day GIMs are estimated right prior to the ambiguity resolution step. These GIMs are subsequently used to improve the resolution of the initial carrier phase ambiguities on baselines up to 2000 kilometers.

(ii) Improved GIMs (ambiguity-fixed, with single-layer heights estimated) are derived after ambiguity resolution.

At present, the GIM files containing the TEC coefficients for one day are available with a delay of 4 days.

The main characteristics of the daily GIMs produced by the CODE Analysis Center may be summarized as follows: The *geometry-free* linear combination of double-difference carrier phase observations is processed performing a least-squares adjustment of the observations of the complete IGS network to extract the global TEC information. One observation epoch per 3 minutes is processed using an elevation cut-off angle of at present 20 degrees. Note that — even under AS — *no* restrictions concerning receiver types or satellites have to be made in our approach. The global TEC distribution is represented over 24 hours by spherical harmonics up to degree 8 in a geographical reference frame which is rotating with the *mean* Sun. We adopt a spherical ionospheric shell in a height of 400 kilometers above the Earth's mean surface.

Let us mention that we estimate furthermore *regional* ionosphere maps for Europe based on about 30 European IGS stations in a fully automatic mode since December 1995. These ionosphere maps are used in the processing scheme of the European cluster to support the Quasi-Ionosphere-Free (QIF) ambiguity resolution strategy, too. A description of the QIF strategy is given in (Mervart and Schaer, 1994) and (Mervart, 1995). The European TEC maps are *not* discussed in this article.

Re-Processing of the Year 1995

Supported by the Bernese Processing Engine (BPE), six parallel CPUs, and a powerful data archive system, the re-processing of the entire IGS data set of the year 1995 — GIM products only — could be performed without major problems within eight days.

LONG-TIME SERIES OF DAILY GLOBAL IONOSPHERE MAPS

At present (March 1996), the CODE Analysis Center is processing the data of about 75 globally distributed stations of the world-wide GPS tracking network of the IGS. Figure 1 shows the stations used by CODE.

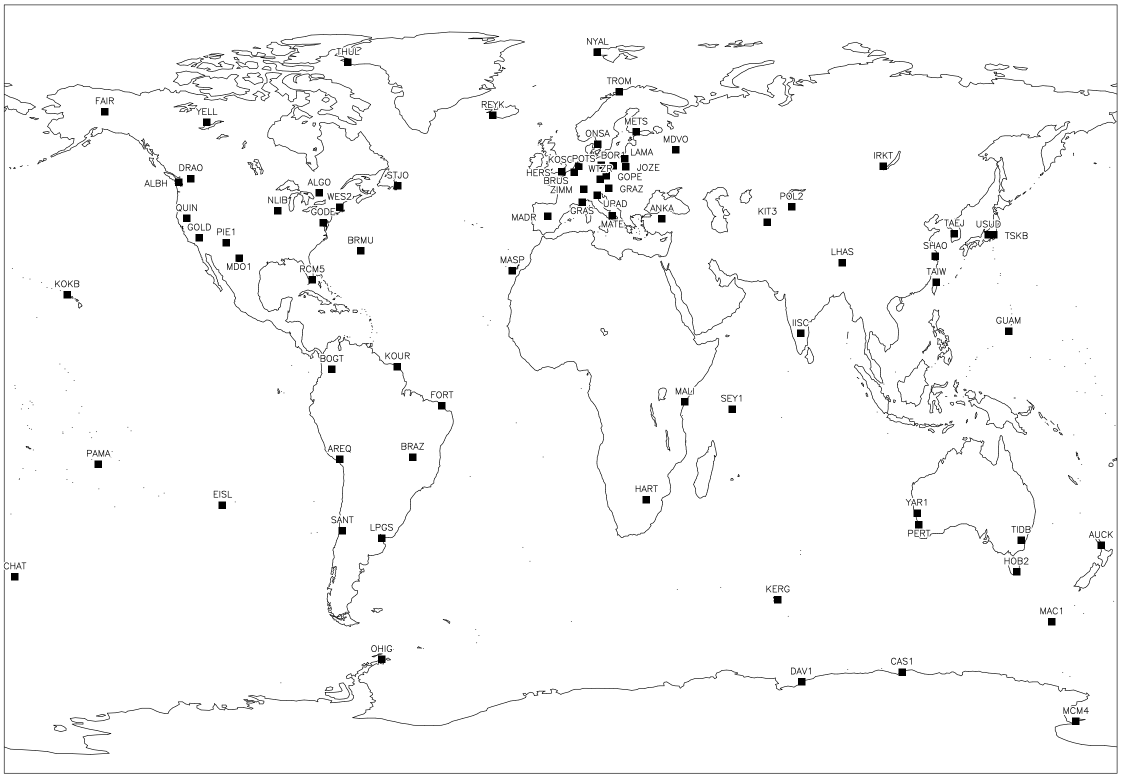

Figure 1. IGS stations used by CODE in 1996.

After re-processing all IGS data of the year 1995 and gathering already generated 1996 GIMs, we may interpret a long-time series of daily global ionosphere maps covering a time span of 427 days, from day 001, 1995 to day 062, 1996 (GPS weeks 782 to 842). This GIM series is represented by thousands of parameters, hence we have to limit the following discussion to few *special* TEC parameters, only.

Important TEC Parameters Describing the Deterministic Part

We already showed in (Schaer et al., 1995) that the zero-degree TEC coefficient a_{00} may be interpreted as the *mean* TEC E_0 per square meter which can be easily converted to the *total* number of ionospheric electrons in the shell. For that reason the quantity E_0 is an excellent parameter to roughly describe the deterministic part of the ionosphere. Figure 2 brings the evolution of the global TEC into focus showing the mean TEC E_0 and, in addition, the *maximum* TEC which has also been extracted from the CODE GIMs. The TEC values are given in so-called TEC Units (TECU), where 1 TECU corresponds to 10^{16} free electrons per square meter. Remember that our one-day GIMs approximate an average TEC distribution over 24 hours, hence our maximum TEC values have to be interpreted accordingly. The three non-AS periods within the time period considered are indicated by dashed lines.

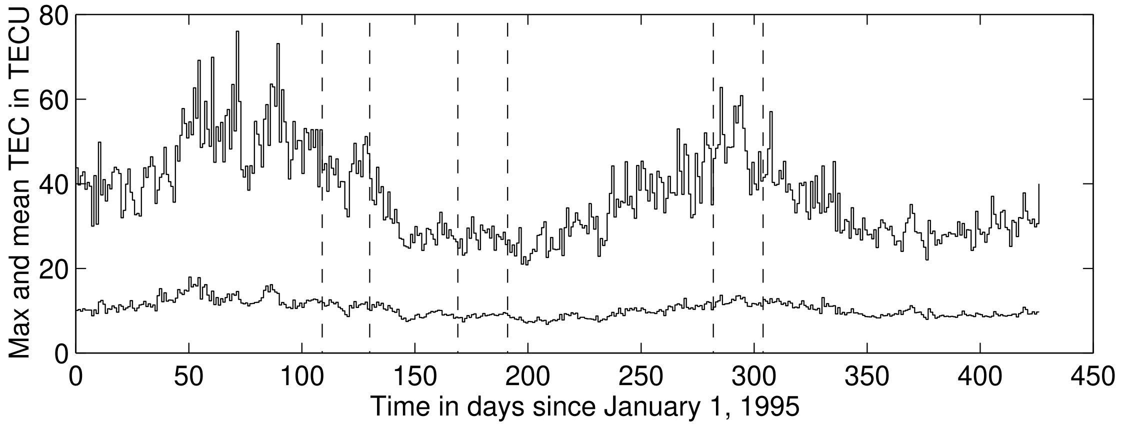

Figure 2. *Maximum* and *mean* TEC extracted from the CODE GIMs roughly describing the *deterministic* part of the ionosphere.

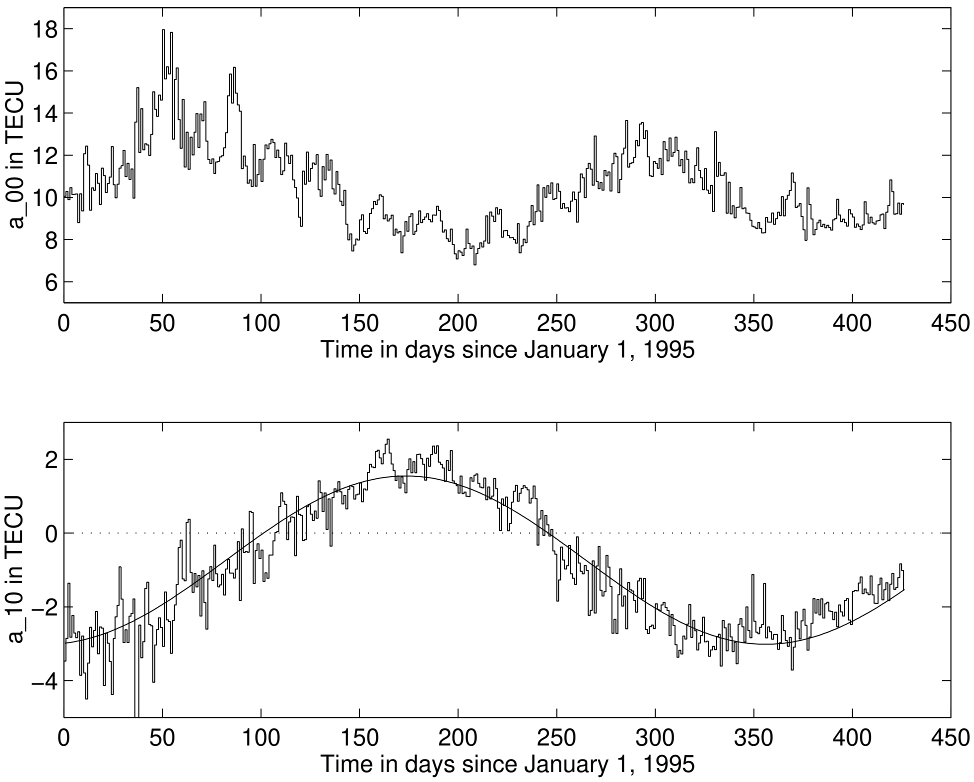

Figure 3. (a) zero-degree TEC coefficient a_{00} (*mean* TEC E_0) and (b) the first-degree coefficient a_{10} which mainly describes the zonal variation.

Figure 3 shows two special TEC parameters of the GIM representation (1) namely the coefficients a_{00} and a_{10}. The zero-degree coefficient a_{00} which corresponds to the mean

TEC E_0 already shown in Figure 2 is plotted in a larger scale here. The variations of the mean TEC even under low-activity conditions is quite impressive. Minima and maxima correspond to 6.8 and 18.0 TECU respectively, or, expressed in number of free electrons, to $3.9 \cdot 10^{31}$ and $1.03 \cdot 10^{32}$ free electrons. The first-degree coefficient a_{10} which describes the latitudinal variation of the global TEC distribution is shown in Figure 3b. The annual variation caused by the inclination of the equatorial plane with respect the ecliptic plane may be seen easily.

A newer example of a CODE GIM (with 64 contributing stations) given in the solar-geographical coordinate system is shown in Figure 4, where the latitude range covered is indicated by two dashed lines. Each individual GIM is parameterized with 81 TEC coefficients.

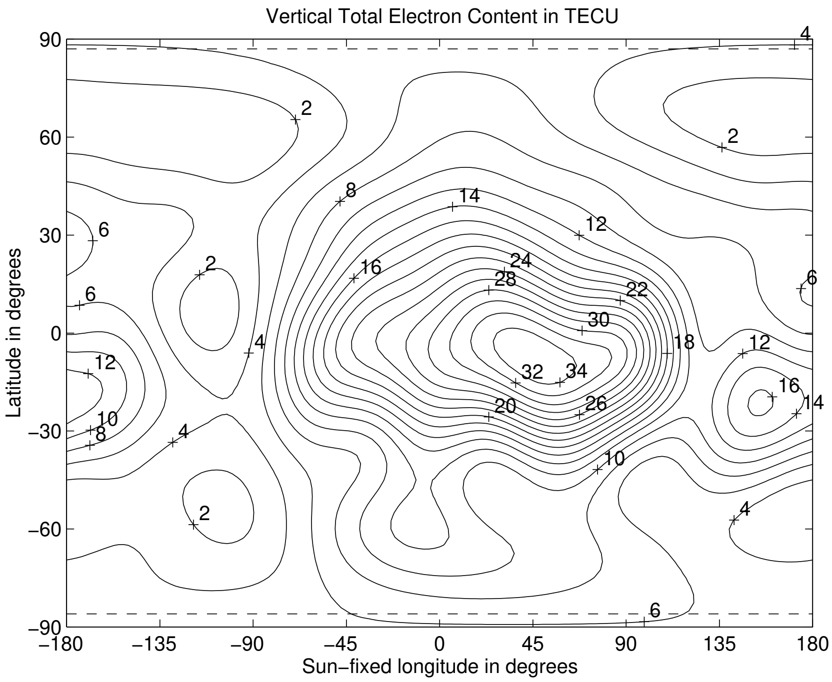

Figure 4. Global Ionosphere Map (GIM) for day 073, 1996.

Derivation of Mean Ionosphere Maps

Let us extract *mean* ionosphere maps — e. g. monthly maps from our daily results. Such maps may be easily derived by averaging the TEC coefficients a_{nm} and b_{nm} over certain time periods. An example is given in Figure 5. Mean GIMs primarily contain average TEC information as visualized in Figure 6 which shows an equatorial cross-section of the mean TEC structure of Figure 5 and in addition the temporal derivative of $E(0,t)$. Here we may recognize for instance that (a) between the end of evening twilight and the beginning of morning twilight the zenith TEC is statistically decreasing with more or less a constant rate or that (b) the maximum TEC is reached at about 2 hours after midday on average, confirming a well known phenomenon.

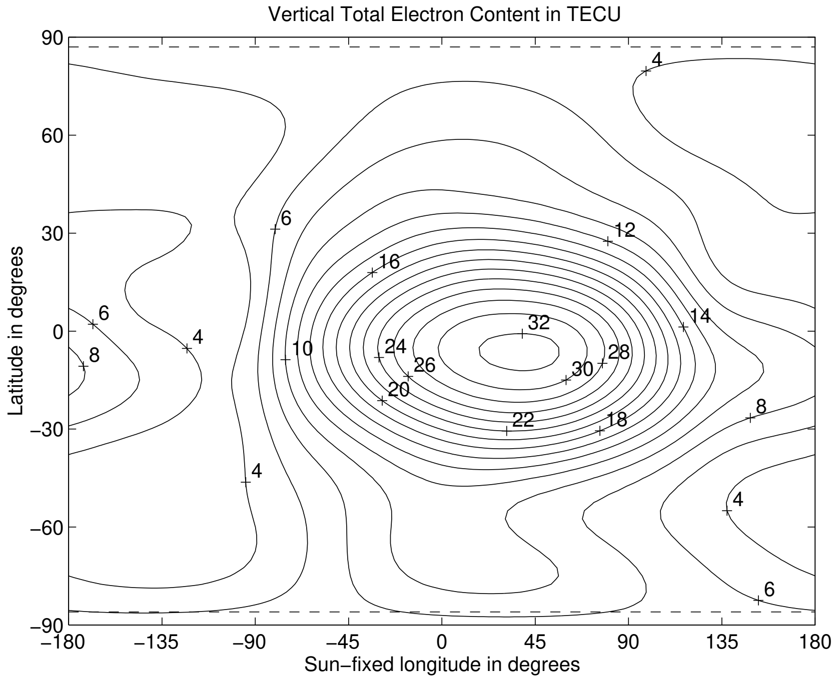

Figure 5. *Mean* global ionosphere map averaged over all 427 days (61 weeks).

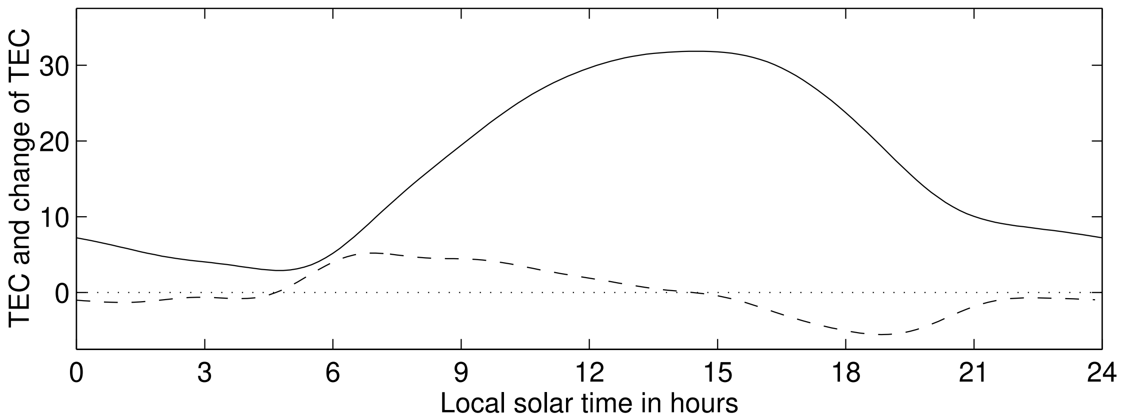

Figure 6. TEC (in TECU) and change of TEC (in TECU/hours) for an average equatorial TEC profile.

Monitoring of the Stochastic Part

At present only one parameter describing the "agitation" of the ionosphere is at our disposal, namely the a posteriori RMS error of unit weight of the least-squares adjustment, which mainly reflects the ionosphere-induced noise of the geometry-free phase observable caused by ionospheric disturbances. The resulting RMS values converted from meters to units of TECU are shown in Figure 7. Notice that we cannot detect any jumps in the evolution of this quantity at the boundaries of the three non-AS periods indicated by dashed lines. This fact again confirms that the quality of CODE GIMs is *not* affected by Anti-Spoofing.

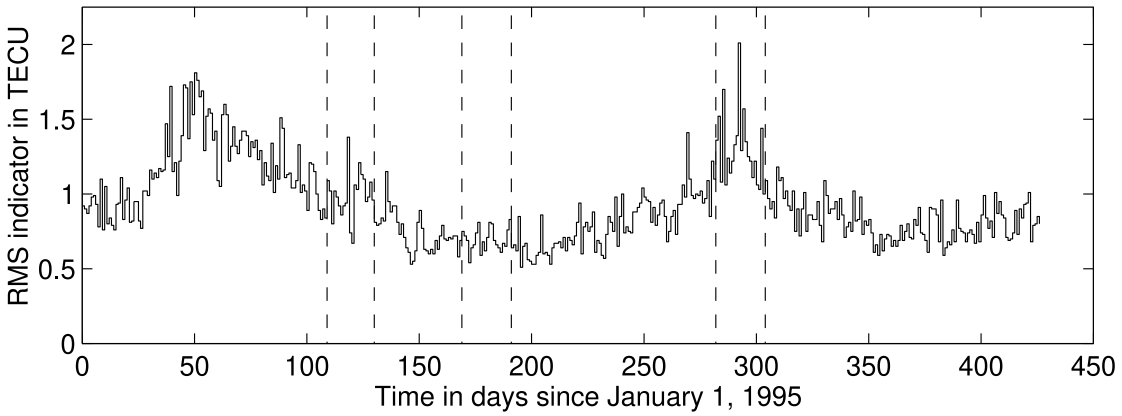

Figure 7. RMS indicator, characterizing the *stochastic* part of the ionosphere on a global scale.

Estimation of Global Shell Heights

We mentioned already that we also derive global ionosphere models where in addition to the TEC coefficients the shell height of the ionosphere is set up as an unknown parameter. In this case the parameter estimation problem is no longer a linear one, which means that we have to improve the GIMs iteratively starting from an initial adjustment. Our daily estimates of the shell height are shown in Figure 8. The dotted line indicates the a priori value used and the solid line shows a linear approximation which lies significantly above the 400-kilometer level generally adopted. We recognize a small linear trend, but this should be interpreted with care because it is based on a trivial shell height model and a mapping function which has to be refined. General considerations concerning the shell height may be found in (Komjathy and Langley, 1996).

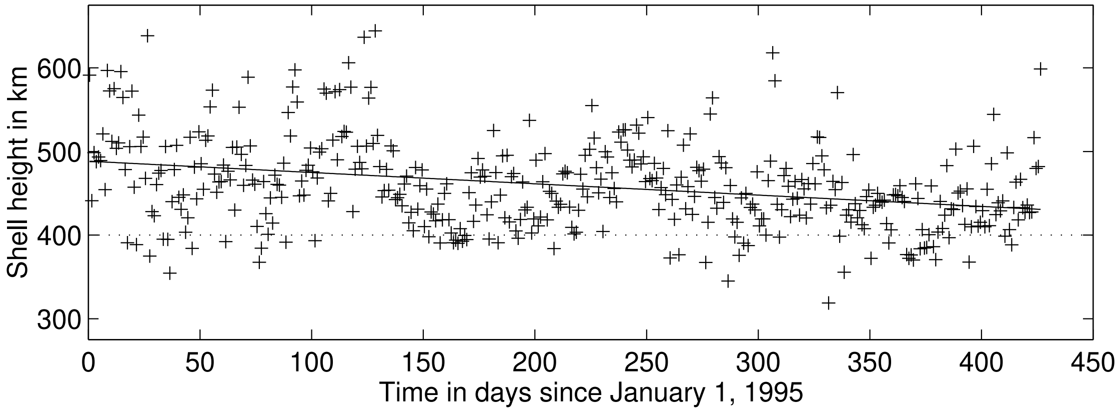

Figure 8. Daily estimates of a common shell height.

Correlation With Solar and Geomagnetic Indices

We may now correlate our TEC coefficient series with solar and geomagnetic indices like *Sunspot number*, *solar radio flux number*, *Kp index*, *Ap index*, etc. This has not been done in detail yet, but we may summarize that

(i) the dominant double peak within the time span analyzed (see Figures 2 and 9a) is recognizable in solar and geomagnetic parameter series as well (see Figures 9b to 9e),

(ii) the times of increasing or decreasing *mean* TEC are highly correlated with the times where the solar activity level changes (see Figures 9b and 9c),

(iii) when performing a spectral analysis the evolution of the mean TEC shows a prominent period of 25 to 30 days which comes from the differential rotation of the Sun, and

(iv) our RMS indicator (see Figure 7) representing the *stochastic* behaviour of the ionosphere seems to be well correlated with the Ap index which characterizes the activity of the geomagnetic field.

Finally the GPS-derived mean TEC E_0 and four solar and geomagnetic parameters obtained from the National Geophysical Data Center, Boulder, Colorado, USA are compared in Figure 9.

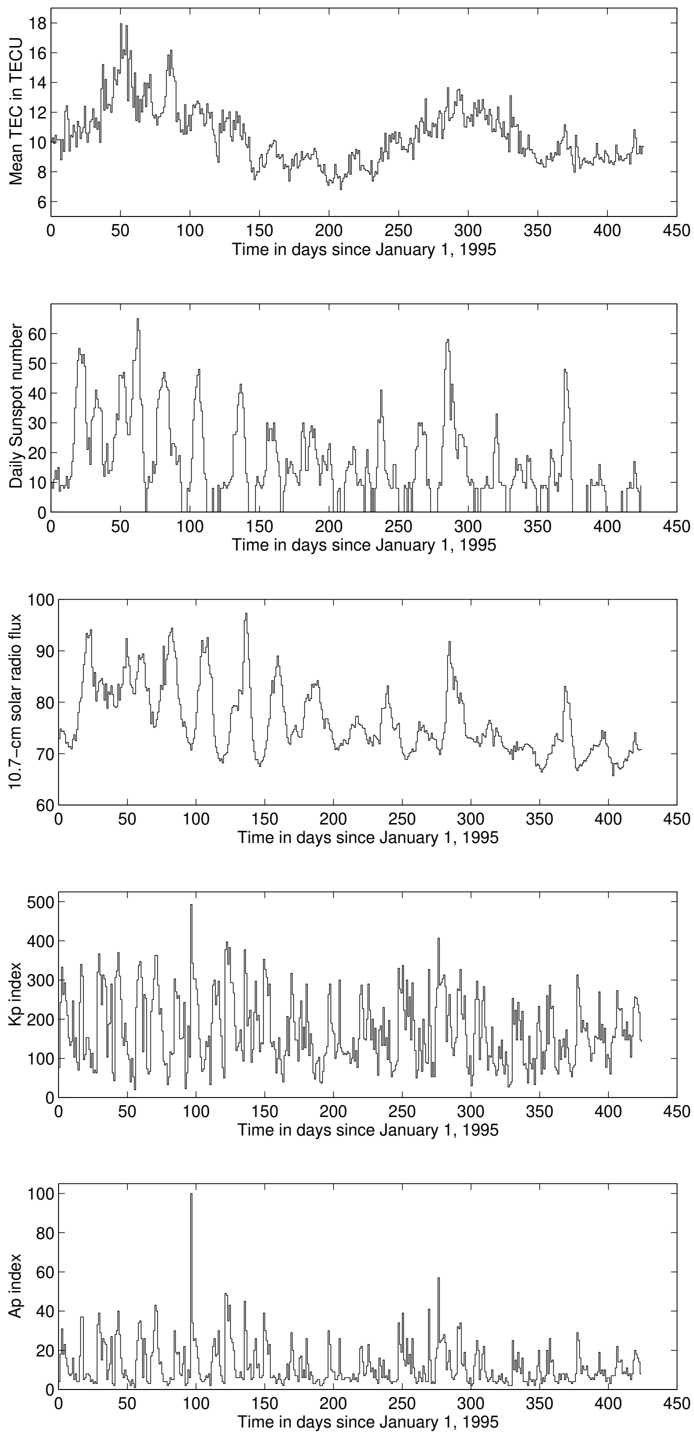

Figure 9. (a) Mean TEC derived by CODE, (b) daily Sunspot number, (c) Ottawa 10.7-cm solar radio flux (in solar flux units), (d) Kp index, and (e) Ap index.

CONCLUSIONS AND OUTLOOK

The global IGS core network of permanently tracking dual-frequency GPS receivers provides a unique opportunity to *continuously* monitor the Vertical Total Electron Content on a global scale. A first long time series of TEC parameters indicates that *absolute* TEC determination is possible even when applying *interferometric* processing techniques. The CODE Analysis Center of the IGS shows that the production of Global Ionosphere Maps (GIMs) in an *automatic* mode is possible — even under Anti-Spoofing (AS) conditions. *No* restrictions concerning receiver types or satellites have to be observed in this approach. If we support the global QIF ambiguity resolution using our one-day GIMs, the number of *resolved* ambiguity parameters is significantly higher. Since January 1, 1996 85 % instead of 75 % of the ambiguity parameters are resolved.

GIM files containing the global TEC information in an internal data format are available via the anonymous FTP server of the CODE processing center starting with January 1, 1995. *Regional* ionosphere maps for Europe routinely generated since December 1995 are available on special request. If there is an interest in *rapid* GIMs, we might consider to establish such a service as part of our *rapid* orbit service. These GIMs (with less contributing stations) could be made available with a delay of about 12 hours, only.

At present one may *not* speak of a high degree of consistency of ionosphere maps produced by several groups analyzing GPS data, therefore TEC comparisons within the IGS and other interested organizations are necessary. Spaceborne applications like e. g. altimetry experiments might be used to validate GPS-derived ionosphere maps, too. Another essential aspect for the future development is an interface between the IGS and the ionosphere research community. We foresee that with high probability the IGS will be heavily involved in the ionosphere research area.

Monitoring the spacial and temporal variability of the *stochastic* part of the ionosphere by analyzing the *time-derivative* of phase observations using similar methods as for the global TEC determination will be our focus in the near future.

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