Regional Ionosphere Modeling Using Smoothed Pseudoranges

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Abstract

This paper demonstrates the concept and some practical examples of the ionospheric total electron content (TEC) modeling using undifferenced phase-smoothed pseudorange GPS observations. After the smoothing process, the pseudorange observations are, in fact, equivalent to the carrier phase observations, where the integer ambiguities might be biased. The resulting TEC estimates were tested against the International GPS Service (IGS) TEC data for some American, European and Antarctic stations. The point-measurements of TEC were interpolated using the Kriging technique, in order to create TEC maps. The quality of the ionosphere representation was tested by comparison to the reference IGS Global Ionosphere Maps (GIMs).

Key words: GPS, Ionosphere, Kriging

1. INTRODUCTION

Spatial and temporal characteristics of the ionosphere are of primary interest in their own scientific context, but they are also of special interest to communication, surveillance and safety-critical systems, as they affect the skywave signal channel characteristics. The TEC is one of the important parameters in ionospheric research and one of the most important parameters in the trans-ionospheric radio propagation studies (Ma and Maruyama, 2001).

Today, GPS delivers large volumes of data suitable for continuous, near or real-time ionosphere monitoring during the disturbed and quiet geomagnetic conditions, and offers an attractive alternative to the traditional methods. Currently, the well established and commonly used GPS-derived GIMs provided by IGS have spatial resolution of 2.5° and 5.0° in latitude and longitude, respectively, and 2-hour temporal resolution (Feltens and Jakowski, 2002). Thus, although IGS supports the scientific community with quality GPS products, IGS GIMs cannot reproduce local, short-lasting processes in the ionosphere. In addition, the resolution of these products might not be sufficient to support high quality GPS positioning, especially in the presence of local ionospheric (Cisak et al., 2003a).

The need to produce high-resolution regional ionosphere models, supporting navigation, static and kinematic positioning and space weather research, is commonly recognized (Komjathy, 1997). Gao and Liu (2002) pointed out that the interpolation methods might give better results, as compared to the mathematical function representation of TEC (e.g., spherical harmonics expansion). Thus, in this paper we investigate the applicability of the Kriging interpolation/prediction method for TEC representation (Journel and Huijbregts, 1992). This paper presents some preliminary test results and the comparison with the IGS GIMs.

2. METHODOLOGY

The double frequency GPS phase and code observations, collected at the reference station network, were used in the approach presented here. The carrier phase observations are used to smooth the pseudoranges, as described by Springer (1999). The Differential Code Biases (DCBs) for satellites, denoted as Δb^k, are provided by IGS (ftp://gage.upc.es/pub/gps_data/GPS_IONO) and the DCBs for the receivers, Δb_i, are derived from the

GPS receiver calibration performed using the BERNESE software (Hugentobler et al, 2001). Next, the geometry-free linear combination of the un-differenced GPS observations is applied to derive the ionospheric delay related to the first GPS frequency (Schaer, 1999):

$$I_i^k = (\tilde{P}_{i,4}^k - c(\Delta b^k + \Delta b_i)) / \xi_4 \qquad (1)$$

where:

I_i^k - ionospheric delay

$\tilde{P}_{i,4}^k$ - un-differenced pseudorange geometry-free linear combination (phase-smoothed)

c - speed of light

Δb^k - DCB of satellite k

Δb_i - DCB of receiver i

ξ_4 - coefficient converting ionospheric delay on P_4 to P_1

The relationship between the absolute TEC and the ionospheric delay is shown in the following formula (Schaer, 1999):

$$I_i^k = \pm \frac{C_x}{2} TEC f_1^{-2} = \xi_{TEC} TEC \qquad (2)$$

where $\frac{C_x}{2}$ = 40.3 $\times 10^{16}$ ms^{-2}/TECU is the proportionality factor; ξ_{TEC} = 0.162 m/TECU is the ionospheric delay caused by 1 TECU on the first GPS frequency — f_1.

For the TEC representation, a single layer model (SLM) was used. SLM assumes that all the free electrons are contained in a shell of infinitesimal thickness at altitude *H*. A mapping function converting slant TEC to the vertical one is needed as shown in (Mannucci et al., 1993).

In order to create regional TEC maps, the Kriging method was used (Davies, 1986; Stanislawska et al., 2000 and 2002). Kriging is an estimation and interpolation method applied in geostatistics, which uses the known sample values and a variogram to determine the unknown values at different locations/times. It utilizes the spatial and temporal correlation properties of the underlying phenomenon, and incorporates the measures of the error and uncertainty of the estimates. At each location, Kriging produces an estimate and a confidence bound on the estimate, the Kriging variance.

3. NUMERICAL TESTS

At the first stage of the numerical analysis, GPS observations from five CORS stations (COLB, SIDN, MCON, LEBA and PKTN) with the average separation of ~100km, located in the southern part of the State of Ohio, were selected. The 60-second sampling rate and the elevation mask of 20° were used in the processing. The vertical TEC values were obtained according to the methodology presented above using the MPGPS^{TM} software (Wielgosz et al., 2003). The data from the magnetically active day of April 29, 2003 were processed and analyzed. Figure 1 indicates that the active geomagnetic period started around 12:00 UT, and the Kp index reached the value of 6 between 18:00–21:00, which reflects a minor geomagnetic storm.

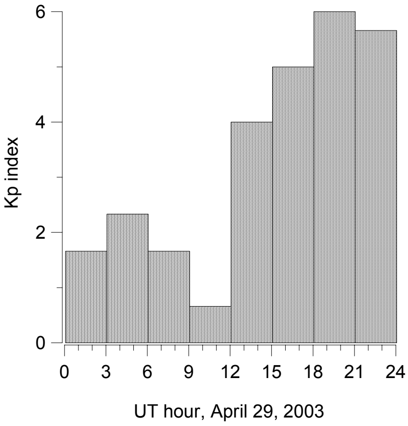

Figure 1. Kp index during the experiment.

The TEC values and the respective ionosphere pierce point (IPP) coordinates were calculated in geographic reference system (geographic latitude and longitude). Geographic reference frame was used to produce the epoch-specific instantaneous regional maps of the ionosphere. After analyzing the geographic location of IPPs for all the observational epochs, a region located between 35° – 45° north geographic latitude and 272° – 282° longitude was selected to produce the regional ionosphere maps. This area was covered by IPPs for most of the processed epochs; thus, the instantaneous ionosphere mapping was possible.

The TEC values obtained at the IPPs were interpolated using Kriging to create high-resolution instantaneous regional maps of the ionosphere. The results were analyzed and compared to the reference IGS maps, as described in the following section. In order to compare the IGS TEC over different geographic regions, TEC was calculated using observations from the European IGS station, LAMA, and the Antarctic IGS station, CAS1. The results were compared to those obtained from the IGS GIMs. In the following, the TEC calculated using the MPGPS^{TM} software is denoted as “OSU-TEC”.

4. RESULTS AND ANALYSIS

The first analysis is concerned with the internal consistency of the model and the satellite/receiver DCB validation. The TEC values calculated from several CORS stations and GPS satellites were compared (Figure 2). It was shown that the TEC derived from the observations to each satellite is consistent between the neighboring stations, what confirms that the calibrated receiver DCBs are correct.

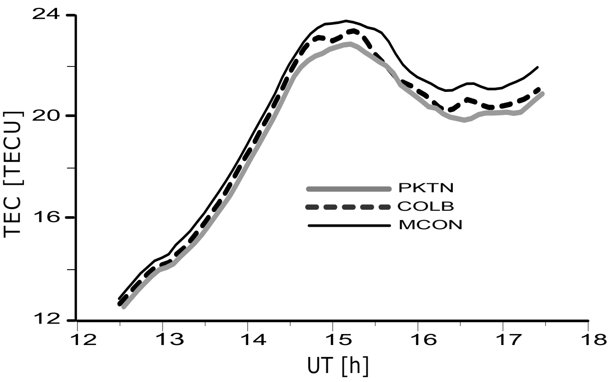

Figure 2. Comparison of the OSU-TEC observed to satellite PRN 04 from three CORS stations (COLB, PKTN and MCON) on April 29, 2003.

Figure 3, left column, illustrates the examples of regional instantaneous ionosphere maps produced with the Kriging technique. For every map a semi-variogram was calculated and introduced to the interpolation process. The approach applied here allows a fast generation of the regional ionosphere maps, practically, for every observational epoch. Figure 3 illustrates the maps at the selected epochs. Notice that the local time for this region is –5 UT hours, and the maximum electron density, due to the geomagnetic disturbances, occurred for this area in the local evening. The resulting maps may allow detecting the local ionospheric phenomena, e.g. local TEC peaks of 1–3 TECU (Figure 3). The obtained ionosphere grid has the resolution of 0.08º in latitude and 0.12º in longitude. Such a dense TEC grid can be easily interpolated using simple linear interpolation and can be effectively used to support global navigation satellite systems (GNSS).

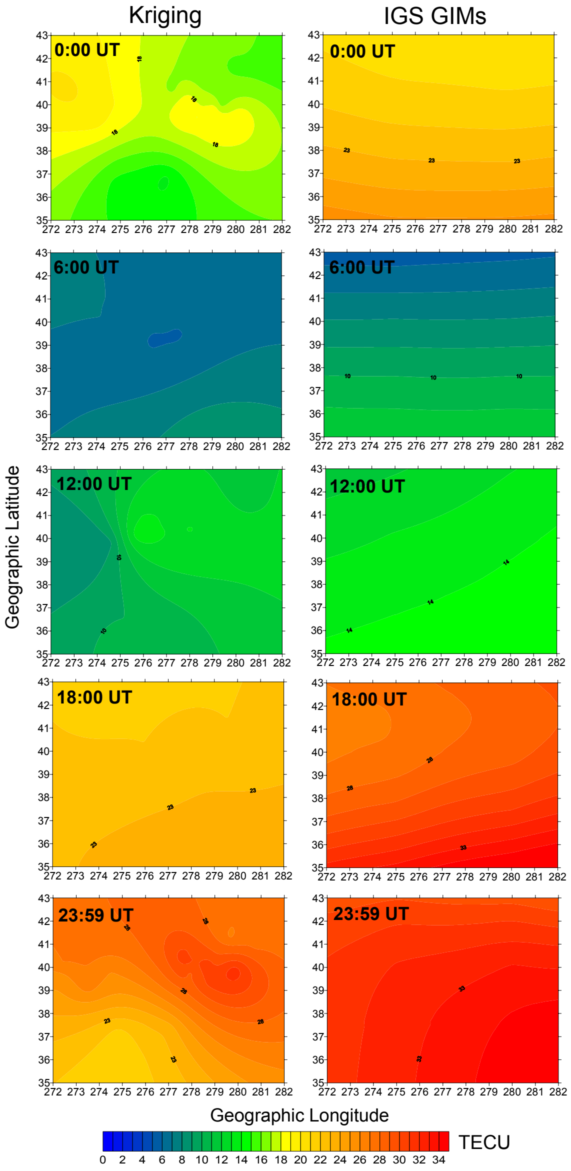

Figure 3. Comparison between the ionosphere maps derived using Kriging (OSU-TEC) and the IGS GIMs (April 29, 2003).

4.1 Comparison to IGS GIMs

In order to validate the instantaneous regional ionosphere maps, a comparison to IGS GIMs was performed. It should be noted that the IGS GIMs are a combination of GIMs provided by several analysis centers (ACs). All the ACs involved may use different approaches to the TEC derivation from GPS observations, as well as different TEC representation/modeling techniques. As it was mentioned in the introduction, the spatial resolution of the final IGS GIMs is 2.5° in latitude and 5.0° in longitude. For the comparison purposes, an area covering regional model was extracted from the IGS GIMs. Figure 3, right column, presents the example ionosphere maps for the selected epochs extracted from the IGS GIMs.

In general, the OSU-TEC is comparable to the IGS GIMs. It is noticeable, however, that GIMs' general TEC level is higher about 3–5 TECU, as compared to the maps generated using the Kriging method. This could be explained by the global nature of GIMs. IGS ACs often use TEC representation algorithms, which result in the model resolution comparable with the whole area of the region under investigation (Schaer, 1999). In addition, the sampling rate of the data sets and the network density used in the global and some regional models is much lower than the one investigated here. It should be noted that the investigated region is covered by only 8 GIM grid points. This also explains why the TEC derived from GIMs is very smooth over the entire analyzed region. In contrast to GIMs, local features in the ionosphere represented by the regional models can be observed. However, some of these features might be caused by a clustered distribution of IPPs. Local distribution within the clusters, however, is more than sufficient. We believe that a regional model should correspond to a more accurate local ionosphere representation.

4.2 TEC comparison over different regions

The reasons for the above-mentioned systematic bias between the OSU-TEC and the IGS GIMs were further investigated using two additional data sets (OSU and IGS GIMs' TEC values at IPPs) for comparison of some permanent IGS stations in North America, Europe and Antarctica. First, the consistency of the results in time domain from both data sets was tested for the COLB station, as shown in Figure 4 (DOY 163/2003). This Figure displays a very similar diurnal TEC behavior for both curves and a difference in the scale factor. This difference in scale is shown in Figure 5 and 6 by the means of direct comparison of both data sets.

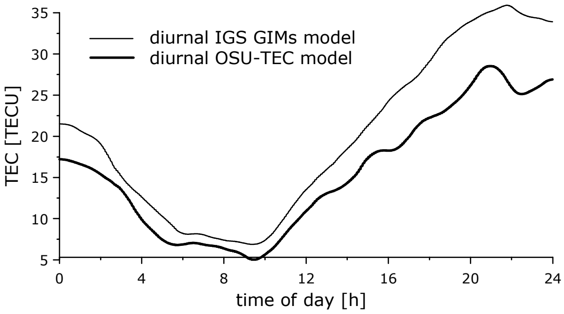

Figure 4. Diurnal TEC variations interpolated over COLB station derived from OSU-TEC and IGS GIMs, June 12, 2003.

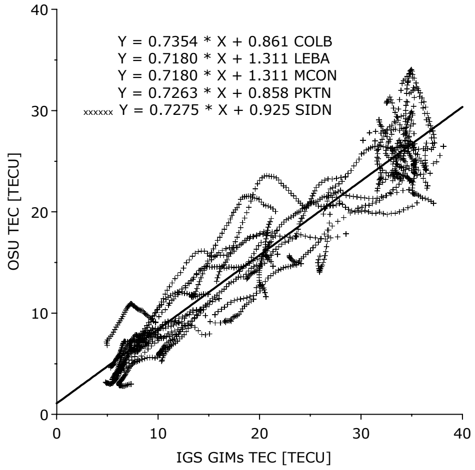

Figure 5. Comparison of the OSU-TEC variations for all satellites observed at SIDN station on June 12, 2003, to the TEC interpolated from the IGS GIMs (plot) and linear trends for the rest CORS stations (equations)

Similar investigations were performed for the TEC data obtained from the international project "Atmospheric impact on GPS measurements in Antarctica" (Cisak et al., 2003a and 2003b). Some of the results are shown in Figure 7. The TEC data with the 1-minute temporal resolution for some Antarctic stations were provided by Dr. M. Hernandez-Pajares from UPC (Hernandez-Pajares at al, 1999). In that case, the earlier conclusion that the scale difference is caused by the very smooth character of the IGS GIMs seems to be confirmed.

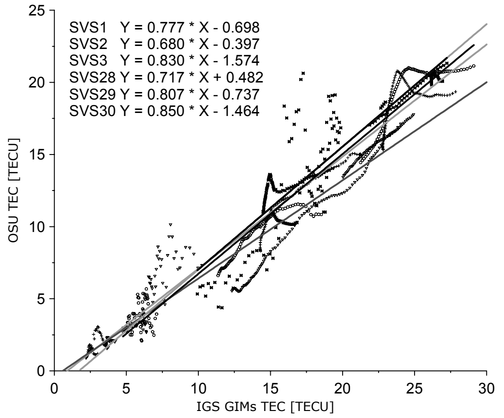

Figure 6. Comparison of the OSU-TEC variations for different satellites observed in COLB, LAMA and CAS1 data with the TEC interpolated from the IGS GIMs (June 12, 2003).

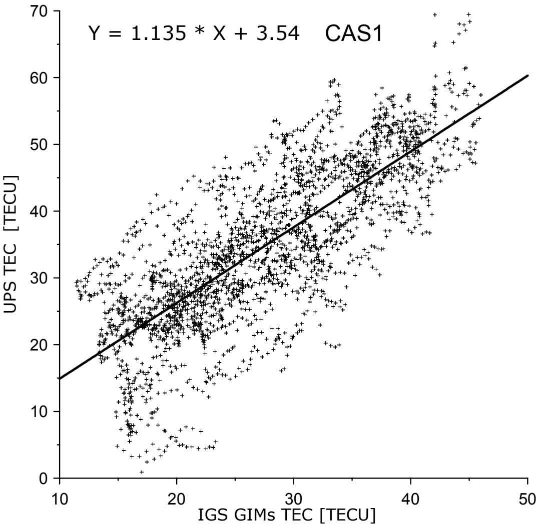

Figure 7. Comparison of TEC over the Antarctic CAS1 station derived from the UPC data with the TEC interpolated from the IGS GIMs' (November 2001).

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The analyses presented here show that the TEC-recovery methodology, which takes the advantage of the phase-smoothed pseudoranges, is efficient, and enables generation of the real-time regional TEC maps, when applying the Kriging method. The primary advantages of the instantaneous regional ionosphere mapping presented here are the high temporal (one observational epoch) and spatial (0.08° in latitude and 0.12° in longitude) resolutions. Owing to the fact that DCBs do not change significantly during the course of a day, their values can be used even a few days after the calibration. This may allow producing instantaneous TEC maps in near-real time. However, the systematic bias between both TEC estimation sets (OSU-TEC and IGS GIMs) needs to be further investigated.

Future studies will include the investigations of the behavior of the selected ionospheric storms over the Antarctic region using the proposed approach. The impact of the ionospheric disturbances on the variations of the GPS vector components, at high latitudes, will be also investigated.

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