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Scale factor mitigating non-compliance of double-frequency altimeter measurements of the ionospheric electron content over the oceans with GPS-TEC maps

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This paper presents results from a study of GPS total electron content (TEC) grid maps and ionospheric electron content (IEC) over the oceans delivered by the TOPEX/Jason satellites during half a solar cycle (July 2001 to December 2008). The IEC data are averaged and binned at latitudes from 60°S to 60°N in steps of 5°±2.5°, at longitudes from 180°W to 180°E in steps of 15°±7.5°, and for 0–23 h UT in steps of 1±0.5 h UT. The ratio of monthly averaged TEC/IEC over the oceans from the observations was compared to the reference model ratio of TECm/IECm obtained using the plasmaspheric model augmented with the International Reference Ionosphere. By definition, TEC should exceed IEC by the plasmaspheric electron content (PEC) contribution at the altitude range from 1336 km (TOPEX orbit) to 20,200 km (GPS orbit). However, as solar activity tends to the minimum, we found that IEC estimates systematically exceed those of GPS TEC. An empirical scale factor was derived in terms of the smoothed sunspot number, and this factor reduced the systematic excess of the TOPEX/Jason-derived IEC over the GPS TEC by a factor of 1.5 towards the solar minimum. This factor was tested with observations made at the solar minimum and revealed that the plasmaspheric electron content to be a residual of the GPS TEC and modified TOPEX/Jason IEC.

Key words: Ionosphere, plasmasphere, GPS, TOPEX/Jason, total electron content.

1. Introduction

Total electron content (TEC) is one of the key parameters used during investigation of the Earth's ionosphere. It is defined as either the line integral of electron density along a ray path or the measure of the total number of electrons along a path of the radio wave. TEC is given in units of TECU where 1 TECU = 10^{16} el/m^2. TEC is a derived quantity, and it is a function of electron density and the chosen ray path. There are various alternatives approaches to compute TEC, such as by the TOPEX/Poseidon (T/P) and Jason satellites with double frequency altimeters and Global Positioning System (GPS) satellite phase and delay recordings (Komjathy *et al.*, 1998). The T/P system can provide the ionospheric electron content (IEC) for altitudes ranging from 65 to 1336 km, whereas the GPS TEC system contains contributions from both the ionosphere and the plasmasphere due to the fact that the GPS satellites are located in an orbit of 20,200 km. Therefore, it is inherently expected that GPS TEC measurements should exceed IEC ones due to the higher satellite altitude and longer ray path of the former's radio signals.

The plasmasphere is a region of the magnetosphere containing low-energy plasma particles with an energy level that ranges typically a few to a few 10's eV and with density equal to or more than 10 m^{-3} (Carpenter and Park, 1973; Kotova, 2007). The transition from the ionosphere to plasmasphere is conventionally located at 1000 km over the Earth's surface, which represents that surface where principal differences in plasma dynamic processes become congruent. Plasma exchange between the ionosphere and plasmasphere implies vertical fluxes up and down inside of the ionosphere that are dependent on atmospheric parameters. In contrast, an ionization flow tends to proceed along rather than across magnetic field lines in the plasmasphere due to magnetospheric convection by which plasma in the outer magnetosphere circulates under influence of the solar wind.

Knowledge of the plasmaspheric processes is relevant for applications that need to measure and model the ionosphere to altitudes much lower than that of GPS satellites, such as ground-based trans-ionospheric radars that must detect and track orbital and ballistic objects. To this end, different three-dimensional (3-D) ionosphere-plasmasphere models have been established (Chasovitin *et al.*, 1998; Gallagher *et al.*, 2000; Webb and Essex, 2004; Gulyaeva and Titheridge, 2006; Reinisch *et al.*, 2007). Though the electron density above the Earth's ionosphere is exponentially reduced by more than two orders of magnitude relative to the ionospheric peak density, the path through the plasmasphere is 20-fold greater than that through the ionosphere so that the integrated electron content in the plasmasphere may reach an appreciable magnitude (Soicher, 1976; Gulyaeva *et al.*, 2002; Manju *et al.*, 2008).

A space-based radio navigation system is capable of providing global monitoring of the ionosphere and plasmasphere through an analysis of dual-frequency signals from multiple GPS satellites (Klobuchar, 1997). A propagating navigation signal is slowed down by an amount proportional to the TEC along its path. In GPS TEC computations, the TEC on the slant ray path from the satellite to the receiver is called the slant TEC (STEC). When the STEC values are projected to the local zenith at the ionospheric pierce point, accepting the assumption of the thin shell model of the ionosphere with a mapping function, the computed TEC value is called the vertical TEC (VTEC) (Arikan *et al.*, 2003, 2004; Nayir *et al.*, 2007). A more sophisticated 3-D model of the ionosphere would improve the accuracy of the conversion of the slant TEC to the vertical TEC (Smith *et al.*, 2008). There are only a limited number of reports in the literature on attempts to estimate plasmaspheric content from GPS-derived TEC. One of these is the study of Mazzella *et al.* (2002) in which the Self-Calibration of Range Errors (SCORE) was modified to include a parameter denoting the protonospheric contribution in the estimation of GPS TEC. In comparisons with measurements from 1997 and 1998 (low solar activity), these authors show that the distribution of plasmaspheric TEC is not uniform, and dominant effects are observed in equatorial regions.

The International GPS Service (IGS) for Geodynamics (http://igs.ens.ign.fr) is the major source for several GPS-derived ionospheric products. These products are available from the internet through six analysis centers: the Geodetic Survey Division of Natural Resources Canada (NRCan); the Center for Orbit Determination in Europe (CODE), University of Berne, Switzerland; the Jet Propulsion Laboratory (JPL), Pasadena, CA, USA; the European Space Operations Center (ESOC) of the European Space Agency (ESA), Darmstadt, Germany; gAGE/UPC of Polytechnical University of Catalonia, Barcelona, Spain; the Geodynamics Research Laboratory, Univarsity of Olsztyn, Poland (GRL/UWM). Global Ionospheric TEC maps (GIM) and interfrequency differential code bias solutions (DCB) for satellite and receivers of these analysis centers are available at the web sites ftp://igs.ensg.ign.fr/pub/igs/iono or ftp://cddis.gsfc.nasa.gov/gps/products/ionex/ in the form of IONosphere Map EXchange Format (IONEX) files. The spatial resolution of 2-D world-wide grids of vertical TEC GIM is 5° in longitude and 2.5° in latitude. GIMs are made available every 2 h UT daily (Mannucci *et al.*, 1998; Shaer *et al.*, 1998; Ijima *et al.*, 1999).

Figure 1 illustrates the latitudinal distribution of the GPS receiver network routinely used for the global TEC mapping. Figure 1(a) shows the dominance of sea area (63%) on the Earth's surface compared with the land (37%). At the same time, the latitudinal distribution of GPS receiving stations can be seen in Fig. 1(b) to be much more prevalent over land than over oceans, where they are indeed rather sparse (mainly on the islands and the sea shore). The process of spatial interpolation between observing sites at these large distances over the oceans yields "a global relative error" of 15–25% (Orus *et al.*, 2002; Jee *et al.*, 2005). Consequently, data assimilative interpolation procedures are required to improve mapping results (Todorova *et al.*, 2008).

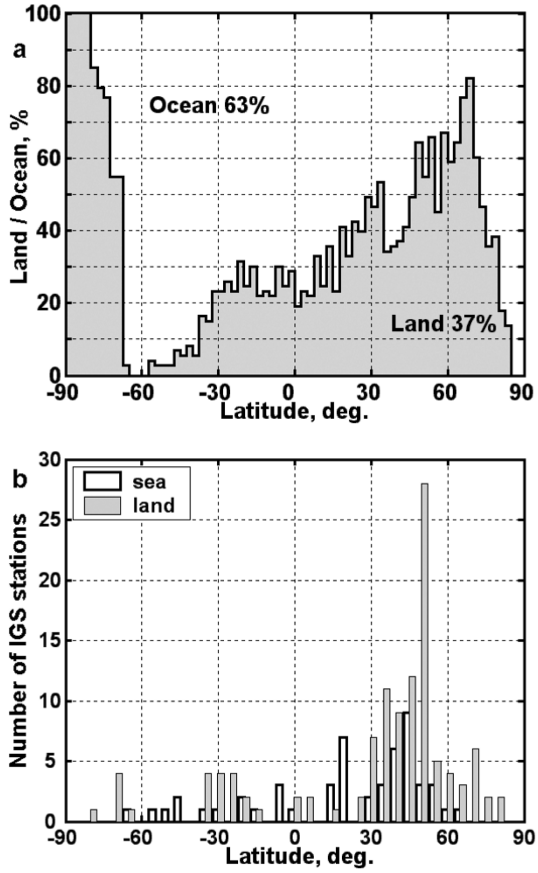

Fig. 1. (a) Proportions of the Earth's land/sea surface. (b) Distribution of the GPS receiver stations with geodetic latitudes.

The Topographic Experiment (TOPEX) mission, which started with Poseidon in 1992 followed by the Jason satellite since 2004, has a circular orbit at an altitude of 1336 km (830 miles) with an inclination of 66° (Fu *et al.*, 1994; Delay and Doherty, 2004). The spacecraft's dual frequency NASA altimeter measures the precise distance between the satellite and the sea surface by calculating the round trip travel time of microwave pulses bounced from the spacecraft to the sea surface and back. In order to provide an accurate distance measurement, the system corrects for the path delays due to changes in the atmospheric index of refraction. These changes are primary due to free electrons in the ionosphere, but they also arise as a result of tropospheric and stratospheric water vapor. Because the ionosphere is a dispersive medium, the path delay can be estimated to the first order by transmitting at two frequencies: 5.3 GHz (C-band) and 13.6 GHz (Ku-band). Once the path delay is known, it is used to obtain the vertical ionospheric electron content (IEC), which is actually a by-product of the experiment, thereby avoiding the inherent slant to vertical conversion errors of the slant delay measurements made by the GPS satellites. With the TOPEX orbit geometry, IEC is measured over all of the oceans in the world, thereby providing data for numerous ionospheric applications.

The TOPEX database has been utilized to establish the general morphology of the global TEC distributions (Codrescu *et al.*, 1999; Jee *et al.*, 2004), and comparisons with the ionospheric models are provided in studies such as those of Robinson and Beard (1995) and Jee *et al.* (2005). Schreiner *et al.* (1997) compared T/P TEC with parameterized the real-time ionospheric specification model (PRISM) using GPS data and with IRI-90 for certain passes of the satellite on 12 March 1993 (medium solar activity). They found that T/P overestimates TEC when compared with PRISM and IRI-90. Komjathy *et al.* (1998) studied a group of consecutive days in 1993 (medium solar activity) and 1995 (low solar activity) and found that T/P TEC and GPS-derived TEC agreed within a confidence bound of 5–9 TECU level. A more detailed comparison of T/P TEC and GPS-derived TEC used in the La Plata ionospheric model (LPIM) is provided in Brunini *et al.* (2005) for measurements taken in 1997 and 1998 with increasing solar activity. These authors discuss various possible error sources for T/P TEC and GPS-derived LPIM TEC estimates. They observed that the major differences in T/P TEC and GPS-derived LPIM TEC are apparent in the southern hemisphere, which is dominated by oceans and where the significant wave height (SWH) is higher. Brunini *et al.* (2005) deduced that T/P TEC estimates are larger than both LPIM and IRI-95 model outputs for the years of increasing solar activity. A literature search also presented in Brunini *et al.* (2005) shows that DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellites) system TEC estimates are consistently lower than T/P TEC ones.

Here, we report our attempt to deliver the plasmaspheric electron content (PEC) component of GPS TEC by subtracting the ionospheric component measured by TOPEX IEC. The data used in our study were JPL-provided IONEX TEC files and TOPEX IEC files that span the period from July 2001 to December 2008, thus covering half a solar cycle from solar maximum to minimum. Data for 2001–2007 were used as a training database and data for 2008 served as a testing database. The results of measurements were compared with a model simulation. To be able to fit the simulation results to the observations, we integrated the electron density distribution from 65 to 1336 km (TOPEX altitude) in order to obtain a model value of IECm with the International Reference Ionosphere (IRI). The advanced version of IRI, which extends towards the plasmasphere (Bilitza *et al.*, 2006; Gulyaeva and Titheridge, 2006), has been modified to produce a grid map, TECm, by integrating the electron density at altitudes from 65 to 20,000 km near the GPS satellites orbit. To the best of our knowledge, this is the first systematic study reported in the literature in which data for half a solar cycle are included into the analysis. Data/model comparison suggests a need of TOPEX IEC reanalysis to comply with GPS TEC measurements. An empirical expression was derived that introduces a scale factor required for reducing the systematic excess of TOPEX IEC data over GPS TEC grids towards the solar minimum. Finally, the scale factor was applied to the measurements made in 2008, allowing the estimation of the PEC as the difference between the TEC and IEC measurements. The scale factor will also be utilized to obtain better 3-D global modeling of the ionosphere by providing improved IEC data over regions of the Earth where GPS TEC data is non-existent or very sparse.

2. Data-Model Comparisons

Since July 2001, the long time-series of GPS IONEX maps and TOPEX IEC files have been accessible from the NASA web page daily. In this study, we used the GPS maps provided by the Jet Propulsion Laboratory (JPLG maps) due to their having the best coherence with TOPEX IEC data (Orus *et al.*, 2002). The JPL TEC map is modeled in a solar-geomagnetic reference frame using bi-cubic splines on a spherical grid. A Kalman filter is used to solve simultaneously for instrumental biases and TEC on the grid. Each map is then transformed into an Earth-fixed reference frame with geodetic latitudes from 87.5°S to 87.5°N in steps of 2.5° and geodetic longitudes from 180°W to 180°E in steps of 5°, in standard IONEX format (Shaer *et al.*, 1998). For the separation of grids over the land and ocean on the GPS TEC map, we developed a special subroutine SEALAND to serve as a driver in the process of reformatting the TEC IONEX maps to the format used in our study.

The TOPEX IEC measurements were taken almost 1-s intervals along the ascending and descending nodes of the orbit over the oceans. The TOPEX/Jason IEC data were binned around the grids at latitudes from 60°S to 60°N in steps of $5°\pm2.5°$ and at longitudes from 180°W to 180°E in steps of $15°\pm7.5°$. According to the TOPEX orbit geometry (orbit plane inclination of 66° and revolution period of 112 min), a cycle of 10 days was the time needed for the satellite to pass over the same point of the sea surface (Ijima *et al.*, 1999). The monthly mean IEC data for a period of 28–31 days were considered to be a representative data sub-set providing a full coverage of the sea surface with the orbit passes. The negligibly small geomagnetic dependency of observations (Jee *et al.*, 2005) was ignored. The TOPEX IEC at each spatial grid over the ocean was extracted for 0–23 h UT averaged with steps of 1 h±0.5 h UT. For those grids where monthly mean T/J data are not missed, the results of IEC were with relevant monthly mean TEC derived from 2-hourly UT maps provided by the IGS via internet.

The ratio of electron content at grids over the oceans was a subject of further investigation:

$$\mathrm{REC} = \mathrm{TEC}/\mathrm{IEC} \qquad (1)$$

This ratio by definition should be greater than unity (i.e. TEC > IEC) in order to characterize the plasmaspheric electron content PEC as their residual:

$$\mathrm{PEC} = \mathrm{TEC} - \mathrm{IEC} \qquad (2)$$

The results were averaged for those UT hours which were provided with 2-h UT intervals of GIM.

Figure 2 illustrates the difference obtained between two data sets. The monthly mean TOPEX grid IEC was subtracted from GPS TEC (Eq. (2)) at grids of IEC and the result averaged over the sea surface in the northern and southern hemispheres. It follows from Fig. 2 that only data for 2001 and 2002 proved to indicate the PEC (positive values) retrieved from the two experiments difference. As solar activity tends to a minimum for the years of 2002–2007, the

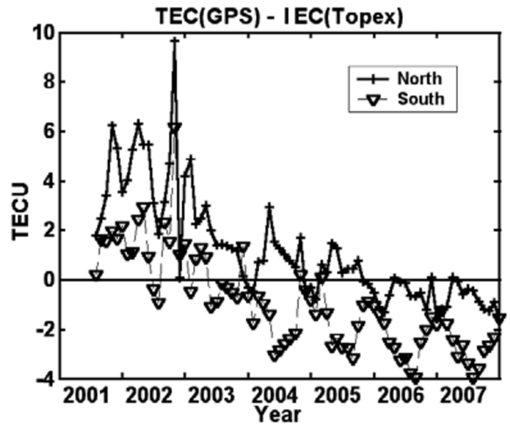

Fig. 2. Results of subtracting the monthly mean TOPEX IEC from GPS TEC averaged over the sea surface in the north and south hemisphere.

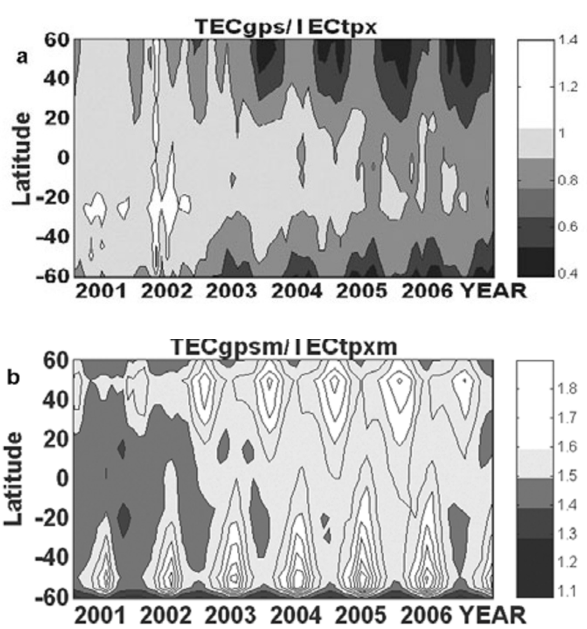

Fig. 3. (a) Monthly latitudinal variation of the longitudinally average of observed ratio TEC/IEC over the oceans. (b) Results of model simulations.

monthly mean GPS TEC values become equal to or less than the TOPEX IEC mean (negative difference), particularly for the southern hemisphere where the ocean surface is dominant. This graph suggests that either GPS TEC is underestimated over the oceans or that TOPEX IEC is overestimated during the measurement period.

To resolve this ambiguity, we integrated the model electron density profile of the IRI extended towards the plasmasphere—first for IECm between the altitudes of 65 and 1336 km and second for TECm between 65 and 20,000 km (http://ftp.izmiran.ru/pub/izmiran/SPIM/). The month-to-month latitudinal variation of the longitudinally average of the TEC/IEC ratio from the measurements (Eq. (1)) is depicted in Fig. 3(a) for the period of July 2001 to December 2007. The data-driven pattern of the ratio (Fig. 3(a)) contains values of less than unity for most of the latitudes/months, with extreme values as small as 0.4 (i.e., GPS TEC comprising only 40% of TOPEX IEC). At the same time, the model ratio, TECm/IECm, presented in Fig. 3(b) varies from 1.1 to 1.8, thereby depicting a seasonal/latitudinal excess of GPS TECm over TOPEX IECm owing to PEC.

3. Scale Factor Derivation

For capturing the solar activity dependence of the data and model ratio given in Eq. (1), we computed the monthly mean for the global sea surface in terms of the variation of smoothed sunspot number R_{12}. This computation is depicted in Fig. 4 where the data driven ratio is represented by circles, and the model results are denoted by filled triangles. The mean data ratio varies from 0.85 at the solar minimum to 1.1 at the solar maximum. The model ratio shows absolute values greater than unity, varying from 1.3 to 1.2 from solar minimum to solar maximum. The displacement of the two curves suggests a shortage of the data ratio, leaving no chance to extract the PEC from the difference between the two data sources. The largest difference between the model and data ratios is at the solar minimum, and this difference slowly becomes smaller towards the solar maximum. However, it is still not clear whether the GPS TEC is underestimated (due to errors arising at the stage of the slant TEC to vertical TEC conversion and/or mapping interpolation errors at the sparse receiver network over the oceans) or whether TOPEX IEC is overestimated due to some physical or technical reason.

One possible approach that can be used to resolve mismatch between IEC and TEC is a comparison of T/P and GPS data models, respectively. The IRI model extended to the plasmasphere computes IECm and TECm through the same path using the same model values up to the height of plasmasphere. Therefore, both measurements of IEC and TEC can be compared using the IRI model as a reference. In this study, a scatter plot of TEC versus TECm and IEC versus IECm are obtained and plotted in Fig. 5(a) and 5(b), respectively. An examination of the plots in these figures reveals a misrepresentation of TOPEX IEC data for low IEC, i.e., IEC $<$ 25 TECU, at low solar activity.

The main feature observed in Fig. 5 is more evident in Fig. 6 where the relative mean data-model differences

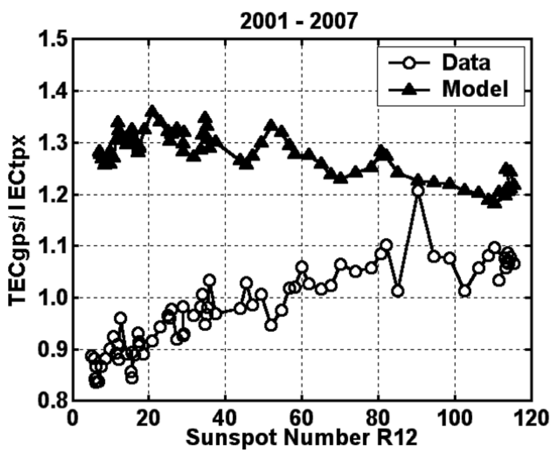

Fig. 4. Monthly mean ratio of TEC/IEC for the global sea surface in a function of the smoothed sunspot number.

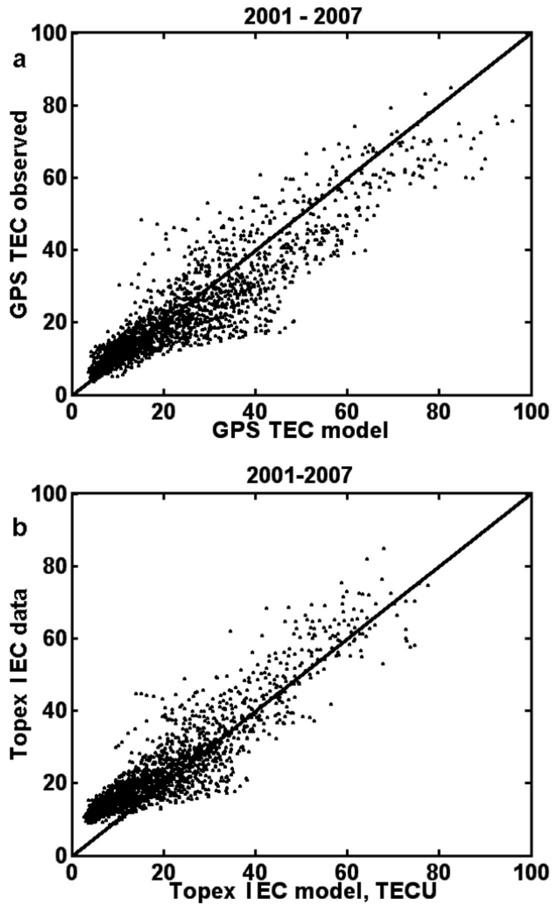

Fig. 5. (a) Scatter plots of data GPS TEC versus model TECm. (b) Observed TOPEX IEC values against model IECm.

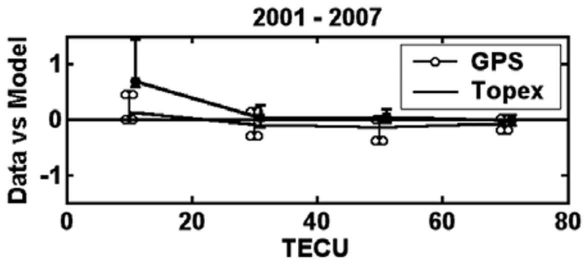

Fig. 6. Relative mean data-model difference ((data−model)/model) averaged in successive TECU ranges. The upper and lower mean bars are also shown.

((data−model)/model) are given with the upper and lower mean bars at the successive TECU ranges of 0:20, 20:40, 40:60, 60:80 TECU. An excess of IEC data over the IECm model is evident at the lower edge of this graph, which refers to TECU pertinent to the solar minimum epoch. The mean and standard deviations (Std) of GPS TEC and TOPEX IEC relative model grids are listed for four selected ranges of TECU in Table 1. The number of grids involved in each mean and std calculation is also indicated twice by 'n' sets involved (one data set of 'n' values and another model 'n' grid set) for calculation of the relative difference. Figures 5 and 6 and Table 1 suggest that TOPEX-derived IEC requires a reduction by a scale factor, depending on solar activity, to avoid misrepresentation at low TECU.

Table 1. Mean and standard deviation (Std) of the data-model differences during 2001–2007 ((data−model)/model) for the different ranges of TECU (n = number of grids).

	TECU	0:20	20:40	40:60	60:80
GPS	Std(−)	.110	.165	.301	.524
	Mean(−)	−.151	−.217	−.230	−.128
	n	32534	46068	17955	6053
TOPEX	Std(−)	.070	.131	.280	.480
	Mean(−)	−.097	−.169	−.093	−.088
	n	7902	28223	6774	2361
GPS	Std(+)	.284	.527	1.004	1.553
	Mean(+)	.310	.217	.135	.079
	n	57268	20212	5643	2360
TOPEX	Std(+)	.553	1.063	1.945	4.511
	Mean(+)	.746	.229	.150	.095
	n	104683	29455	8826	1642
GPS	Std	.324	.458	.796	1.338
	Mean	.143	−.085	−.143	−.070
	n	89802	66280	23598	8413
TOPEX	Std	.576	.846	1.634	3.229
	Mean	.687	.034	.045	−.013
	n	112585	57678	15600	4003

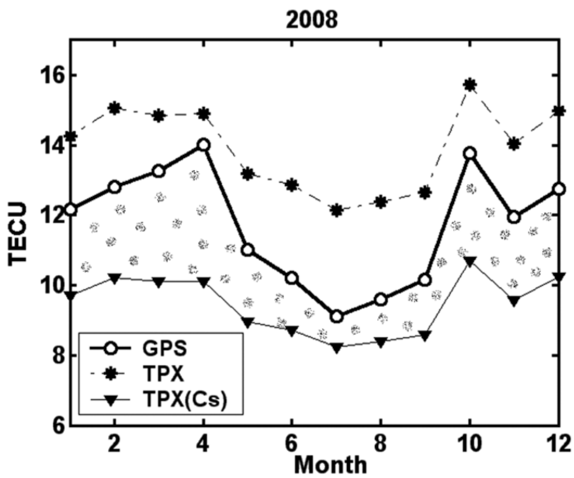

Fig. 7. Validation of scale factor effect on TOPEX/Jason measurements during 2008 at the solar minimum. The residual plasmaspheric electron content is shown as the hatched area.

Results of the ratio TEC to IEC (Fig. 4) enable the scale factor as a function of the 12-month mean sunspot number R_{12} to be derived:

$$\mathrm{Cs} = 1.4869 - R_{12} * 0.001 * (3.955 - 0.00519 * R_{12}) \quad (3)$$

Re-evaluation of TOPEX IEC with the scale factor Cs yields modified IECs:

$$\mathrm{IECs} = \mathrm{IEC}/\mathrm{Cs} \quad (4)$$

The proposed scaling of TOPEX IEC has been validated with the T/J measurements made during 2008, which was the year of the solar minimum of the 23rd solar cycle. Monthly mean results for 2008 are presented in Fig. 7. Here, the excess of the original TOPEX IEC over GPS TEC is demonstrated, which has been removed after scaling the

TOPEX IECs. The difference between GPS TEC and IECs represents the PEC (hatched area in Fig. 7).

4. Discussion and Summary

Here, we compared the total electron content estimated from GPS-derived GIM maps and TOPEX/Poseidon Altimeter Satellite signals for half a solar cycle and a scale factor with the aim of accounting for the bias in T/P IEC estimates. The coherency of the two data sources was assessed by inter-comparisons of GPS TEC with TOPEX IEC products and with simulated values obtained by numerical integration of the model electron density profile. This resulted in our detection of an excess of TOPEX IEC over GPS TEC towards the solar minimum. Using the proposed scale factor for TOPEX IEC, we estimated a modified scaled IEC for 2008 and demonstrated that the PEC can be estimated as the difference between GPS TEC and the scaled TOPEX IEC.

As mentioned in Section 1, various studies have suggested overestimates of TEC by T/P emission. The ionosphere and plasmasphere are not only temporally and spatially variable, but they are also temporally and spatially dispersive. There is no complete physical model of the ionosphere and plasmasphere currently available that can account for this high level of variability. Unfortunately, the measurements that are available have been obtained from sources whose main goals can not be listed as identifying the parameters of the ionosphere or the protonosphere. Earth-based ionosondes can not probe distances above the maximum ionization density level. Incoherent backscatter radars measure ionospheric parameters up to a specified upper limit in the topside ionosphere, but these installations are very sparse over the globe. The top-side ionosondes can probe only the section of the ionosphere between their orbit and the maximum ionization level. GPS provides a cost-effective alternative with world-wide receivers and a range estimate model that accounts for the frequency-sensitive delays in the ionosphere. Altimeter satellites, such as T/P or Doris, provide a possible means for estimating the TEC over those parts of the world where there are no or very few GPS receivers located. However, neither GPS nor T/P is designed for taking measurements to determine the parameters of the ionosphere. Therefore, TEC estimates from GPS and T/P are obtained with inherent modeling, computation and estimation errors. As a result, T/P can systematically overestimate TEC as compared to GPS.

The most common sources of error for GPS TEC estimates are (1) the pseudorange estimate model that includes frequency-dependent satellite and receiver clock biases; (2) an assumption of azimuthal homogeneity of the ionosphere; (3) an assumption of inherent temporal stability of the ionosphere for 15 min to 2 h; (4) conversion from slant TEC to vertical TEC (mapping function); (5) determination of thin shell height corresponding to the maximum ionization height of the ionosphere; detection of cycle slips and resolving integer phase ambiguity; (6) scaling the absolute TEC to the relative TEC in order to estimate low noise TEC estimates for each satellite in view; (7) combination of TEC estimates from different satellites in view to obtain one value of vertical TEC for a given instant for any location; (8) estimation of satellite and receiver DCBs (Arikan *et al.*, 2003, 2004, 2008; Nayir *et al.*, 2007).

Global or regional mapping or interpolating TEC from sparse samples is another issue that needs to be handled very carefully. Sayin *et al.* (2008) observed that spatial interpolation error increases by orders of magnitude for clustered and sparse sampling compared to regular and dense sampling patterns. Global Ionosphere Maps are produced every 2 h by IGS centers that utilize different algorithms for TEC and DCB estimates obtained from non-uniformly distributed IGS-GPS receivers world-wide. The best knowledge is published on IGS web sites. The TEC samples that are used in TEC mapping are obtained from GPS receivers that are located on land and islands.

T/P IEC is obtained from the range estimates of altimeter returns in C-band (5.3 GHz) and Ku-band (13.6 GHz). As mentioned in Section 1 and in Brunini *et al.* (2005) and Azpilicueta and Brunini (2009), the altimeter range estimates suffer from the possible miscalibration of sea state returns in these two frequencies. Sea State Bias (SSB) is the most common source of error and is a function of significant sea height (SSH) and wind speed. SSH and wind speed are the two parameters used to determine sea state (SS). The reflection and scattering of electromagnetic signals in C- and Ku-bands are frequency- and SS-dependent (Skolnik, 1991). The effects of sea surface backscattering are summarized with the normalized radar cross section of the sea surface, σ°, which is a complex function of various parameters, such as SS, radar frequency, grazing angle, wind direction, and electromagnetic wave polarization. At SS 3 (moderate sea surface), the difference between the σ° of two signals in C- and Ku-bands can be as high as 3.3 dB at a 60° grazing angle to 4.2 dB at an 80° grazing angle. As the wind speed increases from 2 to 60 knots, the difference between the σ° at grazing angles of 90° and 70°, respectively, can get as high as 18 dB (Skolnik, 1991). For rough sea surfaces at SS 4, the difference between the C- and Ku-band returns at an 80° grazing angle was found to be 12 dB (Arikan and Raemer, 1996; Arikan and Vural, 2005). These findings demonstrate the difficulty in modeling the sea surface under various parameters that affect the range estimates of the radar altimeters which in turn reflect as SSB in the T/P TEC computation.

Apart from possible inherent computational and modeling errors in GPS- and T/P-derived TEC, our findings also provide strong bases for observation of the general trends and future development of statistical models for ionosphere and plasmasphere. This study provides the most complete, and systematic analysis of the bias between T/P IEC and JPL/GIM-TEC for a half solar cycle. The proposed empirical scale factor provides an efficient means for compensating for the overestimates of T/P IEC which has potential applications in estimating PEC and improving global mapping of TEC.

Acknowledgments. The GPS TEC grid maps and the source TOPEX data files are available at internet page (ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex/). The International Reference Ionosphere & Plasmasphere model source code and the results, IECm and TECm, are provided at (http://ftp.izmiran.ru/pub/izmiran/SPIM/). The authors wish to thank two anonymous reviewers for their comments, which were very helpful and constructive in improving the paper.

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