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ORIGINAL ARTICLE

Analysis of the bias between TOPEX and GPS vTEC determinations

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Abstract The TOPEX/Poseidon satellite was jointly developed and deployed by the National Aeronautics and Space Administration (NASA), USA, and the Centre National d'Etudes Spatiales (CNES), France (for details see Chelton et al. In: Fu L-L, Cazenave A (eds) International geophysics series, vol 69, ISBN 0-12-269545-3, Academic Press, CA, pp 1–131, 2001), with the main scientific goal of sea surface height monitoring. The process that ends with the TOPEX main observable (the range between the satellite and the sea surface) involves the measurement of several parameters of the radar pulses reflected by the sea surface and the computation of several other corrections. After several calibration campaigns performed by the Calibration/Validation team of the mission, it was found that TOPEX range determinations were systematically shorter than expected and it was decided to add an empirical correction of +15 mm to the TOPEX range-computation algorithm. As a by-product, TOPEX provides vertical total electron content (vTEC) determinations which have turned out to be a very important data source for the ionospheric research community. Since TOPEX vTEC measurements became available, several comparison studies have detected a constant bias, from +2 to +5 TECu, when TOPEX is compared to other vTEC sources, e.g., Global Positioning System (GPS), Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS), (TOPEX always greater than the others). In this work, we show that miscalibration of the corrections used in the TOPEX processing algorithm can cause the shortening effect of TOPEX ranges and at the same time the constant bias on the TOPEX vTEC values. It is also shown that changes on TOPEX System Biases of less than 10 mm for the Ku-band and between 40 and 70 mm for the C-band, can make both effects disappear. The analyzed hypothesis is supported by theoretical considerations and data analysis available in the specialized literature.

Keywords TOPEX total electron content (TEC) bias · TOPEX system biases · GPS TEC

1 Introduction

During 15 years of continuous service, the TOPEX/Poseidon (T/P) mission proved to be such a success that it has marked the beginning of a new era on oceanographic studies (see Chelton et al. 2001). T/P has pushed the ocean research to never-before reached levels of resolution, accuracy, data continuity, etc. A clear example of this is the vast list of works and publications that can be found in the specialized literature based on data/results produced by the T/P mission (e.g., NASA—CNES Workshop, 15 years or Radar Altimetry, Venice, Italy, 19–21 April 2006).

The process that ends with the TOPEX main observable (the range between the satellite and the sea surface) is very complex since it involves the measurement of several parameters of the radar pulses reflected by the sea surface and the computation of several other corrections (a brief description

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On behalf of the authors of the contribution 'Analysis of the bias between TOPEX and GPS vTEC determinations', I declare that the paper has not been, nor is in the process of being published in any other publication.

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is presented in next section). The TOPEX radar altimeter estimates the range between the satellite and the sea surface at two different frequencies in a process that involves correcting the measurements by several frequency-dependent effects (not associated with the ionosphere). Then, the range free of the ionospheric error is computed by combining the range estimates on both frequencies.

After several calibration campaigns performed by the mission Calibration/Validation (CAL/VAL) team comparing data provided by the satellite with in situ measurements at dedicated calibration sites, the team found that TOPEX range determinations were systematically shorter than expected and added a new empirical correction of +15 mm to TOPEX range computation algorithm (Blanc et al. 1996; Benada 1997), after which the TOPEX ranges reach an accuracy of few millimeters.

Due to the high-precision capability of the T/P main radar to measure the vertical total electron content (vTEC), T/P has also played an important role on ionospheric research (e.g., Imel 1994; Ho et al. 1997; Codrescu et al. 2001). The vTEC is defined as the integral of the electron density along the vertical. The unit chosen for measuring the vTEC is called total electron content unit (TECu), 1 TECu being equivalent to 10^{16} electrons m^{-2}. Depending on local time, solar activity, geomagnetic conditions, region of the Earth, etc., the vTEC can vary from about 1 to more than 250 TECu (e.g., Brunini et al. 2003).

Since TOPEX vTEC measurements became available, several comparison studies to vTEC determinations from other sources have been carried out (e.g., Imel 1994; Ho et al. 1997; Codrescu et al. 2001; Hernandez-Pajares 2003; Delay and Doherty 2004; Brunini et al. 2005). Many of these studies have detected a constant bias ranging from 2 to 5 TECu when TOPEX vTEC is compared to GPS and DORIS vTEC (TOPEX greater than the others). This is a paradoxical result because GPS estimates are sensitive to the ionosphere plus the plasmaphere contribution, whereas TOPEX samples only the portion that goes from the sea surface to the 1,336-km satellite altitude.

After Ciraolo and Spalla (1997), Gallager et al. (1988), the contribution to vTEC from the region above TOPEX altitude (1,330 km) can reach values as large as 10 TECu for low geomagnetic latitudes. From this, GPS vTEC determinations should be at least few TECu larger than TOPEX vTEC and not the other way around, as the results show. This issue is addressed in Sect. 6, where the plasmaspheric effects are accounted for by using the parameterized ionospheric model (PIM) (Daniell et al. 1995) to compute the contribution to the vTEC due to the ionosphere above the T/P satellite and the plasmasphere.

Chelton et al. (2001) pointed out the possibility that the TOPEX vTEC bias could be related to systematic errors applied to TOPEX range observations on each frequency before computing the vTEC. As will be presented in Sect. 4, analyzing more than 2 years of GPS and TOPEX data we found a constant bias between GPS and TOPEX-derived vTEC, which is in accordance with the other results already cited in this paper. Pursuing the hypothesis postulated by Chelton et al. (2001), we found that an inaccuracy in some of the corrections applied to TOPEX range estimates may cause the bias in vTEC and, at the same time, create the need of the empirical correction to achieve the accuracy of few millimeters in the TOPEX range estimates.

2 TOPEX vTEC and range computation

TOPEX—the first dual-frequency altimeter on board a satellite—operates a primary signal in the Ku-band ($f_k = 13.6\,\mathrm{GHz}$) and a secondary in the C-band ($f_c = 5.3\,\mathrm{GHz}$). Combining the estimates from both frequencies it is possible to compute a precise correction of the ionospheric range delay error and to obtain, as a byproduct, an estimate of the vTEC just below the satellite. The precision of TOPEX vTEC estimates is accepted to be 1 TECu (Imel 1994). This precision is obtained by reducing observational random errors through low-pass filtering raw observations over 15–25 successive measurements (Imel 1994; Zlotnicki 1994). The accuracy of the TOPEX vTEC is more difficult to assess as no systematic error affecting the estimates can be detected unless comparisons with external data sources are performed.

Following Chelton et al. (2001), the computation of TOPEX ionospheric corrected (ionospheric-free) range involves two main steps. The first one consists of correcting the range measured by the altimeter on each frequency, $r_j (j = k, c)$, for all those frequency-dependent errors not associated with the ionosphere. The expression for the corrected range is:

$$R_j = r_j + \Delta R_j \tag{1}$$

where the net range correction, ΔR_j, for frequency j can be written as:

$$\begin{aligned} \Delta R_j = {} & \Delta R_{\mathrm{Mod.Intr.}\ j} && \text{modeled instrumental delay} \\ & + \Delta R_{\mathrm{Dop.}\ j} && \text{Doppler correction} \\ & + \Delta R_{\mathrm{Sys.Bias}\ j} && \text{system bias} \\ & + \Delta R_{\mathrm{SSB}\ j} && \text{sea state bias} \end{aligned} \tag{2}$$

where the $\Delta R_{\mathrm{Sys.Bias}\ j}$ are constant. The obtained $R_j (j = k, c)$ are still affected by the ionospheric error and can be written as $R_j = R + \Delta R_{j\mathrm{iono}}$, where R is the distance between the satellite and the sea surface, $\Delta R_{j\mathrm{iono}} = \frac{\alpha\ \mathrm{vTEC}}{f^2}$ and α is a constant.

In the second step, the ionospheric corrected range is computed from the following expression:

$$R = a_k R_K - a_c R_c \tag{3}$$

where $a_k = \frac{f_k^2}{f_k^2 - f_c^2} = 1.18$ and $a_c = \frac{f_c^2}{f_k^2 - f_c^2} = 0.18$.
From Eq. (3) it follows that any systematic errors ε_k on R_k and ε_c on R_c, will result in a systematic error ε_R on R given by:

$$\varepsilon_R = a_k \varepsilon_k - a_c \varepsilon_c \tag{4}$$

Apart from the ionospheric corrected range, TOPEX provides vTEC estimates using the following expression:

$$\mathrm{vTEC} = \frac{a_c}{\beta_k}(R_c - R_k) \tag{5}$$

where $\beta_k = \frac{40.25 \times 10^{16}}{f_k^2} = 2.2$ mm/TECu.
From Eq. (5) it follows that any systematic errors ε_k and ε_c will result in a systematic error $\varepsilon_{\mathrm{vTEC}}$ on vTEC given by:

$$\varepsilon_{\mathrm{vTEC}} = \frac{a_c}{\beta_k}(\varepsilon_c - \varepsilon_k) \tag{6}$$

The computation of the ionospheric corrected range R given by Eq. (3) is equivalent to correcting the Ku-band measured range R_k by the ionospheric error due to the vTEC computed using Eq. (5). Thus, any systematic error on the determination in the vTEC will be coupled with a systematic error in the determination of R. In other words, if the vTEC is overestimated, the ionospheric correction would be greater than the real one and the corrected range R would be underestimated.

As was mentioned in Sect. 1, TOPEX CAL/VAL team compared the sea surface height determined by TOPEX to tide gauge records at two dedicated sites (Point Conception, near California; and Lampedusa, Mediterranean Sea) and found that TOPEX range determinations were too short (see Blanc et al. 1996; Benada 1997). The same problem was also verified when TOPEX computed ranges were compared with the ranges computed with the Poseidon instrument (a redundant altimeter on board TOPEX/Poseidon satellite). In order to account for this difference, TOPEX CAL/VAL team decided to add an empirical correction of +15 mm to the ionospheric-free range estimated by TOPEX.

After Chelton et al. (2001), the unique difference between TOPEX and Poseidon processing strategy to compute the range is that TOPEX corrects the ionospheric error based on the computation of the vTEC using the ranges measured on both frequencies (as was explained before), while Poseidon ionospheric correction is based on observations from the DORIS system (see http://ids.cls.fr). This strengthens the hypothesis that a constant error in the estimation of the vTEC from the TOPEX measurements may create the need for the +15 mm empirical correction in order to achieve a few millimeters accuracy in the range estimates.

3 GPS vTEC computation

The GPS vTEC values used in this work were computed using the La Plata Ionospheric Model (LPIM) (Brunini et al. 2005; Azpilicueta et al. 2005). The slant total electron content is obtained from the geometry-free linear combination of the dual-frequency carrier phase observations with elevations greater than 10°. LPIM approximates the whole ionosphere to a spherical shell of infinitesimal thickness located 450 km above the Earth's surface. Signals coming from the satellites to a receiver pierce the shell at the so-called piercing point. The slant total electron content is related to the vTEC at the piercing point by the approximate mapping function $\sec(z')$, where z' is the satellite zenith distance at the piercing point. The two-dimensional vTEC distribution on the shell is described by a spherical harmonic expansion up to a degree and order 15, depending on LT and modip. The coefficients of the spherical harmonic expansion series are estimated by least squares adjustments, using observations from a global network of tracking stations. The observations are processed on a day-to-day basis to simultaneously estimate a set of spherical harmonic coefficients at every 2-h UT interval [0–2), [2–4),. . .,[22–24); and the differential code biases for each receiver and each satellite. The estimated coefficients allow the computation of vTEC for any location and time.

4 Data processing and results

Based on GPS data from an average of globally distributed 120 continuous tracking stations (Fig. 1) belonging to the International GNSS Service (Beutler et al. 1999) and using the LPIM, we compute one Global Ionospheric Map (GIM) of the vTEC distribution every 2 h, for the period from 1 January 1998 until 10 February 2000. For the same period, TOPEX vTEC measurements were processed using a low-pass-band filter. This process reduced the measurement noise and provided one vTEC-smoothed measurement approximately every 25 s. The TOPEX vTEC measurements used in this work are publicly available at the Physical Oceanographic Distributed Active Archive Center (National Aeronautics and Space Administration—Jet Propulsion Laboratory, ftp://podaac.jpl.nasa.gov).

During the time period analyzed, TOPEX control mission decided to switch from Altimeter A to Altimeter B due to a malfunction detected on Altimeter A. Therefore, we split our analysis in two different periods of time: the first one goes from 1 January 1998 to 9 February 1999 (Altimeter A), while the second one goes from 11 February 1999 to 11 February 2000 (Altimeter B).

Based on the GIMs computed with LPIM, one $\mathrm{vTEC}_{\mathrm{LPIM\_GPS}}$ value was calculated for the location and time of every $\mathrm{vTEC}_{\mathrm{TOPEX}}$ and the difference $\Delta\mathrm{vTEC} =$

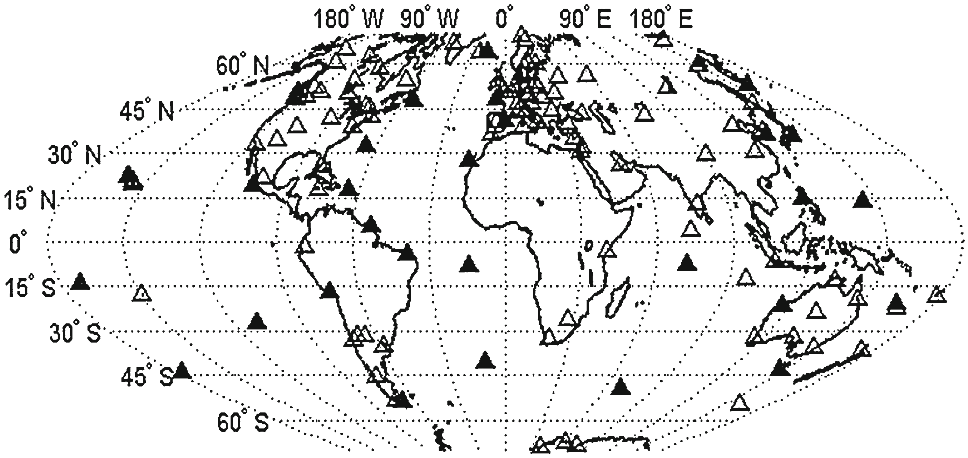


Fig. 1 IGS continuous tracking stations used in this work. The *filled triangles* indicate the selected sites for computing mean values (sinusoidal projection)

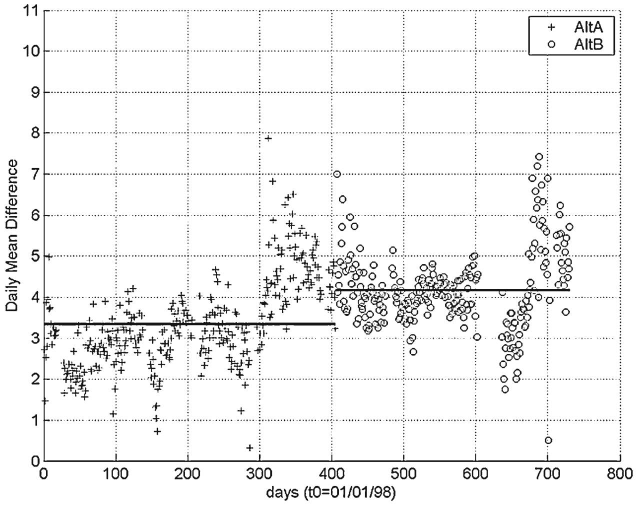


Fig. 2 Time series of ΔvTEC daily means along the 2-year-period analyzed. The *crosses* correspond to Altimeter A and the circles to Altimeter B data

$\mathrm{vTEC_{TOPEX}} - \mathrm{vTEC_{LPIM\ GPS}}$ was computed. Figure 2 shows a time series of ΔvTEC daily means along the 2-year-period analyzed. The crosses correspond to Altimeter A and the circles to Altimeter B data. This figure clearly shows a bias whose mean value is in the order of 3–4 TECu for both altimeters. A linear trend is also present in the time series, particularly for Altimeter A data, but this effect is comparatively small in relation to the bias itself.

The variability of the vTEC in space and time is mostly driven by the Sun and the geomagnetic field. The use of the Local Time (LT) coordinate smoothes-out the vTEC variability due to the day-night cycle while the use of the modip coordinate smoothes-out the latitudinal variability, particularly in low-latitude regions and, moreover, in the region of the South-Atlantic geomagnetic anomaly (Azpilicueta et al. 2005). In the LT-modip coordinate system, the Equatorial Anomaly stays quiet in a region that spans from approximately −2:00 to +18:00 LT and from approximately ±20° to ±30° of modip. A similar coordinate system was introduced in Codrescu et al. (2001). In order to investigate the behavior of the vTEC bias in this coordinate system, the ΔvTEC values were binned into a mesh of spherical triangles defined in that system. After this, a mean ΔvTEC was computed for every triangle for the Altimeter A time period and the same was done for the Altimeter B time period. It is important to note that since the coordinate system is LT—modip, the mean value for every triangle is computed using a set of data corresponding to different geographic latitude, geographic longitude, universal time and day of the year. Figures 3 and 4 show the mean ΔvTEC values mapped in the LT—modip system for Altimeter A and Altimeter B data, respectively. The dominant feature in these figures is a constant bias ranging from 3 to 4 TECu, as it was already pointed out after Fig. 2.

TOPEX only measures the vTEC over the sea, in order to improve the determination of the mean ΔvTEC value; a set of 28 IGS tracking stations close to coasts—distributed as homogenously as possible on the Earth surface—were selected (filled triangles in Fig. 1). Data points within a 5°-radius circle centered on each of these stations were analyzed, thus obtaining mean values of (+3.03 ± 0.03) TECu for the Altimeter A period and of (+3.72±0.04) TECu for the Altimeter B period. This procedure warrants that the mean ΔvTEC values are computed where LPIM is driven by GPS measurements, thus minimizing interpolation errors.

As mentioned in the Sect. 1, GPS vTEC must be greater than TOPEX vTEC mostly due to the contribution of the plasmasphere that is located much higher than the 1,330-km orbital altitude of the T/P satellite. The plasmapheric contribution to vTEC and its effect on ΔvTEC is analyzed in Sect. 6.

5 Analysis of the results

From the comparison presented in Sect. 4, it is clear that a constant bias exists between vTEC estimates from TOPEX

Fig. 3 ΔvTEC (TOPEX-LPIM_GPS) averaged for the Altimeter A data, mapped against local time-modip coordinates (sinusoidal projection)

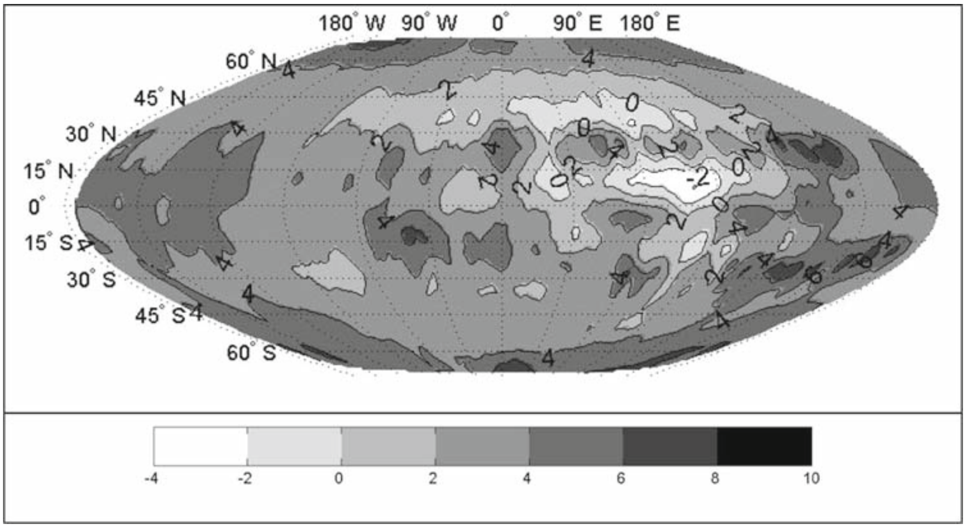
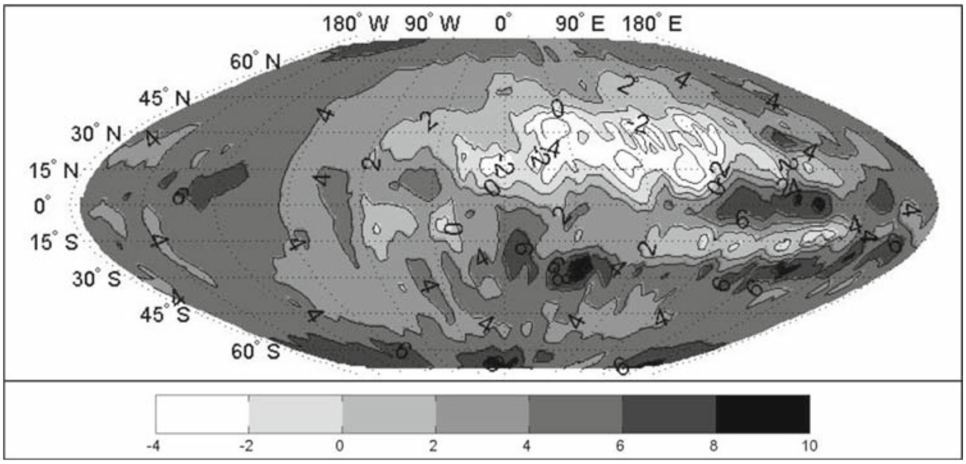


Fig. 4 ΔvTEC (TOPEX-LPIM_GPS) averaged for the Altimeter B data, mapped against local time-modip coordinates (sinusoidal projection)



and LPIM_GPS. In principle, this bias could be produced by an overestimation on TOPEX vTEC and/or by an underestimation of LPIM_GPS vTEC. However, the discussion presented in the last paragraph of Sect. 2 indicates that a systematic error source should be associated to TOPEX. From Eqs. (4) and (6), it follows that a miscomputation of the net range corrections applied to TOPEX range measurements (2) could cause at the same time: (i) the underestimation of TOPEX-computed range with the consequent need for applying the empirical correction of +15 mm; and (ii) a TOPEX vTEC bias of 3–4 TECu.

Assuming that the observed TOPEX-LPIM_GPS bias is completely caused by a TOPEX miscalibration problem and constraining the analysis to the Altimeter A time period, from Eqs. (6) and (4) it follows that:

$$\frac{0.18}{2.2\ \text{mm/TECU}}(\varepsilon_c - \varepsilon_k) = -3.03\text{TECU} \tag{7}$$

and

$$1.18\varepsilon_k - 0.18\varepsilon_c = +15\ \text{mm} \tag{8}$$

Solving Eqs. (7) and (8) for ε_k and ε_c leads to:

$$\varepsilon_k = 8\ \text{mm}$$
$$\varepsilon_c = -28\ \text{mm}$$

Repeating the previous analysis for the Altimeter B period, i.e., making the left-hand side term of Eq. (7) equals to −3.72 TECu and solving Eqs. (7) and (8) for ε_k and ε_c, leads to

$$\varepsilon_k = 7\ \text{mm}$$
$$\varepsilon_c = -37\ \text{mm}$$

This means that errors lower than 10 and 40 mm on the corrections applied to the TOPEX range measurements on frequency Ku and C, respectively, can result on the TOPEX vTEC bias and the need for the 15-mm empirical correction. Since these two biases are constant, the error source should also be constant.

In Sect. 2, it was said that the only TOPEX constant corrections were the so-called System Biases with values of $\Delta R_{\text{Sys.Bias}\ k} = 0$ mm and $\Delta R_{\text{Sys.Bias}\ c} = +100$ mm for Altimeter A and $\Delta R_{\text{Sys.Bias}\ k} = -20$ mm and

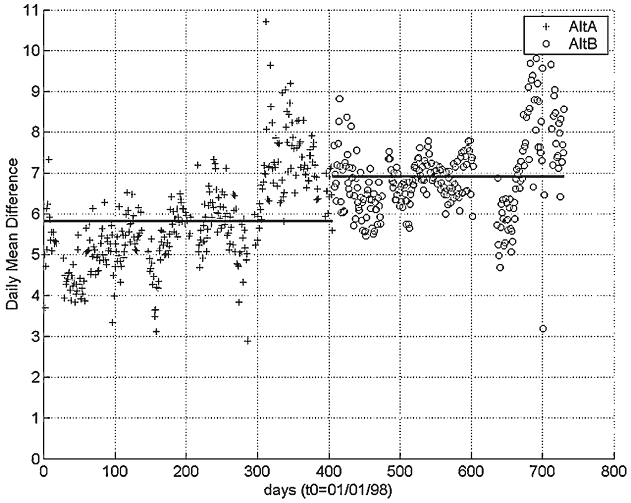


Fig. 5 Time series of ΔvTEC daily means along the 2-year-period analyzed when the upper ionosphere and plasmasphere contributions are considered. The *crosses* correspond to Altimeter A and the *circles* to Altimeter B data

$\Delta R_{\text{Sys.Bias}\ c} = +130$ mm for Altimeter B. The previous results indicate that if the System Biases for Altimeter A are replaced by $\Delta R_{\text{Sys.Bias}\ k} = 8$ mm and $\Delta R_{\text{Sys.Bias}\ c} = +72$ mm, and the ones for Altimeter B are replaced by $\Delta R_{\text{Sys.Bias}\ k} = -13$ mm and $\Delta R_{\text{Sys.Bias}\ c} = +93$ mm, then the TOPEX vTEC bias disappear and the 15-mm range correction is no longer needed.

6 Effect of the plasmasphere

In order to quantify the vTEC contribution from the region of the ionosphere with heights greater than 1,330 km and from the plasmasphere, we have extended our work in the following way. Based on the last release of the Parameterized Ionospheric Model (PIM) source code (publicly available at http://www.cpi.com) (for details see Daniell et al. 1995), which includes a plasmaspheric model developed by Gallagher et al. (1988), the vTEC component from heights greater than 1,330 km was computed for every TOPEX vTEC observation. PIMs main inputs are the Solar Flux at 10.7 cm (f10.7) and the Sun Spots Number (SSN). For the present work, we used monthly means provided by the World Data Center for Solar–Terrestrial Physics, Moscow, Russia (http://www.wdcb.ru/stp/online_data.en.html).

Figure 5 shows the daily mean ΔvTEC when the upper ionosphere and plasmasphere contributions are considered. By a comparison with the Fig. 2, it comes out that the net effect for including this contribution is a +3 TECu average shift of the time series. When the plasmasheric component is considered, the TOPEX vTEC bias is of (+5.81 ± 0.04) TECu for Altimeter A and (+6.92 ± 0.05) TECu for Altimeter B.

In order to account for the effect of the plasmasphere contribution on the estimation of the System Biases Errors, the procedure explained in Sect. 5 was repeated, and Tables 1 and 2 summarize the results. The comparison of the two tables shows that the main effect of including the plasmasphere component is to enlarge the error of the C-band System Bias, from −29 to −61 mm for Altimeter A and from −40 to −76 mm for Altimeter B. The corresponding errors on the Ku-band remain at the order of few millimeters.

7 Conclusions

The main goal of this work is to provide a plausible explanation to the bias between the TOPEX and GPS vTEC observations (but not to provide new values for the TOPEX

Table 1 Summary of the results for Altimeter A

Altimeter A	Mean ΔvTEC (TECu)	Ku-system bias original value = 0 mm (mm)		C-system bias original value = 100.0 mm (mm)	
		Correction	New value	Correction	New value
Excl. the plasmasphere	3.03	8	8	−28	72
Incl. the plasmasphere	5.81	3	3	−61	39

Table 2 Summary of the results for Altimeter B

Altimeter B	Mean ΔvTEC (TECu)	Ku-system bias original value = −20 mm (mm)		C-system bias original value = 130 mm (mm)	
		Correction	New value	Correction	New value
Excl. the plasmasphere	3.72	7	−13	−37	93
Incl. the plasmasphere	6.92	1	−19	−76	64

System Biases), an issue that has been an open task for several years. In the present work, we showed that such a bias could be explained by a miscalibration problem of the system biases, particularly in the C-band.

Based on the results of several dedicated experiments, the T/P CAL/VAL team demonstrated the TOPEX capability to measure the satellite-to-sea surface range with an accuracy of few millimeters; but to reach this accuracy it is necessary to apply an empirical correction of +15 mm to the satellite-to-sea surface range computed from TOPEX (Blanc et al. 1996; Benada 1997). This contribution has presented an analysis that attributes the need of the empirical correction to an error in the System Biases applied to TOPEX range measurement. This hypothesis is in agreement with some theoretical considerations presented in Chelton et al. (2001).

In Sect. 2 of this work, we showed that a miscalibration of TOPEX corrections applied in the first step of TOPEX processing algorithm can cause a shortening of TOPEX ranges and a constant bias on the TOPEX vTEC values, which is in fact confirmed by the data analysis. This indicates that TOPEX vTEC estimates could be biased by a certain constant value whose direct consequence would be the shortening of the TOPEX ranges. Sections 5 and 6 demonstrate that changes of less than 10 mm for the Ku-band and between 30 and 70 mm for the C-band on TOPEX System Biases, can increase the TOPEX range by 15 mm (which means that the empirical correction is no longer needed) and, at the same time, compensate the vTEC bias between the TOPEX and GPS values.

Finally, it is worth to mention that the results presented in this work have no impact on TOPEX/Poseidon sea level studies since the suggested error introduced on the TOPEX range determinations by miscomputing the ionospheric correction has been compensated by the +15-mm empirical correction.

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