SBAS IONOSPHERIC PERFORMANCE EVALUATION TESTS

Xavier Prats (1), Raül Orús (1), Jaume Sanz (1), Richard Farnworth (2), Santiago Soley (2)

(1) Research group of Astronomy and Geomatics, Universitat Politècnica de Catalunya (gAGE/UPC), Barcelona, Spain.
(2) EUROCONTROL Experimental Centre, Bretigny, France.

Key words: SBAS, EGNOS, ESTB, ionospheric corrections, TOPEX

Abstract

Satellite Based Augmentation systems (SBAS) provide to Global Navigation Satellite Systems (GNSS) users with an extra set of information, in order to enhance accuracy and integrity levels of GNSS stand alone positioning. In this context, different test methods to analyze the ionospheric corrections performance are presented. The first set of tests involves two of the ionospheric calculations that are applied daily to the Global Ionospheric Maps (GIM), computed by the IGS Associate Analysis Centers: a TEC TOPEX comparison test and the STEC variations test. The second family of tests provides two very accurate analyses based on large-baselines ambiguity resolution techniques giving comparisons for absolute STEC and double differenced STEC determinations. Those four analyses have been applied using EGNOS System Test Bed (ESTB) data showing some satellite dependent biases.

1. Introduction

The European Geostationary Navigation Overlay Service (EGNOS) system is the first contribution of the European Space Agency (ESA) into satellite navigation. With three geostationary satellites and a network of ground stations, this Satellite Based Augmentation System (SBAS) will be able to transmit to final users with the required additional information on the reliability and accuracy of the positioning signals sent out by US GPS and Russian GLONASS systems, and make them suitable for safety critical applications such as commercial aviation. The EGNOS System Test Bed (ESTB) is the EGNOS prototype, which has been broadcasting a Signal in Space (SIS) since February 2000.

One of the most important parts of SBAS broadcast messages contains the ionospheric corrections, which are an estimate of the satellite signal propagation delay produced by the free electrons distributed in the ionosphere (between 100 and few thousands of Km in height). This delay, which is frequency-dependent, is basically proportional to the integrated electron density along the satellite-receiver ray path and can be removed if dual frequency receivers are used [1]. However, single frequency GNSS users need additional data, provided by an ionospheric model, to correct the errors produced by ionospheric signal delays. Global Positioning System (GPS) broadcast a simple model (using only eight parameters to describe the whole ionosphere) which achieves a reduction of 40-65% of the ionospheric effect (see for instance [2,3]).

In particular, a single thin layer ionospheric model is broadcast in the SBAS message, as vertical delay estimates at specified Ionospheric Grid Points (IGPs), which are defined worldwide. If the approximate user position is known, an interpolation algorithm using surrounding IGPs vertical delay values computes user's position vertical ionospheric delay. This vertical delay is then scaled by an obliquity factor, dependent on the elevation of the satellite (mapping function), to convert it to a slant range correction. The ionospheric corrections and integrity bounds information are broadcast in two different messages (Message types 18 and 26). Message type 18 defines which IGPs are available and message type 26 includes the vertical delay corrections as well as a measure of confidence in the data (for more information about ionospheric corrections in SBAS see [4]).

In this paper, some test procedures and ideas to analyse the performance of such ionospheric corrections are presented and applied, as an example, using data gathered from the ESTB signal. Two different test families are developed. The first set of tests come from the International GPS Services (IGS) and performs a direct vertical ionospheric delay comparison between the ESTB broadcast ionospheric corrections and the TOPEX altimetric satellite Total Electron Content (TEC) measurements, as well as a slant ionospheric delay variation test. The second family of tests provides two very accurate analyses of the slant ionospheric delay at the user's location, based on Long Baseline Ambiguity Resolution techniques.

2. The IGS tests

Since June 1st 1998 Global Ionospheric Maps (GIM) are daily and independently computed by five Ionosphere Associate Analysis Centers (IAAC) to define a common IGS ionospheric product. The IAAC is formed by the Center for Orbit Determination in Europe (CODE), the European Space Agency (ESA), the Jet Propulsion Laboratory (JPL), Natural Resources Canada (NRCan) and our research group (gAGE/UPC) [5]. Data gathered from a huge worldwide IGS permanent network of dual frequency GPS receivers is used for such computation, and the results are compared daily and analyzed using, among others, two different tests. One of them involves a direct comparison between the Total Electron Content (TEC) of the computed GIM and an independent TEC determination from TOPEX altimetric satellite over the oceans or seas. The other test compares predicted versus measured Slant Total Electron Content (STEC) variations from GPS carrier phase measurement along continuous arcs of carrier phase data.

The tests have been applied over 24h data sets of the ESTB signal in space (SIS), within the period from 10 January 2002 to 25 April 2002 during the firsts months of the ESTB Data Collection and Evaluation campaign developed by EUROCONTROL [6].

2.1 Comparing ESTB broadcast TEC with TOPEX measured TEC

TOPEX is an altimetric satellite, orbiting at about 1300 Km of mean height, with a dual transmitter receiver in C-band (5.5GHz) and Ku-band (13.6 GHz) on board, which provides independent vertical ionospheric delays, (or TEC measurements) from the GPS ones, with accuracies of about 2 TECUs [1] (about 30 cm of L1 ionospheric vertical delay) [7].

The TOPEX test consists in computing the BIAS and RMS of the discrepancies between the SBAS and TOPEX TEC (i.e. vertical delays) values:

$$BIAS = < TEC_{TOPEX} - TEC_{ESTB} > \tag{1}$$

$$RMS = \sqrt{< (TEC_{TOPEX} - TEC_{ESTB})^2 >} \tag{2}$$

being hereafter $<\cdot>$ the statistical mean operator. TOPEX TEC is directly obtained from the dual frequency satellite's altimeter measurements and ESTB TEC can be calculated from the ESTB broadcast correction messages.

Finally, the relative error of the measurements is defined as:

$$\varepsilon_r = \frac{RMS}{< TEC_{TOPEX} >} \cdot 100 \tag{3}$$

It must be noted that since TOPEX only delivers altimetric data over significant water surfaces, due to its technical characteristics, only interpolated vertical delays located over seas and oceans can be compared.
In figures 1 and 2, ESTB broadcast TEC values (i.e ionospheric vertical delays) are compared with TOPEX measurements. The TEC is plotted as a function of GPS time and corresponds to the TOPEX tracks which are also given in both figures. Figure 1 corresponds to 25th April 2002, where ESTB vertical corrections match up significantly to TOPEX data, and figure 2 corresponds to 7th February 2002 where large discrepancies between TOPEX and ESTB vertical delays are found.

In figure 3 the ESTB broadcast vertical delays RMS (equation 1) and BIAS (equation 2) are given for different days (one day per week) between 10 January 2002 (*DOY=010*) and 25 April 2002 (*DOY=115*)[2].

---

[1] 1 TEC Unit (TECU) ≈ 10^{16} e^-/m^2 ≈ 16.2 cm of delay on L1 frequency signal.

[2] Some days are not available due to ESTB Signal In Space problems during the data collection

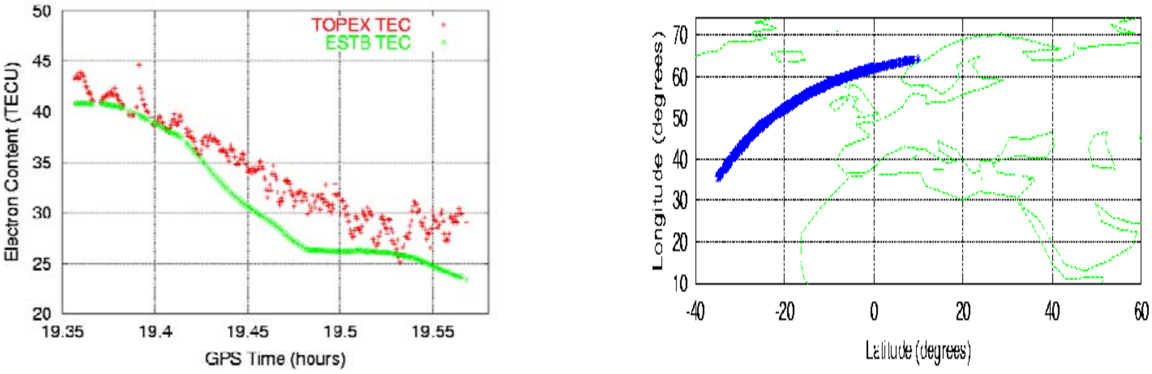

Figure 1: TOPEX-ESTB TEC comparison (left) and TOPEX track (right) for 25th April 2002.

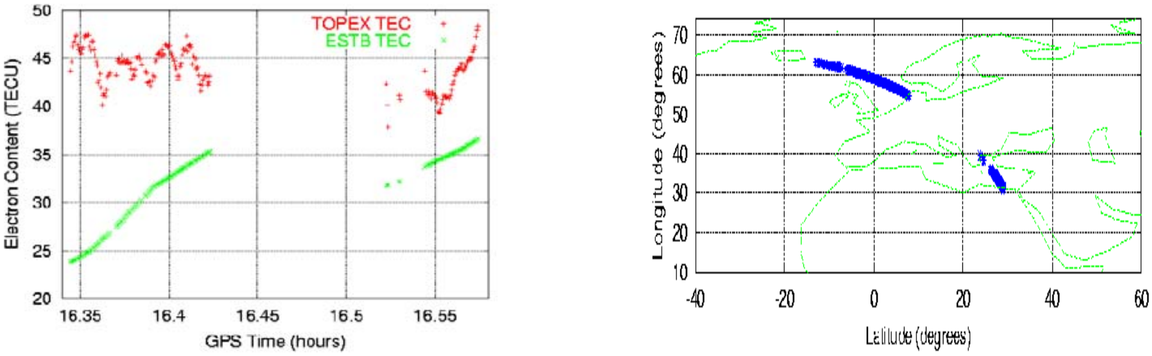

Figure 2: TOPEX-ESTB TEC comparison (left) and TOPEX track (right) for 07th February 2002.

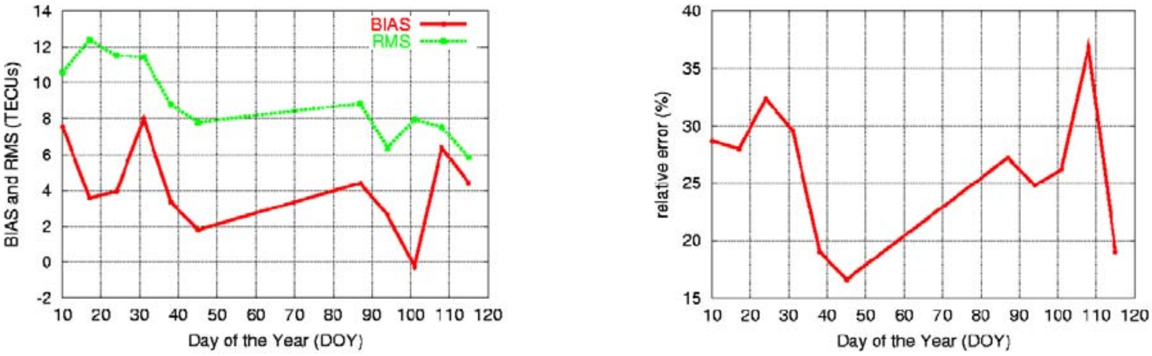

Figure 3: TOPEX test BIAS, RMS (left) and TEC relative error (right).

Each analysed day involves all the TOPEX tracks in the service volume during 24 h from 10 UTC of that day. Notice that, as the TOPEX orbit is at about 1300 Km, the bias should be slightly negative due to the residual TEC between TOPEX and GPS satellite orbits (few TECUS). The relative error between ESTB and TOPEX (equation 3) is also given in the right side of the figure 3.

This test provides an straightforward and independent calibration of the vertical ionospheric delay broadcast for each IGP as well as the interpolation scheme, but does not take into account the contribution of the mapping function in the ionospheric delay model. In order to analyse the slant TEC (STEC), a very simple technique is described in the following section.

2.2 STEC variations test

Computing the ionospheric combination *LI* (as the difference between carrier phase measurements) for each satellite-receiver continuous data phase arc, the following expression is obtained:

$$LI = L1 - L2 = \alpha \cdot STEC + B \tag{4}$$

where carrier phase multipath, wind-up and receiver noise delays have been neglected and being $\alpha \approx 0.105$ m/TECU, and *B* a constant bias including the corresponding carrier phase ambiguity and the instrumental interfrequency biases for each pair satellite-receiver [8].

Thence, the bias *B* being constant along a continuous data phase arc (i.e. without carrier-phase cycle-slips) if, for instance, pairs of observations at the same elevation (at different times) are taken, the following expression is obtained:

$$LI(t_2, e) - LI(t_1, e) = \alpha \cdot dSTEC_{LI}(e) \tag{5}$$

where *e* is the elevation angle of the tracked satellite observed at times t_1 and t_2 along the arc path (figure 4).

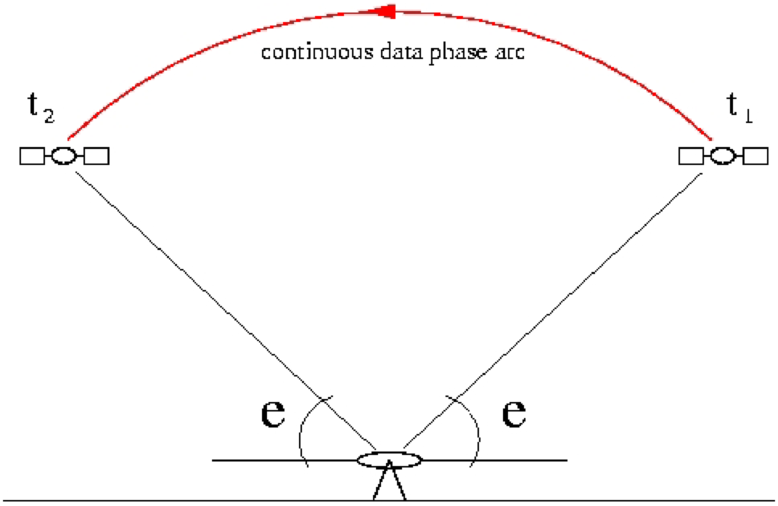

Figure 4: STEC variations test

The same differences can be computed using the STEC values obtained from SBAS algorithms and broadcast message. Hence:

$$dSTEC_{ESTB}(e) = STEC_{ESTB}(t_2, e) - STEC_{ESTB}(t_1, e) \tag{6}$$

The $dSTEC_{LI}(e)$ values are very accurate, giving an error of only few millimetres (less than 0.1 TECUs), corresponding to the carrier phase measurement noise [9]. Therefore, $dSTEC_{ESTB}(e)$ can be compared directly with them, in terms of the elevation:

$$D(e) = dSTEC_{ESTB}(e) - dSTEC_{LI}(e) \tag{7}$$

Finally, a RMS parameter can be computed for different intervals of elevations $[e_1, e_2]$:

$$RMS = \sqrt{\frac{\sum_{e=e_1}^{e_2} \left[D(e)\right]^2}{n}} \tag{8}$$

where n is the number of values compared.

The elevation range [e_1, e_2] is usually taken as [30º, 60º]: the lower bound reduces mapping function and multipath effects and the upper bound assures that significantly time-spaced pair of samples are taken for computation.

This test is quite simple to implement and requires a very low computational cost. Only data from double frequency carrier phase measurements are required (the test is also called *self-consistency test*) and can be easily automated to implement systematic SBAS performance analysis.

In particular it has been applied to data sets gathered using a GPS/SBAS receiver located in Barcelona (UPC). In figure 5 the RMS for this test is plotted for the same days used in the TOPEX test. Similar computations are given in this figure using the TEC values given by Global Ionospheric Maps (computed in post-process and provided by the different IGS IAAC members) instead of ESTB broadcast ionospheric data. As it can be seen, the ESTB RMS shows a similar pattern than the IGS IAAC centers, but with larger RMS values.

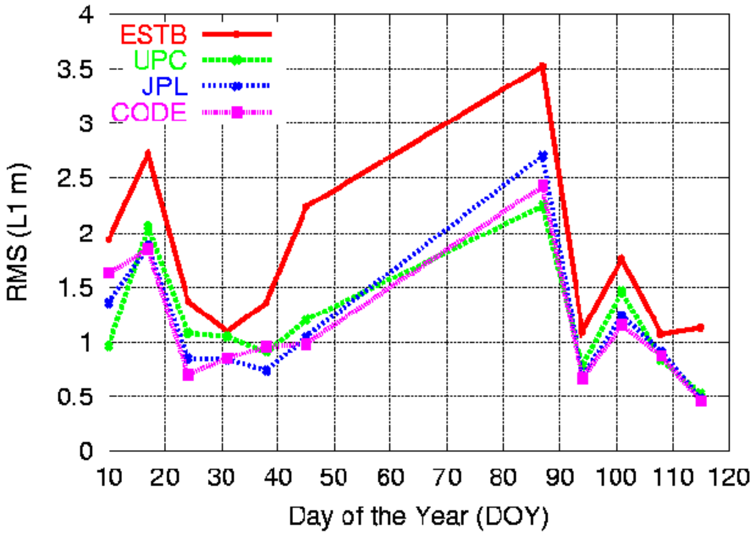

Figure 5: STEC variations test results: RMS

Due to carrier phase ambiguities (term *B* in equation 4) it is not possible to directly compare the SBAS provided STEC values with the received phase measurements, and only differences of STEC, along continuous phase-data arcs can be compared. In the next section this problem is overcomed, where absolute comparison of STEC values can be performed thanks to accurate STEC determinations computed from long-baseline carrier phase ambiguity resolution techniques.

3. The ambiguity resolution tests

In [10,11] it is shown that SBAS control networks have the potential capability to support very accurate GNSS navigation resolving carrier phase ambiguity On-The-Fly (OTF). A sub-decimetric accuracy is achieved for areas of thousand of kilometers across. OTF carrier phase ambiguities resolution requires a very accurate ionospheric refraction estimation, which can be computed in a Master Station (MS) using data gathered from a set of dual frequency reference receivers and broadcast subsequently to the user with range and time corrections (figure 6).

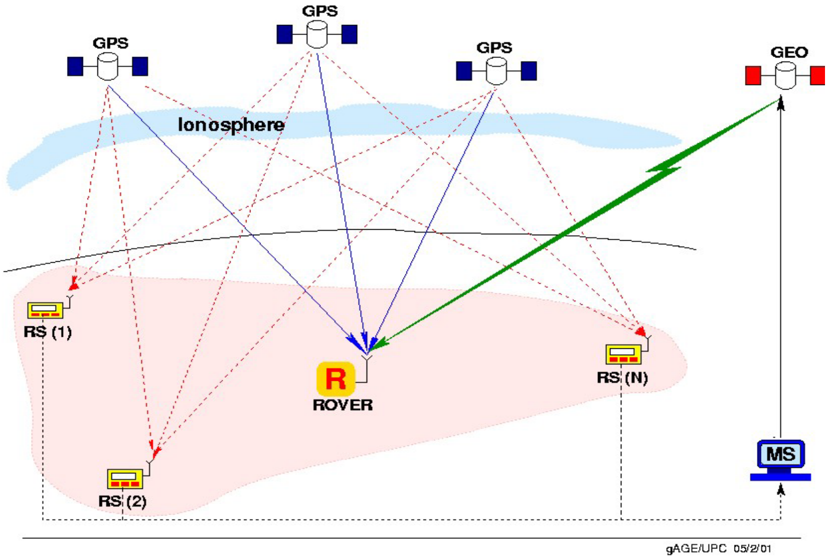

Figure 6: Long-Baseline (hundreds of Km) OTF ambiguity Resolution network

The algorithm running in the MS computes two ionospheric products: an estimation of the absolute STEC ($\overline{STEC}$), and the satellite-receiver double differenced STEC ($\Delta\nabla STEC$). The $\overline{STEC}$ is computed using a tomographic model approach, where the fixed ambiguities are assimilated as new observations. It provides an accuracy of about 1 TECU. On the other hand, the accuracy of the $\Delta\nabla STEC$ values is of few millimeters, because it comes from phase measurements after fixing the ambiguities. For more information about the MS algorithm and the OTF carrier phase ambiguities consult for instance [10,12]. Thence, these $\overline{STEC}$ and $\Delta\nabla STEC$ computed values are used as a precise ionospheric reference in order to test the absolute and double differenced $STEC_{ESTB}$ accuracy.

In particular, this comparison has been performed for 28th march 2002, using a network of ten permanent reference stations (see map in figure 7). These values have been used as references to compare the performance of the ESTB ionospheric corrections computed using broadcast corrections and following the ESTB interpolation algorithm defined in [4].

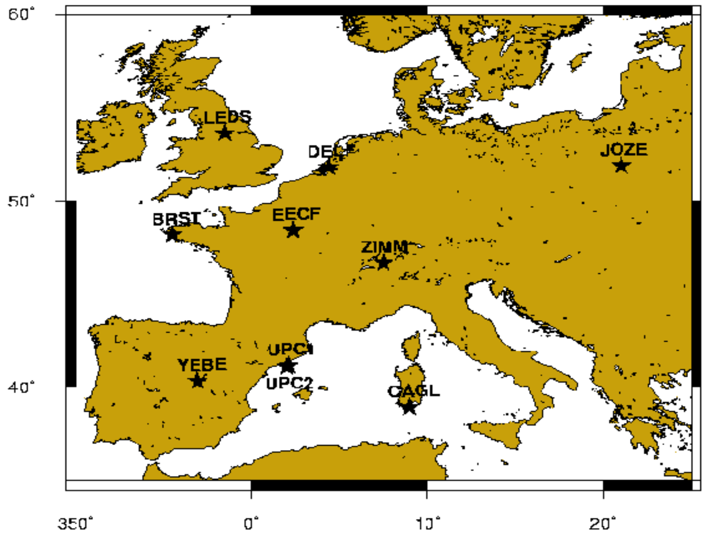

Figure 7: Map of the different reference stations used for the ambiguity resolution test.

Figure 8 show the comparison between absolute STEC values computed from the ESTB message, given by ESTB in DELF, LEDS and UPC1 stations, and the STEC values computed at these sites using the ambiguity resolution algorithm. As an example, the plots for two different GPS satellites (PRN01 and PRN13) are given. In general a clear satellite-station dependent bias can be observed, that can reach up to 2 meters or more and also a discrepancy in the shape of the curves. Note that, as the discrepancies are several times higher than the accuracy of the reference STEC values (about 16cm of L1) these results exhibit a clear missmodelling in the ESTB analysed ionospheric corrections.

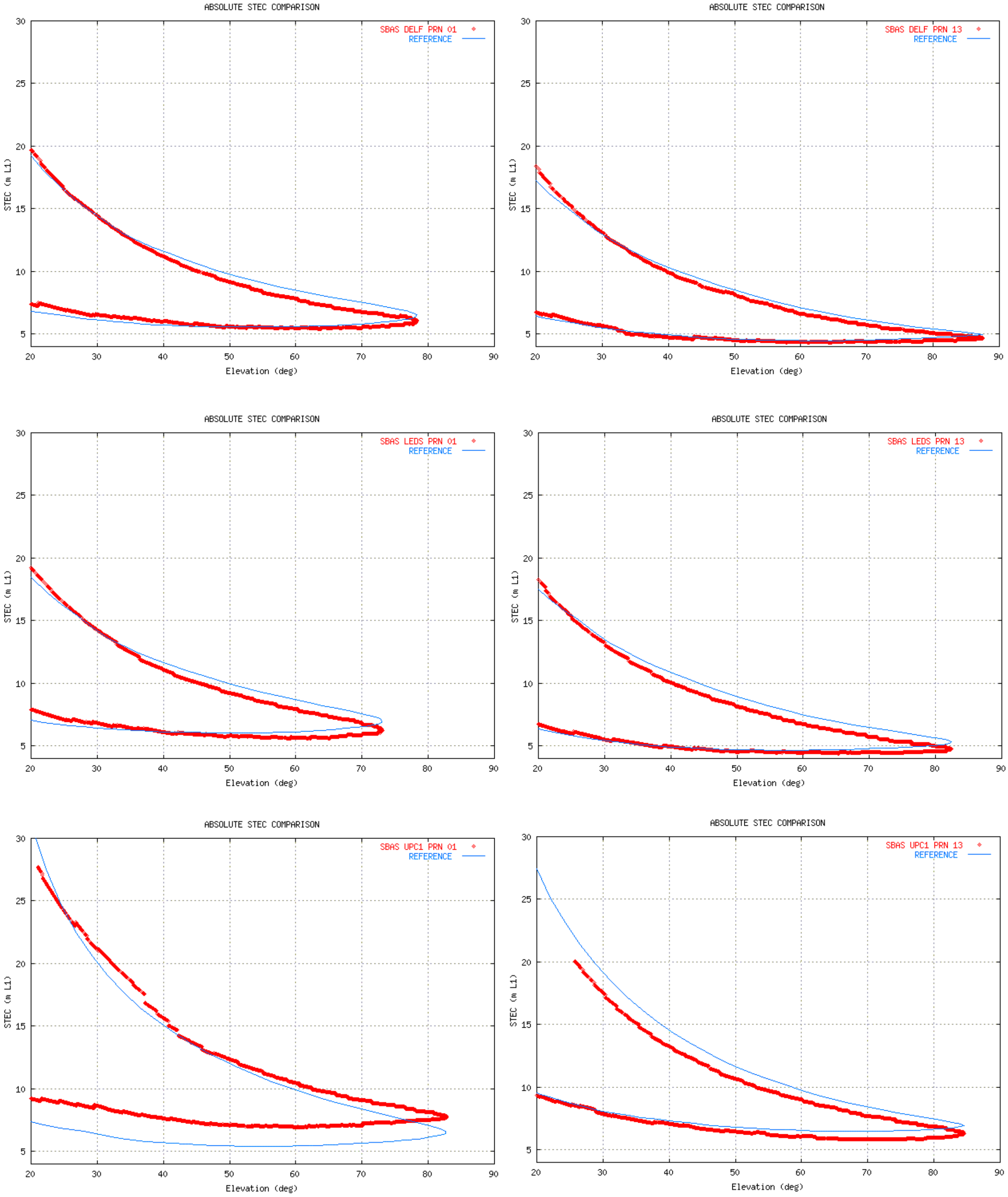

Figure 8: Absolute STEC comparison for PRN01 (left column) and PRN13 (right column). First row corresponds to DELF site, second row to LEDS site and third row to UPC1 site.

Figure 9, shows the discrepancies found between the unambiguous $\Delta\nabla STEC$ and the computed ESTB $\Delta\nabla STEC$ DELF site, for all the satellites in view. The double differences have been computed using UPC1 (1200 Km of baseline from DELF) site as reference station and the satellite with maximum elevation as reference satellite. The particular results for PRN08 are also given in this plot. The horizontal axis corresponds to the elevation of the satellites in view, and the vertical axis corresponds to $\Delta\nabla STEC$ error.

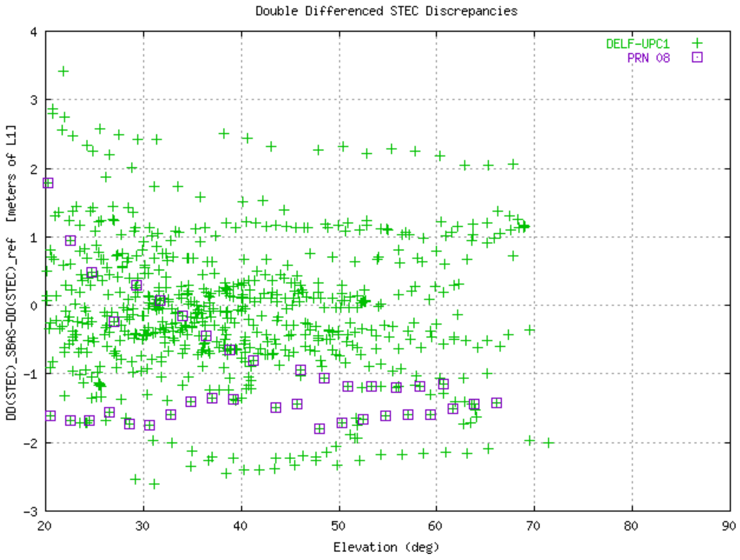

Figure 9: $\Delta\nabla STEC$ error for DELF site using UPC1 as reference station.

Figure 10 shows the same test results applied using LEDS site (with 1400 Km of baseline from UPC1 respectively).

In the same way that it has been observed in the previous test, a clear satellite-station dependent bias appears, that can reach up to 2 meters of error or more and also a pattern as a function of the elevation. Notice that this error in the $\Delta\nabla STEC$ affects directly the positioning error, because it cannot be assimilated in other SBAS broadcast corrections.

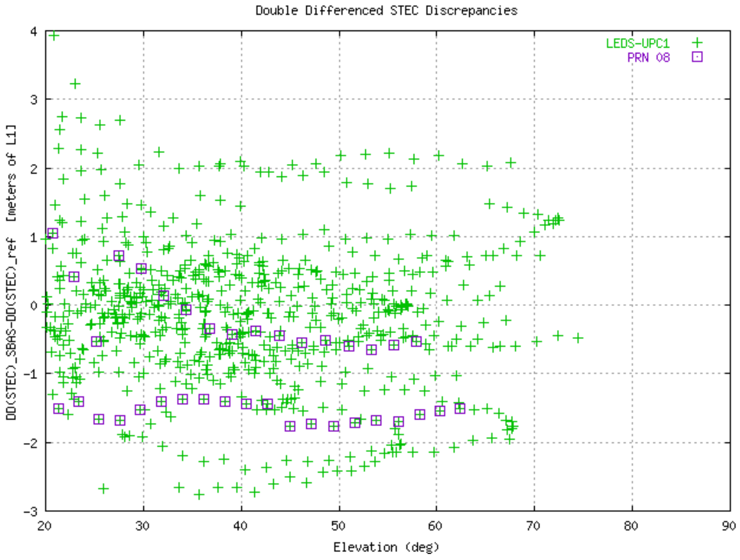

Figure 9: $\Delta\nabla STEC$ error for LEDS site using UPC1 as reference station

4. Conclusions

In this paper four different tests in order to analyse the ESTB ionospheric corrections have been presented.

The first family of tests come from the IGS procedures and can provide reliable analysis of the performance of the ESTB ionospheric corrections. The first IGS test compares ESTB broadcast vertical ionospheric delays with an independent source of TEC measurements, provided by TOPEX altimetric satellite. The second IGS test analyses the variations of the slant corrections for a given site, providing some extra information, concerning the mapping function. These tests provide a straightforward analysis of ionospheric ESTB performances with a low computational cost and with the possibility to be implemented automatically on a regular daily basis. Due to carrier phase ambiguities, the IGS tests can not analyse directly the accuracy of the absolute slant ionospheric delays (i.e. STEC), which are the pseudo-range corrections that will be used for positioning by the ESTB user.

The second family of tests use On-The-Fly Long Baseline carrier phase Ambiguity Resolution techniques in order to compute accurate STEC estimations and unambiguous $\Delta\nabla STEC$ which are compared directly to the ESTB broadcast STEC. This technique allows a direct analysis of slant ionospheric delays, but requires more computational load.

Although all presented tests have been applied to analyse the performance of the EGNOS system test bed (ESTB) signal, those ideas can be applied in any SBAS system.

IGS tests have been applied every week from 10 January 2002 to 25 April 2002 over 24h data sets showing large discrepancies with relative errors that can reach up to 30\% or more for TOPEX comparison, or RMS values in the STEC variations tests 2 or 3 times greater that those obtained when using the Global Ionospheric Maps (GIMs) computed in post-processing by different IGS IAAC centers. Using direct STEC comparison (ambiguity resolution tests) a clear satellite-station dependent bias has been observed leading to errors that can reach up to 2 meters or more.

Acknowledgments

This work has been performed under EUROCONTROL Contract Number C/1.239/CE/JR/01.
We are also grateful to IGS for providing us with the ground GPS data.

References

[1]. Kenneth Davies. Ionospheric radio. Peter Peregrinus Ltd., London, UK, 1990.
[2]. J. A. Klobuchar. Ionospheric Effeects on GPS, volume 1of Parkinson B.W. and Spilker J.J., Global Positioning System: Theory and Applications, chapter 12, pages 485-515. American Institute of Aeronautics and Astronautics Inc. 1996.
[3]. Raül Orús, Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz, and Miquel García-Fernández. Performance of different TEC models to provide GPS ionospheric corrections. Journal of Atmospheric and Solar-Terrestrial Physics, 2002. 64(2002) 2055-2062, 2002
[4]. RTCA Special Committee 159 Working Group 2. Minimal Operational Performance Standards for GPS/WAAS Airborne equipment, June 1998. Doc. No. Do229A
[5]. J. Feltens. The International GPS service (IGS) ionosphere working group. Proceedings of the beacon satellite symposium. Boston. June 2001
[6]. Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz, Xavier Prats, and Raul Orús. Results presented at the 2nd working group meeting. Technical report, ESTB Data Collection and Evaluation, June 2002
[7]. C. M. Ho, B.D Wilson, A.J Mannuci, U. J Lindqwister, and Yuan D. N. A comparative study of ionspheric total electron content measurements using global ionopheric maps of GPS, TOPEX radar, and the bent model. Radio Science, 32:1499-1512, 1995.
[8]. Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz. Global observation of the ionospheric electronic response to solar events using ground and LEO GPS data. Journal of Geophysical Research (Space Physics), 103(A9):20789-20796, 1998.
[9]. David Wells et al. Guide to GPS positioning. Canadian GPS associates, Frederickton, 2 edition, 1987.

[10]. Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz and Oscar L. Colombo. Application of ionopheric tomography to real-time GPS carrier –phase ambiguities resolution, at scales of 400-1000 km, and with high geomagnetic activity. Geophysical Research Letters, 27:2009-2012, 2000.
[11]. Oscar L. Colombo, Manuel Hernández-Pajares, Miguel Juan, and Jaume Sanz. Tomography helps to resolve GPS ambiguities on-the-fly at distances of hundreds of kilometers during high geomagnetic activity. In Position Location and Navigation Symposium, March 2000.
[12]. Manuel Hernández-Pajares, Miguel Juan, Jaume Sanz, and Oscar L. Colombo. Precise ionospheric determination and its application to real-time GPS ambiguity resolution. In ION-GPS, 1999. 1