Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2012, Article ID 734280, 15 pages
doi:10.1155/2012/734280

Research Article

Assessment of the Ionospheric and Tropospheric Effects in Location Errors of Data Collection Platforms in Equatorial Region during High and Low Solar Activity Periods

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Received 15 August 2011; Accepted 3 November 2011

Academic Editor: Maria Zanardi

The geographical locations of data collection platforms (DCP) in the Brazilian Environmental Data Collection System are obtained by processing Doppler shift measurements between satellites and DCP. When the signals travel from a DCP to a satellite crossing the terrestrial atmosphere, they are affected by the atmosphere layers, which generate a delay in the signal propagation, and cause errors in its final location coordinates computation. The signal propagation delay due to the atmospheric effects consists, essentially, of the ionospheric and tropospheric effects. This work provides an assessment of ionospheric effects using IRI and IONEX models and tropospheric delay compensation using climatic data provided by National Climatic Data Center. Two selected DCPs were used in this study in conjunction with SCD-2 satellite during high and low solar activity periods. Results show that the ionospheric effects on transmission delays are significant (about hundreds of meters) in equatorial region and should be considered to reduce DCP location errors, mainly in high solar activity periods, while in those due to tropospheric effects the zenith errors are about threemeters. Therefore it is shown that the platform location errors can be reduced when the ionospheric and tropospheric effects are properly considered.

1. Introduction

The Brazilian Environmental Data Collection System is currently composed by SCD-1 and SCD-2 satellites, hundreds of data collection platforms (DCPs), receiving ground stations located at Cuiabá and Alcântara, and Data Collection Mission Center located at Natal, Brazil.

In this system, a satellite works as a message relay transponder. A DCP to receiving ground station communication link is established when a simultaneous DCP to satellite (uplink) and satellite to receiving station (downlink) occurs simultaneously. UHF frequency bands are used for uplink and S band for the downlink. The uplink Doppler shifts are measured and time-stamped at a receiving ground station while the downlink Doppler shift is compensated for by the receiving equipments. The DCPs messages transmitted by satellites and received by Cuiabá or Alcântara ground station are sent to the Data Collection Mission Center, now located at INPE (Brazilian National Institute for Space Research) Northeast Regional Center in Natal city, Brazil, where the data are processed, stored, and distributed to users. The users receive data at most 30 minutes after the satellite pass.

The DCP geographical location can be determined using the uplink (around 401,635 MHz) Doppler measurements, the statistical least squares method, and knowledge of the satellite orbit. As the S band (2.26752 GHz) downlink is compensated by the ground station receiver, it is not considered in this study.

The signal transmitted from a DCP to a satellite is affected during its travelling across the atmosphere. Among other factors the signal path is influenced by the chemical elements that make up the extensive Earth's atmosphere resulting in propagation delays. As a consequence, errors are present in the final coordinates provided to system users.

As such the ionosphere and the troposphere in vertical direction can be an important source of errors in the platforms location. The errors due to ionosphere can vary from tens to hundreds of meters depending on frequency, while in the troposphere the zenith errors are generally between two and three meters [1–3].

In Celestino et al. [3] the simulated and real effects of ionosphere and troposphere in DCPs geographical location in the Brazilian Environmental Data Collection System were evaluated. In this work, in order to evaluate the effects associated with the ionosphere, the values of total electron content (TEC) were obtained from the standard IRI (International Reference Ionosphere) model. The troposphere values, dry and wet components, were obtained from data of CPTEC-INPE (Weather Forecast and Climate Studies Center). The study did not consider the effects of solar activity periods, but only the time of a day. Results of the analysis indicated that correction of the ionosphere and troposphere effects can, on the average, reduce the location errors to the scale between 10 to 250 meters.

In the absence of the selective availability (signal corruption which was turned off on May 1st, 2000) the largest source of error in GPS positioning and navigation, using L1 frequency receiver, has been the ionosphere. The ionospheric effects were investigated by Camargo et al. [4] in the determination of point positioning and relative positioning using single frequency data. The model expressed by a Fourier series and the parameters were estimated from data collected at the active stations of RBMC (Brazilian Network for Continuous Monitoring of GPS satellites). Experiments were carried out in the equatorial region, using data collected from dual frequency receivers. In order to validate the model, the estimated values were compared with "ground truth". Results show, for point positioning and relative positioning, a reduction of error better than 80% and 50%, respectively, compared to the processing without the ionosphere model. These results give an indication that more research must be done to provide support to L1 GPS users in the equatorial region.

Hence, the present work is divided into two phases: the first is an analysis of the DCP location errors generated by the delay of the signal propagated in the ionosphere.

Therefore, the ionosphere is considered in two different periods according to their intensity (periods of high and low solar activity). The ionosphere representation through TEC values (Total Electron Content) was obtained from IRI model—International Reference Ionosphere [5]—and the one derived from GPS measurements in IONEX version—IONosphere map EXchange [6]. These analyses show the relevance of the errors due to the ionospheric delay in different periods and with use of different models. Doppler shift measurements are simulated for ideal cases in order to measure the influence of the ionosphere at the location. A Doppler shift measurement corresponds to the difference between a received signal frequency at the satellite and the nominal platform transmitter frequency. This shift is caused by the relative velocity between the satellite and platform. In this work, the DCP no. 32590 (15.55293°S and 56.06875°W) was selected for geographical location studies due to its location in Cuiabá, Brazil, in the equatorial region, and data availability. The period of data covers the high (2001) and the low solar activity (2009).

The second phase of the work consisted of the analysis of the best model to express the ionosphere in the equatorial region and the use of the selected model for DCP location with Doppler measurements. This work shows that the IONEX file models the ionosphere with a better accuracy, especially in periods of high solar activity, increasing sufficiently the density of the atmosphere in low latitudes, that is, in the equatorial anomaly region. This motivated the selection of the IONEX model for the second phase of the work. In addition to the correction of the ionosphere, the effects of the troposphere were considered by the use of climate data provided from National Climatic Data Center—NOAA Satellite and Information Service.

Real Doppler shift measurements are also used for DCP no. 109 location (located in French Guyana, at 5.1860°S and 52.687°W) and SCD-2 satellite, taking into account the following conditions: time of the satellite pass from 15:00 to 22:00 UT (Universal Time), periods of high solar activity in 2001, and of low solar activity in 2008.

2. Characteristics of the Ionosphere and Troposphere

The ionosphere is roughly located between 50 to 1000 kilometers above the terrestrial surface, being the electromagnetic radiation the largest agent of the ionization process. Furthermore, the Sun inserts great amount of free electrons that contributes for the composition of ionosphere. The solar wind and the solar electromagnetic radiation can have drastic change during a solar storm, which implies changes in the conditions of the magnetic field and the terrestrial ionosphere.

The location error is associated with the ionosphere which is directly proportional to total electron content (TEC) contained along the signal trajectory in the ionosphere, and it is inversely proportional to the square of signal frequency. TEC and, consequently, the error due the ionosphere vary in time and space, and they are affected by several variables, such as: solar cycle, local time of the day, season, geographical location, geomagnetic activity, and others [4]. Thus, it is very important to know the behavior of the ionosphere, taking into account their dependence on the location and time.

Besides the ionosphere temporal variation over the years, it presents variation of the electron density in cycles of about 11 years. During these peaks, there is a higher incidence of sun radiation (solar activity) with increase of ionization in terrestrial atmosphere layers. TEC values are proportional to the increase of solar activity, that is, the increase of sunspots. In periods of maximum activity, TEC can reach values about twice as larger than in periods

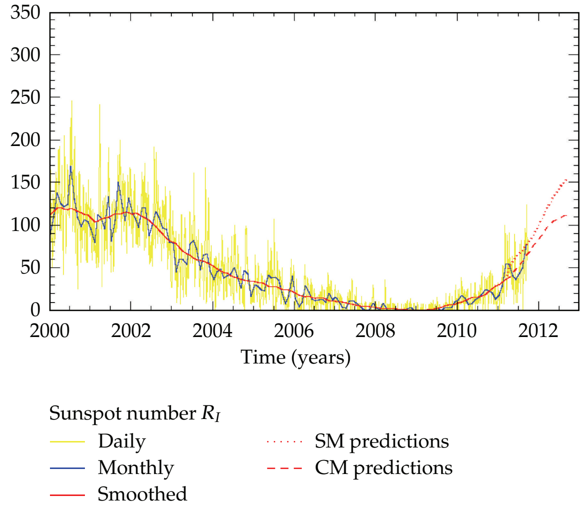


Figure 1: Sunspot numbers of cycle 23 and beginning of cycle 24. The daily (yellow), monthly (blue), and monthly smoothed (red) sunspot numbers since 2000, together with predictions for 12 months ahead: SM (red dots): classical prediction method, based on an interpolation of Waldmeier's standard curves; CM (red dashes): combined method proposed by K. Denkmayr. Source: http://sidc.oma.be/html/wolfjmms.html—Access in October 2011.

of low solar activity. Currently, the Sun is starting the cycle 24 that should have its maximum period between 2012 and 2014. The previous cycle, 23, had its maximum between 2000 and 2002, when there was a considerable increase of the sunspot numbers and, consequently, the number of electrons in the ionospheric layer.

Figure 1 shows the sunspot numbers of solar cycle 23 and the beginning of cycle 24, in a period from 2000 to the first semester of 2011 and a prediction of the new cycle for 12 months ahead.

Figure 2 shows three different geographical regions of the ionosphere on terrestrial globe known as high-latitude region, medium-latitude region, and equatorial region. Figure 3 shows that in the equatorial region, where a great part of South America and Africa region are located, the equatorial anomaly occurs, increasing the TEC values, mainly in the most active period of Sun.

TEC is given along the direction between the transmitting DCP and the satellite. TEC quantities in vertical direction (VTEC) are given by

$$\text{TEC} = \text{VTEC} \sec Z, \tag{2.1}$$

where $\sec Z$ is the mapping function, and Z is the signal path zenithal angle in relation to the plan of a mean reference altitude, estimated by means of so-called Bent Ionospheric Model. For IRI model an altitude of 350 km was used, whereas for IONEX, 450 km was used. The

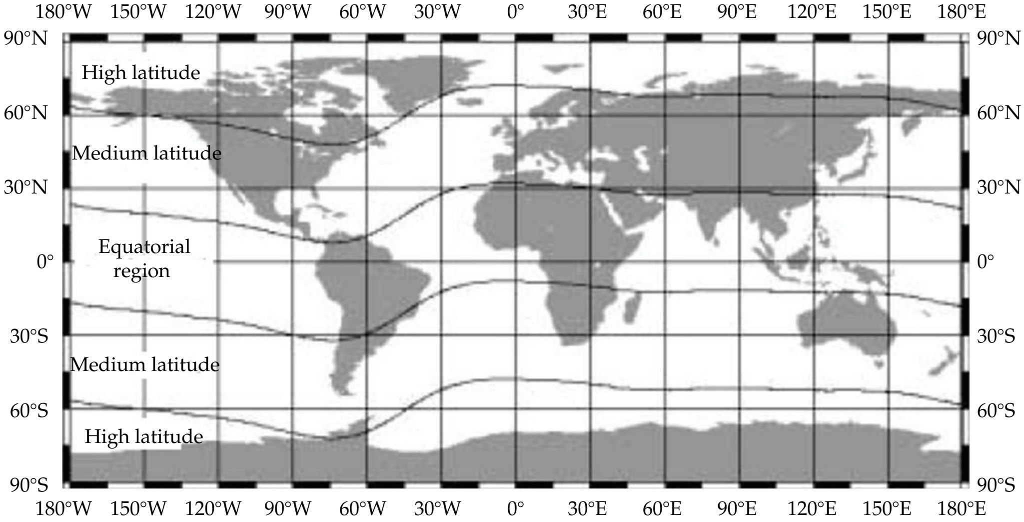


Figure 2: Geographical regions of the ionosphere.

ionosphere signal delay in DCP/satellite direction is calculated, according to Aksnes et al. [7] by

$$R_I = \frac{40.3\,\mathrm{VTEC}\sec Z}{f^2}, \tag{2.2}$$

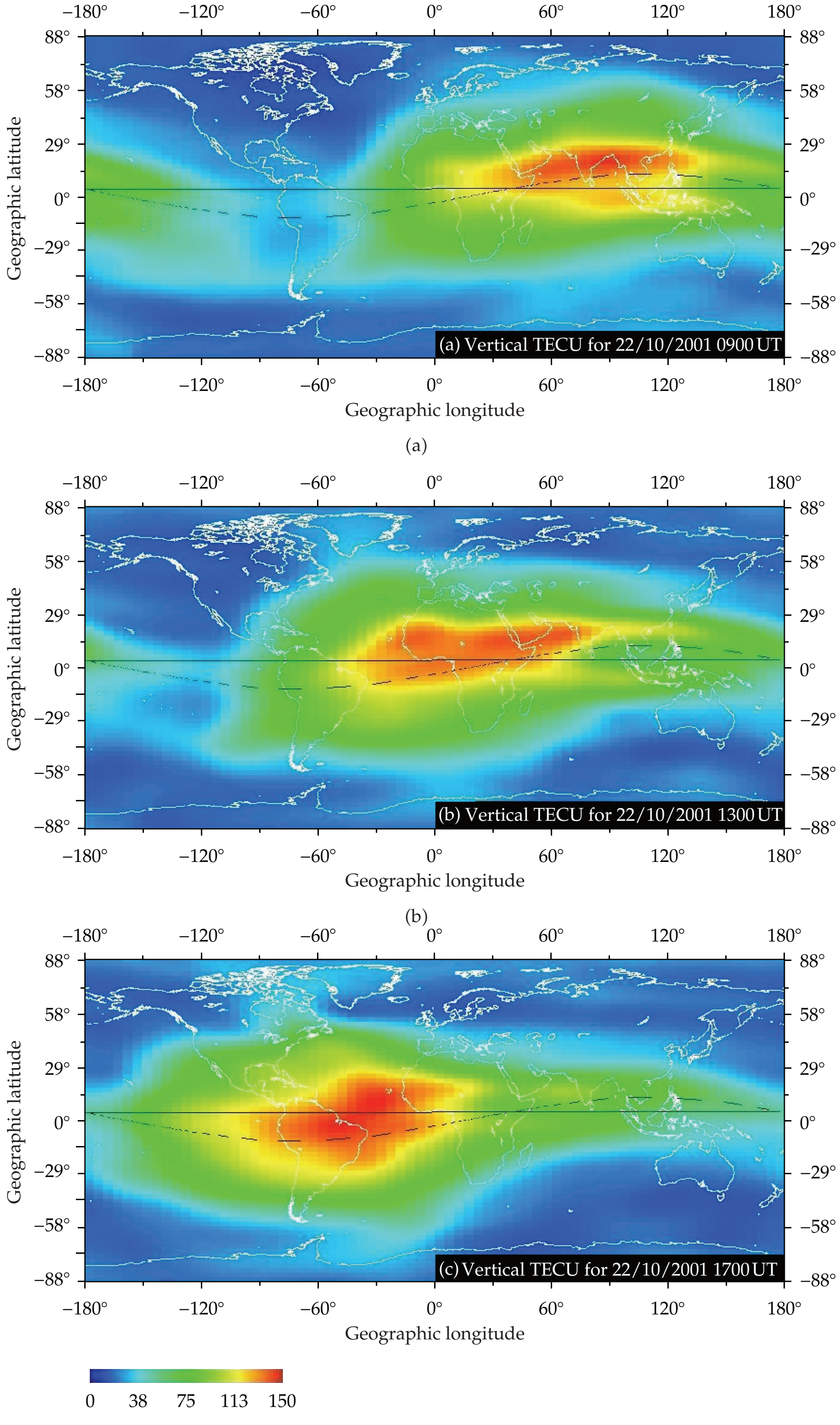
where f is the DCP frequency transmission. Considering VTEC constant for short times, the temporal variation of the signal delay due to the ionosphere is given by

$$\dot{R}_I = -\frac{k_1\,\mathrm{VTEC}\cos\gamma\sin\gamma}{f^2\left(1-k_2\cos^2\gamma\right)^{3/2}}\dot{\gamma}, \tag{2.3}$$

where VTEC is the total electron content in vertical direction, γ is the satellite elevation angle with respect to DCP, and $\dot{\gamma}$ is the satellite elevation angle rate. Depending on the mean reference altitude h, one has for $h = 350\,\mathrm{km}$, then $k_1 = 36.21$ and $k_2 = 0.8985$ and for $h = 450\,\mathrm{km}$, then $k_1 = 35.16$ and $k_2 = 0.8723$.

The last equation can be applied to the ionosphere correction based on Doppler shift measurements. The deviation due to the ionosphere is sensitive to the values of VTEC, which can be obtained from IGS (International GNSS Service) with free access to any users in IONEX format [6]. Such data correspond to vertical TECU that means vertical TEC unitary with the following relationship: a unit of TEC (1 TECU) corresponds to 10^{16} electrons per square meter [8]. Figures 3(a), 3(b), and 3(c) show a set of vertical TECU global maps on October 22, 2001. The figures are presented in different times, 9:00, 13:00, and 17:00 UT and show the equatorial anomaly evolution along low-latitude regions (from 30°S to 30°N).

Tropospheric effect depends on atmosphere density and the satellite elevation angle. This effect can be observed from the terrestrial surface up to about 50 km [9]. The representation of the troposphere deviation depends on the atmospheric pressure,



(a) Vertical TECU for 22/10/2001 0900 UT

(a)

(b) Vertical TECU for 22/10/2001 1300 UT

(b)

(c) Vertical TECU for 22/10/2001 1700 UT

(c)

Figure 3: Vertical TECU from IONEX model for October 22, 2001. Source: Produced by Leica Geosystems/GNSS QC software.

atmospheric temperature, and water vapor pressure. According to the IERS (International Earth Rotation Service) model the tropospheric signal delay is given by [10]

$$R_T = \frac{A + B}{\sin\gamma + B/(A + B)/(\sin\gamma + 0.01)}. \tag{2.4}$$

Thus, the temporary variation of the signal delay due to the troposphere is given by

$$\dot{R}_T = (A + B)^2 \frac{\cos\gamma \left[B - (A + B)\cdot(\sin\gamma + 0.01)^2\right]}{\left[\sin\gamma(\sin\gamma + 0.01)\cdot(A + B) + B\right]^2}\dot{\gamma}, \tag{2.5}$$

where $A = 0.002357P_o + 0.000141e_o$, $B = (1.084 \times 10^{-8})P_oT_oK + (4.734 \times 10^{-8})(P_o^2/T_o)(2/(3 - 1/K))$, $K = 1.163 - 0.00968\cos 2\phi - 0.00104T_o + 0.00001435P_o$, γ = satellite elevation angle, $\dot{\gamma}$ = satellite elevation angle rate, P_o = atmospheric pressure (in 10^{-1} kPa, equivalent to millibars), T_o = atmospheric temperature (in Kelvin), e_o = water vapor pressure (in 10^{-1} kPa, equivalent to millibars), and ϕ = DCP geodetic latitude.

Values of P_o, T_o, and e_o are monthly averages obtained for different geographical latitudes and longitudes from National Climatic Data Center—NOAA Satellite and Information Service [11].

3. Results

The geographical location is computed by the in-house developed GEOLOC (geographical location) program in FORTRAN [12], which processes the uplink measured Doppler shift suffered by the signal transmitted from the DCPs, together with a statistical least squares method and satellite orbit ephemeris [2, 3].

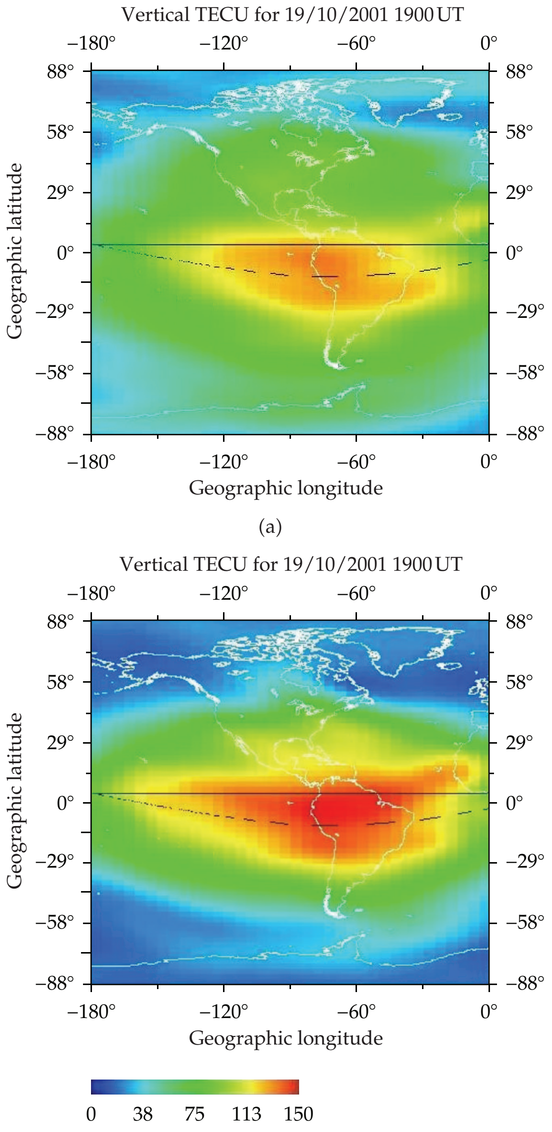
Given the complex dependence of the ionosphere with the solar cycle, local time of the day, season, geographical location, geomagnetic activity, and others, it is important to make an analysis of different models that describe VTECU values for the geographical location, date, and time for the DCP to be located. First we introduce the ionosphere effect using either IRI or IONEX model and through simulation one verifies its impact on location computation. Second we use real data to check the consistency of the findings in the former simulation.

3.1. Ideal Doppler Data for DCP no. 32590 with Ionosphere Influence

Two different models of the ionosphere were analyzed: IRI (International Reference Ionosphere) [5] and IONEX (IONosphere map EXchange) [6].

The chosen periods for the location were in October 2001 and October 2009, periods that are characterized by high and low solar activity, respectively. The month chosen was October, because it is within the time that VTECU has its maximum values (spring equinox), mainly in 2001. Furthermore, it was possible to find a set of SCD-2 satellite pass data in a period of the day that VTECU data are most intense (18-19 UT) for that month, in 2001 and 2009. This plays an important role for the location with real data.

In the first set of results VTECU values on October 19–22, 2001 and 2009 are shown for geographical location of DCP no. 32590 (15.55293°S and 56.06875°W). Doppler shift



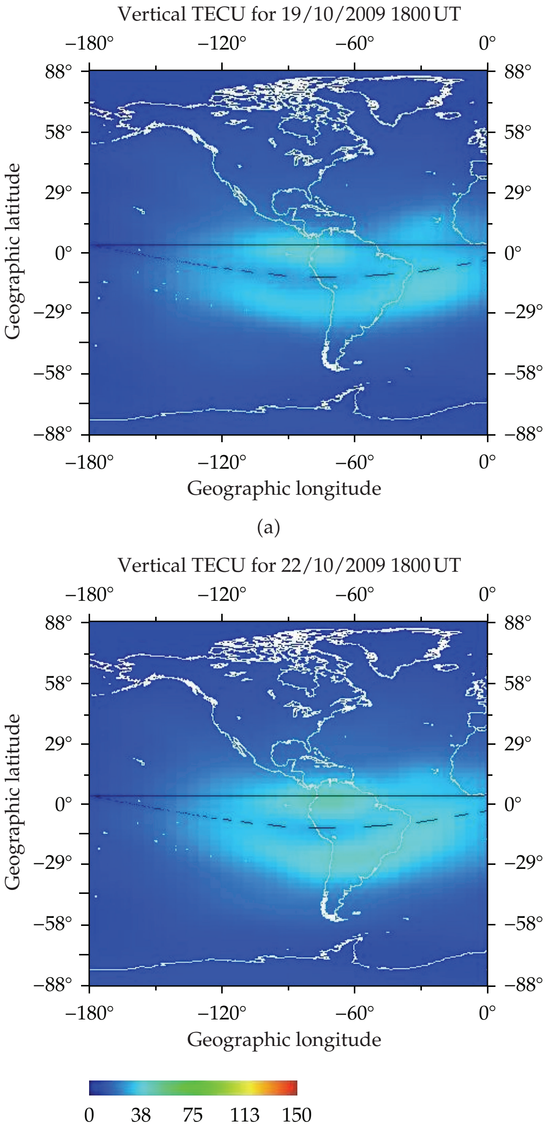
(a)

(b)

Figure 4: VTECU maps on October 19 and 22, 2001 at 19 UT showing the equatorial anomaly crests in the region close to Brazil for maximum values of VTECU (geographic equator in solid line and the magnetic equator in dashed line). Source: Produced by Leica Geosystems/GNSS QC software.

measurements are simulated from this DCP real location, and the ionospheric effect is added to the model that generates such data. Thus, it is possible to verify in the simulation how far the influence of ionosphere in the location error is. VTECU values obtained from IRI and IONEX models are used.

Figure 4 shows a sequence of VTECU maps of the region in latitude between 88° South and 88° North and longitudes between −180° and 0°, where American continent is located. This figure shows maps for two days (October 19 and 22, 2001), a period that is characterized by high solar activity, and it can be seen the equatorial anomaly effect [13], when VTECU

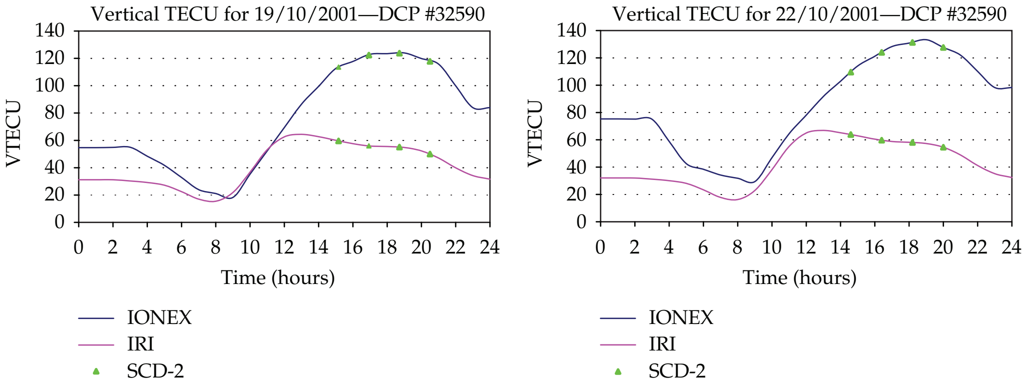


(a)

(b)

Figure 5: VTECU maps on October 19 and 22, 2009 at 18 UT for minimum values of VTECU in low solar activity period (geographic equator in solid line and the magnetic equator in dashed line). Source: Produced by Leica Geosystems/GNSS QC software.

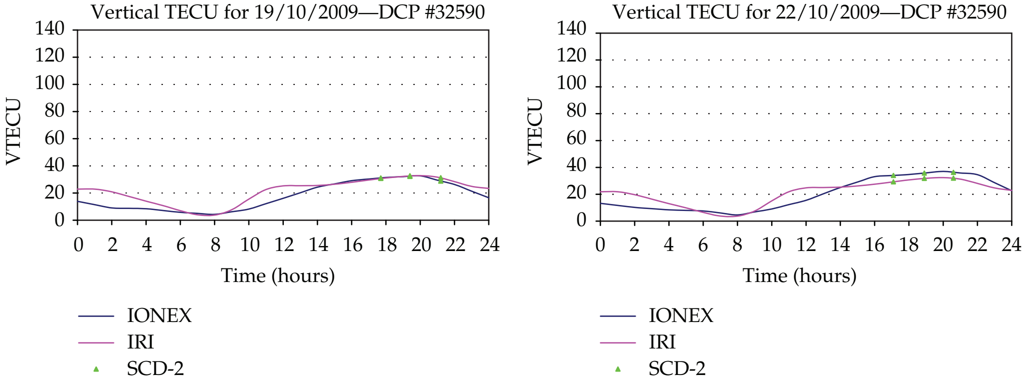
values are maximum in Brazilian region, around 18-19 UT (universal time) or 15 h local time. Through the diagram of colors it is possible to verify that in this period VTECU reaches values close to 150×10^{16} electrons/m^2 in the equatorial anomaly region (red). On the other hand, in Figure 5, which represents the period of October 19 and 22, 2009, there is not a considerable difference in VTECU values for the same time, 18-19 UT. The diagram of colors is maintained between the dark and the light blue, which represents a value about 10 to 40×10^{16} electrons/m^2. This fact is given in low solar activity.



(a)

(b)

Figure 6: VTECU values on October 19 and 22, 2001 in a period of one day at geographical location of DCP no. 32590 (IONEX (blue), IRI (pink), and triangles (green) represent the time of SCD-2 satellite passes).



(a)

(b)

Figure 7: VTECU values on October 19 and 22, 2009 in a period of one day at geographical location of DCP no. 32590 (IONEX (blue), IRI (pink), and triangles (green) represent the time of SCD-2 satellite passes).

Figures 6 and 7 show VTECU values in geographical location where DCP no. 32590 is located, for the same periods mentioned above, 2001 and 2009, using IRI (pink line) and IONEX (blue line). The triangle symbols (green) in the figures represent the time of SCD-2 satellite passes, which span a period between 15 and 22 UT. VTECU is showed with an interval of two hours and in a full period of a day. In Figure 6 it is verified a discrepancy between VTECU values of IRI and IONEX, mainly from 14 to 24 UT, and such values differ by up to 3 times in the comparison between the models; that is, IONEX represents better the total electron content in high solar activity periods. This difference results in an increase of location error in up to 50% when the ionospheric delays are added to the simulated Doppler data. Figure 7 has the same representation as the previous one, however, in 2009 (low solar activity). In this case, it appears that both (IRI and IONEX) express the total electron content in a similar way. Thus, the increase in DCP location error is consistent to any chosen model for obtaining VTECU values. It depicts the importance of the ionospheric correction in high

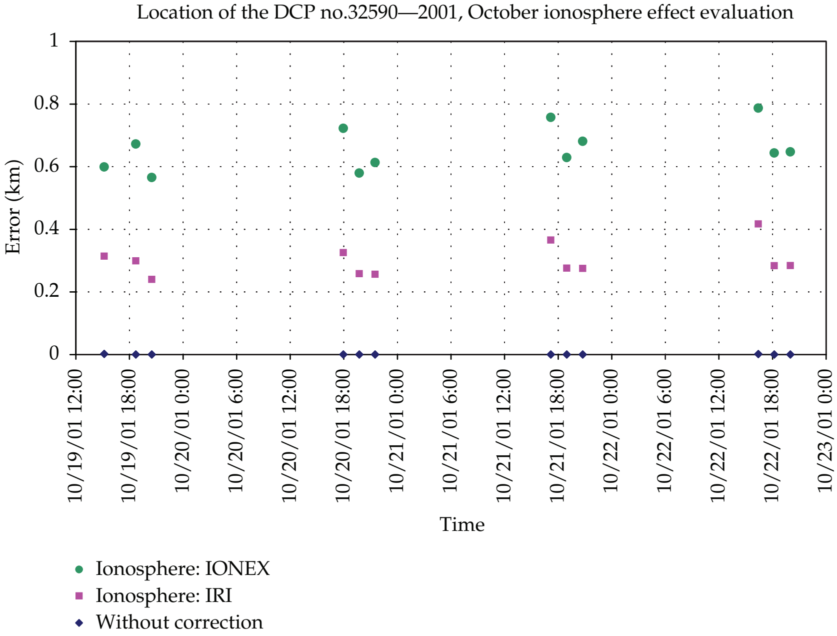


Figure 8: Ionospheric effect evaluation in DCP no. 32590 location error on October 19–22, 2001 (location errors without ionospheric effect (blue), with the addition of the ionospheric delay using IRI model (pink), and with the addition of the ionospheric delay using IONEX model (green)).

solar activity periods, because according to Figure 6, VTECU values jump from about 40 to more than 120×10^{16} electrons/m^2 at the end of the day.

With the data of VTECU from different models (IONEX e IRI), in high and low solar activity periods, geographical location error for DCP no. 32590 due to ionosphere delay is generated.

A first analysis of these results shows that the location error due to ionospheric effect cannot be neglected because the error can increase to around 50% and the model which must be used depends mainly on the intensity of solar activity. In fact, in low solar activity, both models yield VTECU values with similar values. However, in high solar activity, IONEX has yielded the values in a best way, mainly in the region that is called equatorial anomaly, close to magnetic equator, which can be easily observed in Figure 4.

Figures 8 and 9 show DCP no. 32590 location errors in 2001 and 2009, respectively, including the ionospheric effect and making use of VTECU values from both models. These results are compared with the ideal location, that is, without the inclusion of ionospheric effect.

3.2. *Real Doppler Data for DCP no. 109 with Ionospheric and Tropospheric Effects Correction*

This second phase of the study aimed at applying the ionosphere correction in high and low solar activity periods making use of IONEX model, which was previously studied, as well as the tropospheric delay correction with climatic data obtained from National Climatic Data Center—NOAA Satellite and Information Service [11]. Due to the availability of real

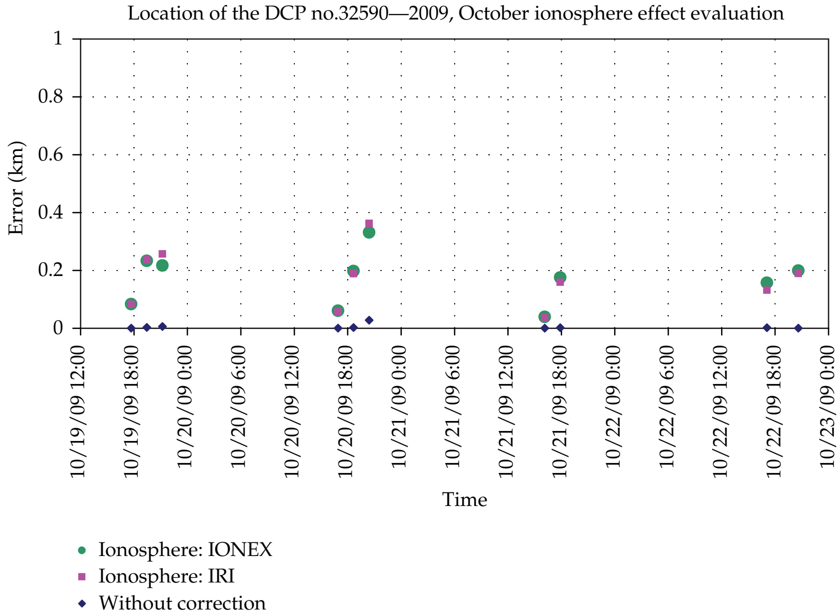


Figure 9: Ionospheric effect evaluation in DCP no. 32590 location error on October 19–22, 2009 (location errors without ionospheric effect (blue), with the addition of the ionospheric delay using IRI model (pink) and with the addition of the ionospheric delay using IONEX model (green)).

Doppler shift data, it has been used the DCP no. 109, located in French Guyana (5.1860°S and 52.687°W), on October 06–15, 2001 for high solar activity and on October 01–14, 2008 for low solar activity.

Figure 10 shows DCP no. 109 location error without ionospheric and tropospheric corrections (blue), with the ionospheric correction using IONEX (green) and with both corrections, ionospheric and tropospheric (pink) for the high solar activity period. Figure 11 makes use of the same color code and shows DCP no. 109 location errors for the low solar activity period.

As in the simulated results, it is observed in real cases of DCP location that both ionospheric and tropospheric effect should be inserted in the signal delay correction to minimize the location error. It also observed that the ionospheric delay is very representative, especially in maximum solar activity period, resulting in location error around 1 km, while the tropospheric delay takes a smaller error scale, about some dozen of meters. In low solar activity period, the ionosphere has much less influence on location error while the troposphere is in the same order as mentioned above.

4. Conclusions and Recommendation

Due to high solar radiation in the equatorial region and Earth electric and magnetic field, the electron density in the ionosphere layers suffers sensitive consequences mainly in Brazilian regions or any areas close to magnetic equator. After some tests it was observed that, in such regions, it is mandatory the use of an ionosphere correction model that takes into account this effect called equatorial anomaly, depending on the solar activity intensity during the period in which the location is accomplished. Then, a detailed study shows VTECU values

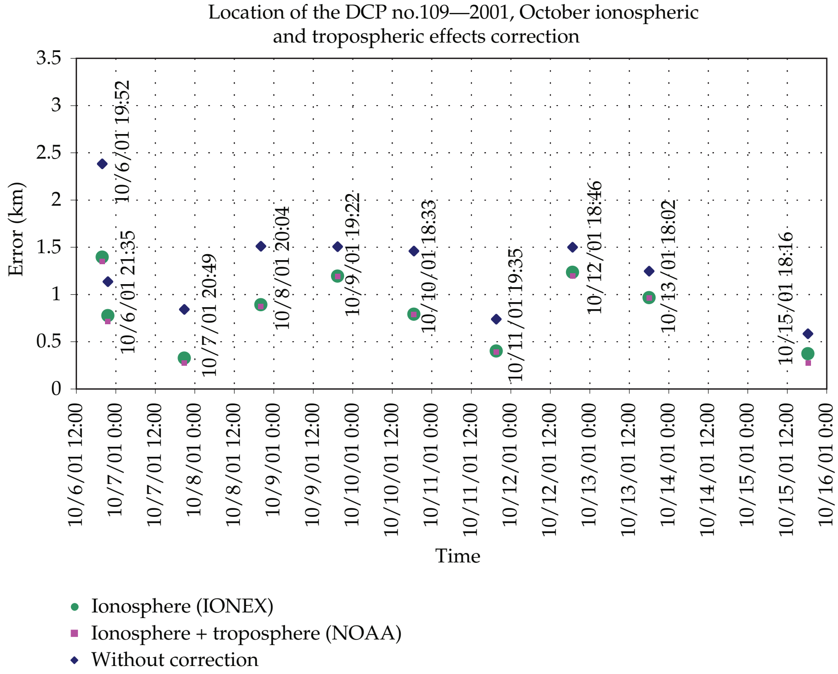


Figure 10: Evaluation of DCP no. 109 error location on October 06–15, 2001 (higher solar activity).

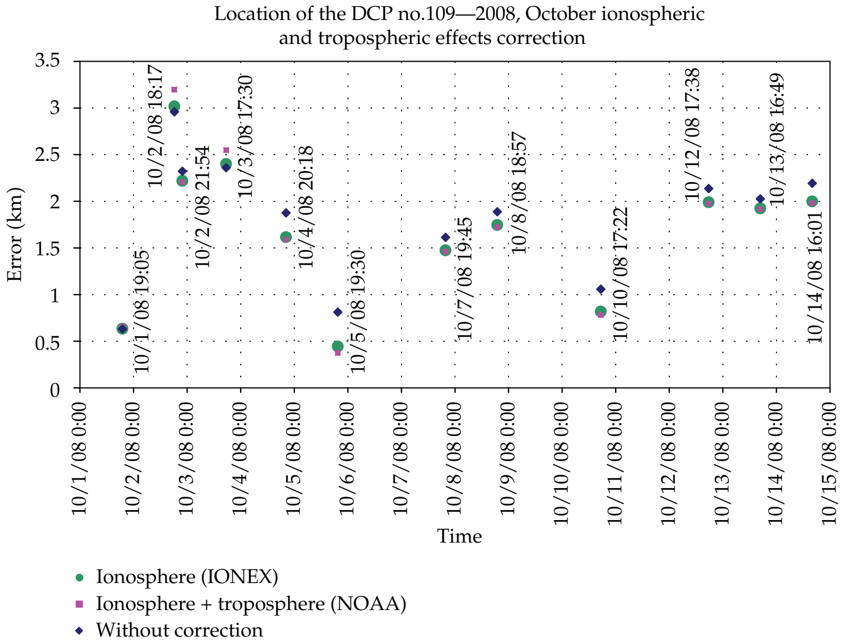


Figure 11: Evaluation of DCP no. 109 error location on October 01–14, 2008 (low solar activity).

for each DCP location in order to have its location errors minimized as much as possible. A comparison was made between two mentioned models (IRI and IONEX) taking into account the local time of the day, the year of high or low solar activity, and the region where the ionospheric effect can cause high location errors.

Through VTECU analysis, mainly in the equatorial region, it is observed the influence on DCPs location, whereas better the ionospheric model better the platform location. According to the results, it is verified that the ionospheric data provided by IONEX are, generally, better than IRI data, especially in high solar activity periods. In this case, VTECU values from IONEX model reach values 2-3 times higher than IRI model, resulting in an ionospheric correction difference of up to 1 km.

When IRI and IONEX model data are used in high solar activity periods, the VTECU values may be quite different and consequently DCPs location. In low solar activity periods both models have shown similar performance.

Simulated ideal Doppler shift measurements were used for the first case. It is shown that the geographical location has its error increased due to the ionospheric effect, and such effect cannot be neglected when the platform location is made with real data. For this first case, IONEX model allows an improvement of about 1 km in location (2001) around 18:00 UT compared to IRI model.

After analyzing VTECU values and its influence on DCP no. 32590 location for the simulated ideal case, it was chosen IONEX data to model the ionosphere. In addition to the ionospheric correction, the second phase of the work considered the tropospheric effect whose data depend largely on climatic conditions in the regions where DCPs are. Such data can be found easily by the users through the National Climatic Data Center [11]. The work is based on real Doppler data of DCP no. 109, taking into account high and low solar activity, in 2001 and 2008, respectively. The analysis is made under the following conditions: first, no correction was applied; then only the ionospheric correction is applied to the location process; finally ionospheric and tropospheric delays are corrected according to the conditions listed above.

Results show that DCPs location error is minimized when the ionospheric effect is considered, mainly in high solar activity period, when VTECU values are about 3 times larger than low solar activity period. The tropospheric delays correction also decreases location error, but in smaller proportions.

Finally, it is important to note that both delays, ionospheric and tropospheric, should be corrected to obtain a better platform location, mainly when mobile platforms were used. The choice of ionospheric model depends largely on the intensity of solar activity, because the level of these activities influences the ionosphere density, due to high VTECU values.

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