Analyses of magnetic storms effects on ionosphere electron content based on GPS data

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Abstract

Magnetic storms can cause a lot of effects such as bright auroras visible at more southern latitudes than usual, or even to interfere with satellite communications; disrupting power grids; even short out orbiting satellites, rendering them permanently inoperable.
Processing GPS data make possible to have a visualization of the Ionosphere behavior on days highly affected by the magnetic storms.
The purpose of this paper is to show the effects of magnetic storms on the behavior of the Ionosphere electron content based on GPS data.

Introduction

The term ionosphere was first applied by Sir Robert Watson-Watt to that part of the atmosphere in which free ions exist in sufficient quantities to affect the propagation of radio waves. The ionosphere can therefore, be considered as lying between about 40 to 50 km and several earth radii [1]. In this layer the signal propagation depends on the frequency. The ionosphere is imbue with the geomagnetic field, resulting in an anisotropic effect that is neglected for GPS signals [2].

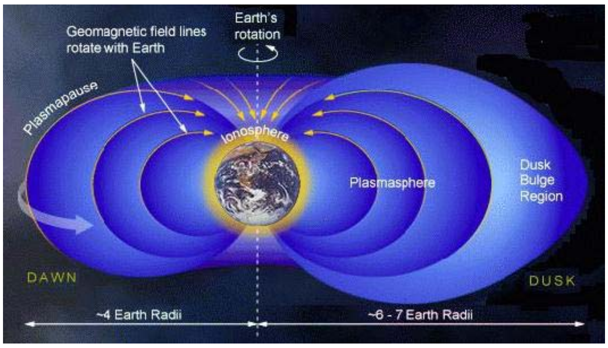

Figure 1 – Plasmasphere region (about 1000 to 20000 km) [3].

The ionosphere is the major source of error in user positioning determination by GNSS, mainly at low geomagnetic latitude regions (±20^0) which are affected by the Ionospheric Equatorial Anomaly (IEA). The IEA is characterized by high values of Total Electron Content (TEC, electron density integral along the path from a GPS satellite to the receiver), what implies in time delays greater than the ones typical of regions outside it. Large ionospheric gradients, as shown in the IEA, may cause refraction on the rays greater than the ones presented at regions far from the IEA. It also happens in periods of maximum solar activity or during geomagnetic storms. Although the IEA is a phenomenon that generally occurs near the geomagnetic equator, it has been found periods that the IEA extended to regions over USA, Europe, and Japan.

There is yet an electron density on layers over 1000 km of altitude. The Earth plasmasphere (Figure 1,about 1000 to 20000 km of altitude) has a peculiar behavior and it is not exactly spherical, because is characterized by a region of deepening in the Earth magnetic axis. It is constituted of plasma (forth estate of materia), that is constituted with Hydrogen ions (proton) and electrons. Its typical electron density is about 10^{10} ele/m^3 [1].

TEC varies along the time and over the space, and it depends on the solar ionization flux, so it is affected by the season, user location and the path crossed by the signal from the satellite to the receiver. When this measurement is made in relation to the local vertical it is called VTEC (Vertical TEC), what has been used to study the ionosphere behavior.

In order to study the global behavior of the Ionosphere during magnetic storms, dynamic maps have been generated based on IONEX data supplied by the Center for Orbit Determination in Europe (CODE).

The geomagnetic activity is given by the K index (local) or by the Kp index (planetary). The VTEC was correlated with Kp index. Analyzing the VTEC behavior along six years (since Jan. 1999), it was possible to identify periods with more intense geomagnetic activity (higher Kp and also Ap values).

Methodology

Slant Total Electronic Content (STEC) is the TEC between the satellite vehicle (SV) and the user but it is more convenient to have a TEC measurement on the vertical (VTEC) because those can be used for any SV elevation after a conversion from VTEC to STEC.

The VTEC can be estimated using just a trigonometric relation applied to the STEC (1):

$$\mathrm{STEC} = \frac{\left(\rho_{L2} - \rho_{L1}\right)}{40{,}3} \frac{f_{L1}^2 f_{L2}^2}{\left(f_{L2}^2 - f_{L1}^2\right)} \quad (1)$$

where ρ_{L1} and ρ_{L2} are the pseudoranges measured at the frequencies 1575.42 MHz (f_{L1}) and 1227.60 MHz (f_{L2}), respectively.

Using (2) the VTEC can be calculated using the trigonometric relation [4]:

$$VTEC = \cos(\chi')STEC \qquad (2)$$

Where χ' is the SV zenithal angle at the observation station. The VTEC calculated in this way can be greater or even equal to the real VTEC. It depends on the elevation, the azimuth, and the gradients along the signal path.

VTEC Global Behavior

IONEX (Ionosphere Map Exchange) data supplies a good estimation of the worldwide VTEC [5]. These data provides VTEC values around the world with intervals of 2.5 degrees for latitude and 5 degrees for longitude. Using IONEX data the ionospheric effects in the GPS signals can be studied for any place in the world with an interval of 2 hours for any day since January, 1999. The delay due to the ionosphere can exceed 85 ns, corresponding to approximately 155 TECU (Total Electron Content Unit = 10^{16} electrons/m^2) or 25 m error in the range, reducing the accuracy of the user position determination.

Figure 2 shows an example of a global VTEC map explaining all the information contained on it. There is a header with the date (mm/ dd/ yyyy), the data collection epoch in Universal Time, the GPS week and the seconds of week. The VTEC is represented by a scale, at the bottom, from dark blue (corresponding to 0 TEC units) to dark red (corresponding to 180 TEC units). All maps generated have at the right side the Kp index value (varying from 0 to 10) for the epoch shown. This allows to relate the geomagnetic activity with the VTEC global behavior.

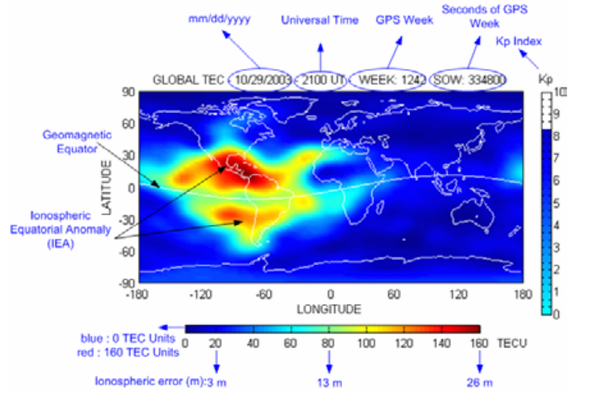

Figure 2: Global VTEC data visualization using IONEX data at 21:00 (UT) Oct. 29, 2003. The Kp index is 8,33.

Magnetic storm periods

October 28,2003

On Oct. 28, 2003, at approximately 6:10 a.m. a gigantic solar flare erupted from surface of the Sun. That explosion blasted tremendous amounts of energy and matter into space, sending a coronal mass ejection (CME) directly toward the Earth. It has headed straight for us like a freight train, but the major effects occurred on Oct. 29 and Oct. 30, 2003.

NOAA classifies geomagnetic storms on a scale from 1 to 5. Indications showed that this had the potential to be a G5 storm - the top of the scale. The most benign effect of such a storm would be bright auroras visible from more southern latitudes than usual. However, the geomagnetic storm triggered by the CME also could interfere with satellite communications; disrupt power grids (as occurred in the 1989 Quebec blackout); even short out orbiting satellites, rendering them permanently inoperable [6].

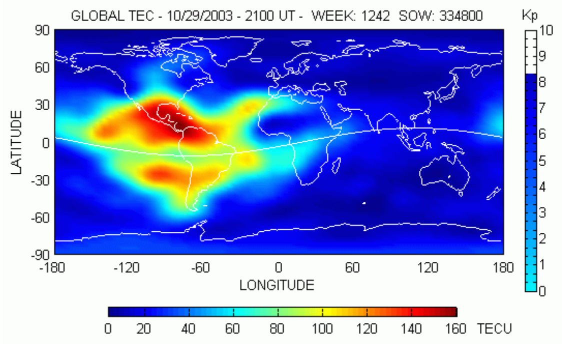

Figure 3: Global VTEC map during a solar storm at 21:00 (UT) Oct. 29, 2003. The Kp index is 8.33 [5].

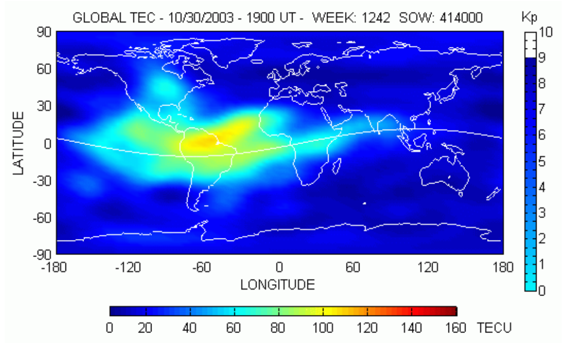

Figure 4: Global VTEC map before arrive the part of energy of the solar storm at 19:00 (UT) Oct. 30, 2003. The Kp index is 9.

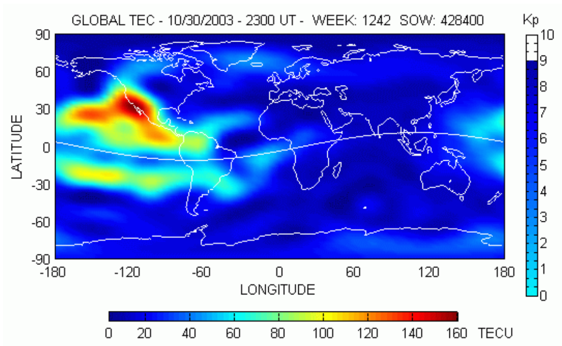

Figure 5: Global VTEC map during a solar storm at 23:00 (UT) Oct. 30, 2003. The Kp index is 9.

Figure 6 shows the image of the Oct. 28, 2003 solar flare that was taken by the Extreme ultraviolet Imaging Telescope (EIT) on board NASA's Solar and Heliospheric Observatory (SOHO) spacecraft. It shows a tremendous burst of x-ray light at a wavelength of 195 Å associated with the flare. The flare was so bright that it overloaded the instrument's detector, causing the horizontal artifacts in the image [6].

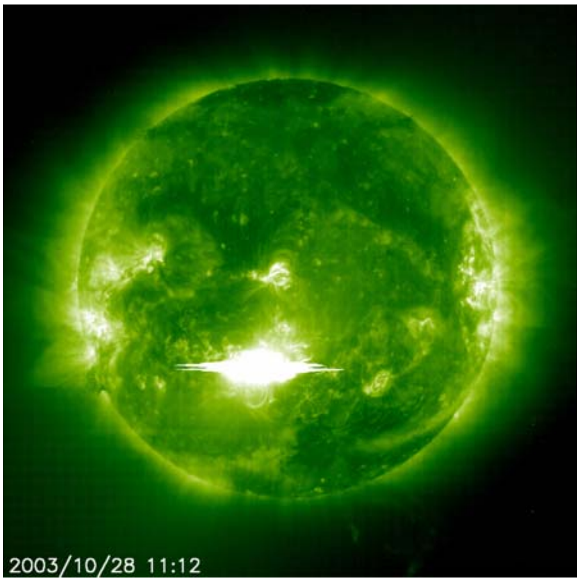

Figure 6: image of the Oct. 28, 2003 solar flare was taken by the EIT [6].

July 14,2000

In the morning of July 14,2000, NOAA satellites and the orbiting Solar and Heliospheric Observatory (SOHO) recorded one of the most powerful solar flares of the current solar cycle. This intense flare have been predicted by Space weather forecasters (Figure 7).

Energetic protons from the flare arrived at Earth about 15 minutes after the eruption," says Gary Heckman, a space weather forecaster at the NOAA Space Environment Center. "This triggered a category S3 radiation storm" [7]. Figure 8 shows the ionosphere behavior on Jul. 15, 2000 and Figure 16 and 17 show the variation of the VTEC behavior for July 15 and July 16, 2000 during 12 hours.

April 06,2000

There is no cause for alarm. When a CME hits the magnetosphere -- the region around Earth controlled by our planet's magnetic field -- most of the incoming material is deflected away. If the shock wave is very strong, as this one might be, it can compress the magnetosphere and unleash a geomagnetic storm. In extreme cases, such storms can induce electric currents in the Earth that interfere with electric power transmission equipment. Satellite failures are possible, too. Geomagnetic storms can also trigger beautiful aurorae. These "Northern Lights" are usually seen at high latitudes, but they have been spotted farther south than Florida during intense disturbances. This happened in April 6, 2000 (Figure 9) [8].

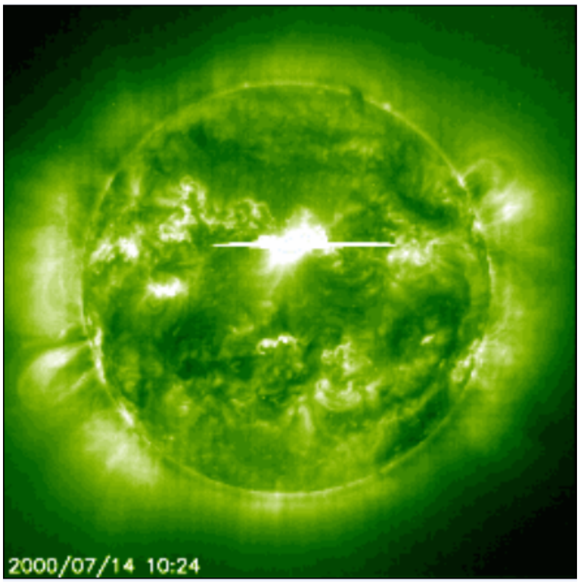

Figure 7: image of the Jul. 14, 2000 solar flare was taken by the EIT [6].

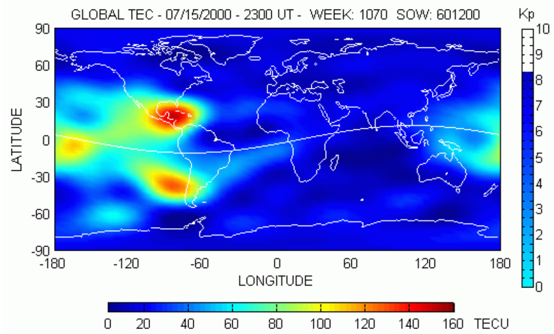

Figure 8: Global VTEC at 23:00 (UT) Jul. 15, 2000. The Kp index is 8.

Figure 9: Apr. 06, 2000. The Kp index is 7,66 [8].

Whether or not an auroral display is triggered by the blast depends on the orientation of the magnetic field within the CME's approaching shock wave. Magnetic fields with a southward directed component can create a weak point in Earth's magnetic defenses and make auroras more likely.

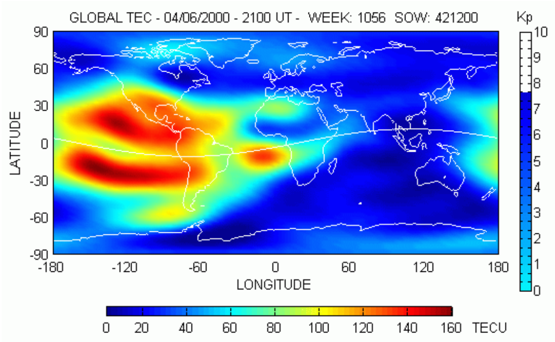

Figure 10: Global VTEC map at 21:00 (UT) Apr. 06, 2000. The Kp index is 7,66.

Others periods that has shown a sudden change in the Ionosphere Global behavior with high values of Kp index are:

- Sep. 07, 2002 (Figure 11).
- Nov. 06, 2001 (Figure 12).
- Oct. 21, 2001 (Figure 13).
- Mar. 31, 2001 (Figure 15).
- Sep. 18, 2000 (Figure 14).

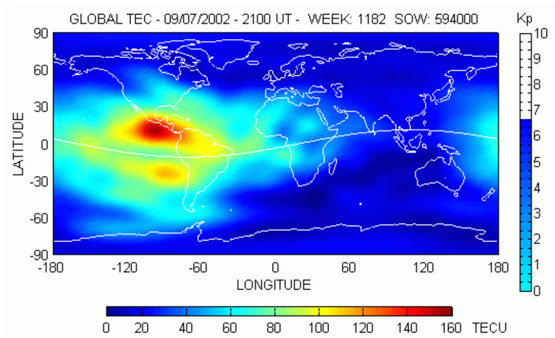

Figure 11: Global VTEC map at 21:00 (UT) Sep. 07, 2002. The Kp index is 6,6.

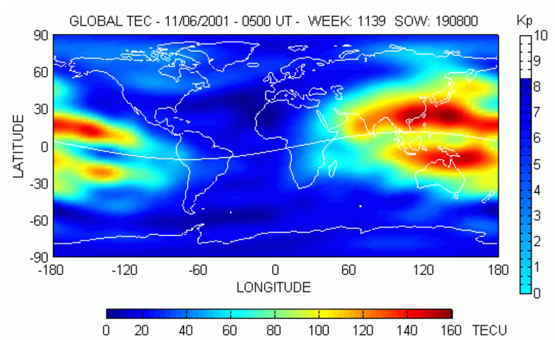

Figure 12: Global VTEC map at 05:00 (UT) Nov. 06, 2001. The Kp index is 8.

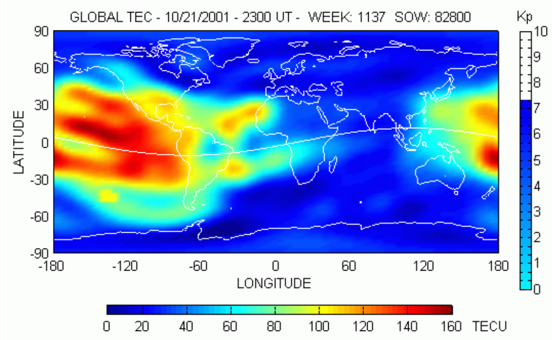

Figure 13: Global VTEC map at 23:00 (UT) Oct. 21, 2001. The Kp index is 7.

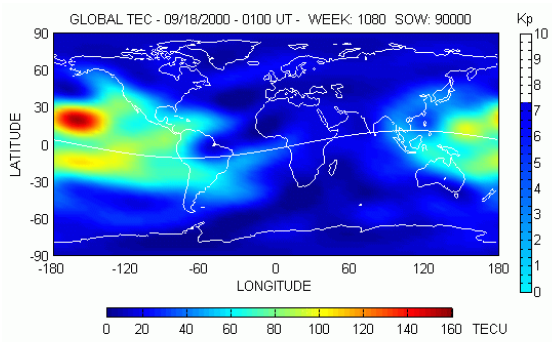

Figure 14: Global VTEC map at 01:00 (UT) Sep. 16, 2000. The Kp index is 7.

Conclusions

This work has as a final product a database composed by VTEC maps since January 1999 which allows making comparisons with the geomagnetic activity, and the ionosphere behavior visualization during magnetic storms periods. All these results were obtained with the initial objective of study the Ionosphere effects on the GPS signal.

References

[1] K. Davies, “Ionospheric Radio Propagation”, National Bureau of Standards Monograph 80, 1965.

[2] Klobuchar, J. A. Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Transactions on Aerospace and Electronic Systems, v. AES-23, n. 3, p. 332-338, 1987.

[3] Available in < www.albany.edu/faculty/rgk/ atm101/ structur.htm >

[4] B. Hofmann-Wellenhof; Lichtenegger, J. Collins, “GPS theory and practice”. 3 ed. 355f. Wien: Spring-Verlag, 1994.

[5] Oliveira, A.B.V., 2003.: The use of GPS to study the Equatorial Anomaly, 2003. [M.S. Thesis], Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil. (In Portuguese).

[6] Available in < http://cfa-www.harvard.edu/press/ pr0322. html >

[7] Available in < http://science.nasa.gov/headlines /y2000/ast14jul_2m.htm>

[8] Available in <http://science.nasa.gov/headlines/y2000/ ast14jul_2m.htm>.

Acknowledgments

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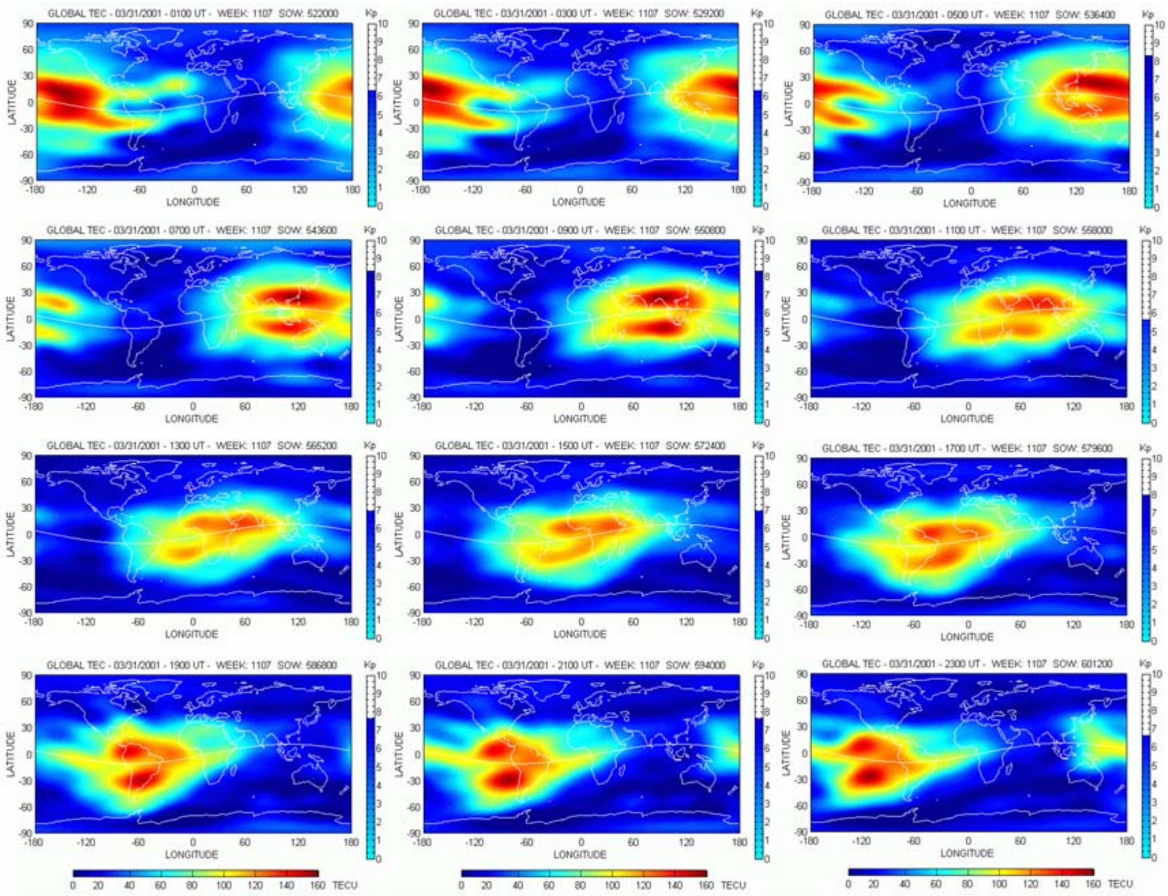

Figure 15: Global VTEC map during all day of Mar. 31, 2001 (0100 UT to 2300 UT, with interval of 2 hours), Periods that presents high Kp index values.

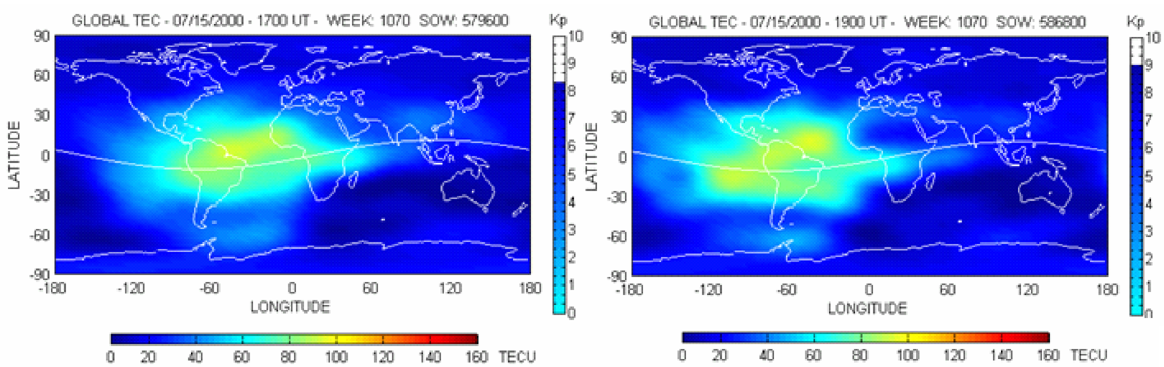

Figure 16: Global VTEC maps showing the quick VTEC variation in the Ionosphere behavior during July. 15,

2000 (1700 UT and 1900 UT). Periods that presents high Kp index values.

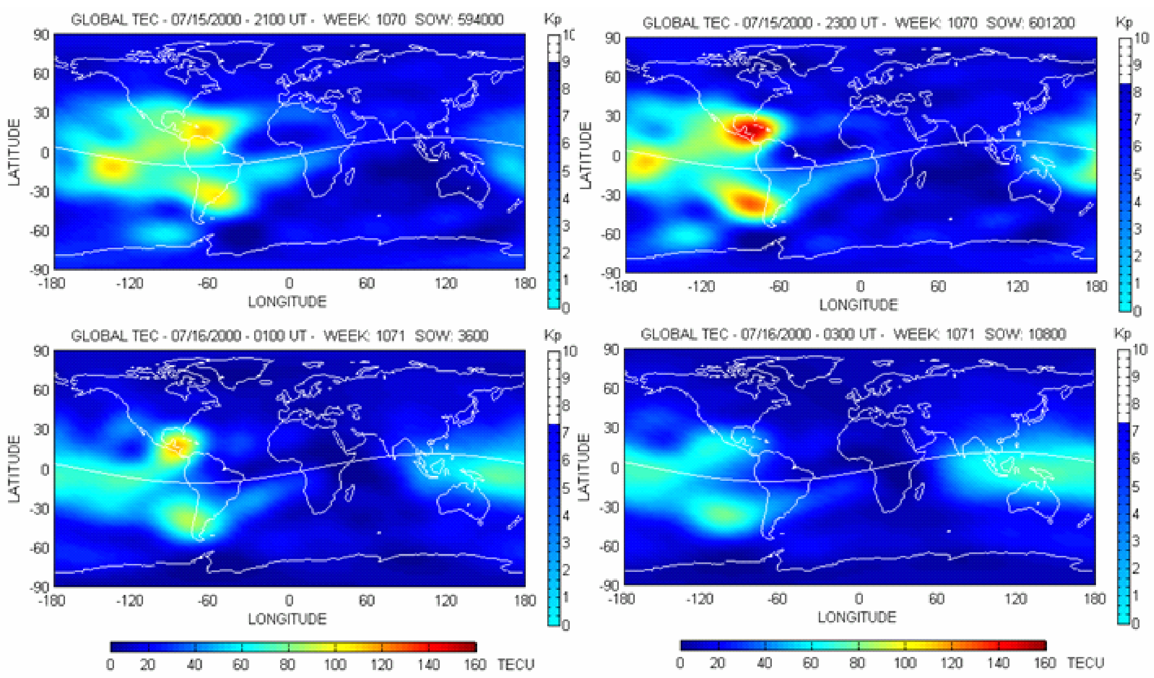

Figure 17: Global VTEC maps showing the quick VTEC variation in the Ionosphere behavior during July. 15, 2000 (2100 UT and 2300 UT) and during July. 16, 2000 (0100 UT and 0300 UT). Periods that presents high Kp index values.