IONOSPHERIC EQUATORIAL ANOMALY STUDIES DURING SOLAR STORMS

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ABSTRACT

The ionosphere is the major error source in GNSS receivers. Models for single frequency time delay correction do not work at low geomagnetic latitude regions (±20º), where the ionosphere has a peculiar behavior, known as the Ionospheric Equatorial Anomaly. In order to study the global behavior of the Ionospheric Equatorial Anomaly, dynamic maps based on IONEX data have been generated. These maps allow to study the Vertical Total Electron Content behavior since January, 1999. They also show the Kp values, Sun Spot Number, and Solar Flux. In this way the effects of the solar and geomagnetic activity on the Ionospheric Equatorial Anomaly can be studied.

INTRODUCTION

The electron density integral along the path between the GPS Satellite Vehicle (SV) and the receiver is known as Total Electron Content (TEC), and this parameter can be used to study the ionosphere behavior.

IONEX (Ionosphere Map Exchange) data supply a good estimation of the worldwide Vertical Total Electron Content (VTEC) [1]. These data provide VTEC values around the world at intervals of 2.5 degrees in latitude and 5 degrees in longitude. Using IONEX data the ionospheric effects on the GPS signals can be studied for any place in the world since January, 1999. The delay caused by 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.

IONEX VTEC EVALUATION

The ionospheric delay (Δt_{ion}) is given by:

$$\Delta t_{ion} = \frac{40.3}{cf^2} TEC \qquad (1)$$

Where c is the free space light velocity, 299,792,458 m/s [2], and f is the transmitted signal frequency (L1 or L2).

Since the frequencies L1 (= 1575.42 MHz) and L2 (= 1227.60 GHz) are closed, it is supposed that they follow the same paths to the receiver. So the TEC is taken to be equal for both frequencies.

TEC through the line of sight can be determined by:

$$TEC = \frac{(\rho_{L2} - \rho_{L1})}{40.3} \frac{f_{L1}^2 f_{L2}^2}{(f_{L2}^2 - f_{L1}^2)} \qquad (2)$$

Where ρ_{L1} and ρ_{L2} are the pseudoranges measured in L1 and L2, respectively. As the TEC between the satellite and the user depends on the satellite elevation angle, this measurement is called Slant TEC (STEC). The TEC varies with time and over the space, and it depends on the solar activity, user location and the SV elevation angle. This measurement made in relation to the local vertical is called VTEC (Vertical TEC).

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VTEC MAPS

Information about the worldwide VTEC can be obtained from the Center for Orbit Determination in Europe (CODE) which provides about 200 globally distributed permanent precise GPS.

IONEX data provide VTEC values for more than 5 thousands points distributed all over the world in a grid of 2.5° latitude by 5° longitude. These data have been used to make maps in the format shown in Fig. 1. The VTEC maps show the date (mm/dd/yyyy), Universal Time, GPS Week, seconds of GPS week. At the right hand side are shown the Kp index (every two hours), Solar Flux (daily), and Sun Spot Number (daily).

The geomagnetic activity is indicated by the K index (local) or by the K_P index (planetary). The VTEC was correlated with K_p index, and analyzing the VTEC behavior along of almost seven years (since Jan. 1999), it has become possible to identify periods with more intense geomagnetic activity (higher K_p and also A_p values).

The VTEC variation was also related with the solar flux at 10.7 cm (2800 MHz) and the sunspot number.

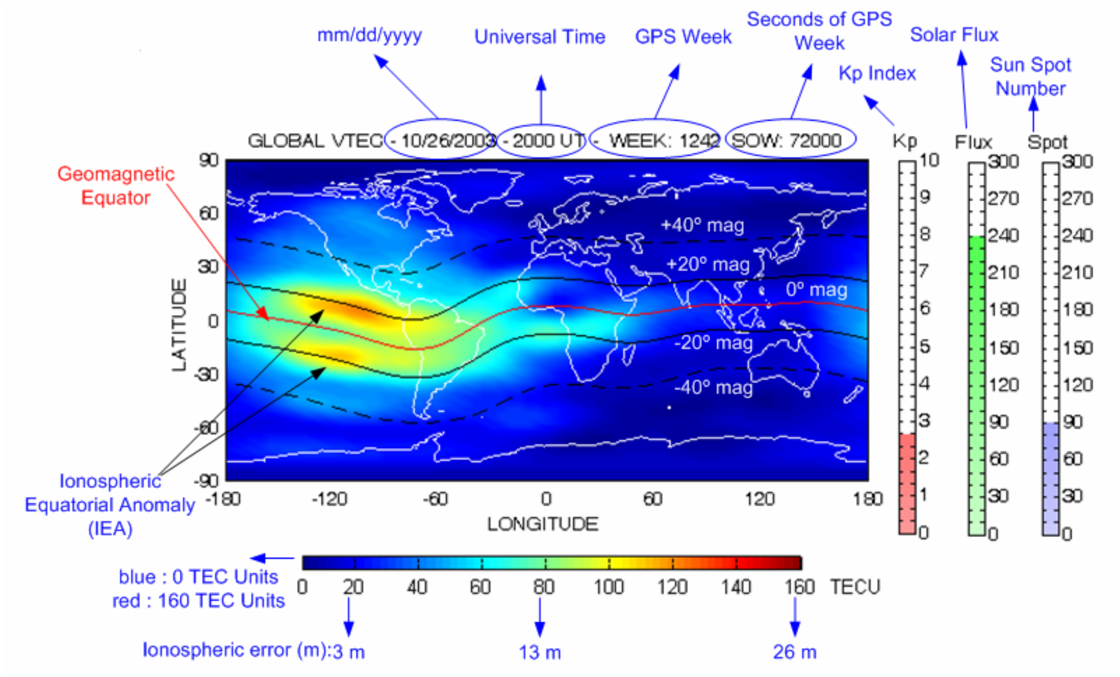

Fig. 1 – VTEC Mapa (10/30/2001) based on IONEX data supplied by Center for Orbit Determination in Europe (CODE).

IONOSPHERIC EQUATORIAL ANOMALY

The region around the geomagnetic equator, located between -20° and +20° of geomagnetic latitude is characterized by an anomaly on the ionospheric behavior (Fig. 2), called the Ionospheric Equatorial Anomaly (IEA). The 3-D graphic illustrates the IEA (Fig. 3), which is characterized by VTEC peaks at ±20^{o} geomagnetic latitude, and a maximum at around 2 pm (local time) [3]. The IEA is caused by the combined action of electric and magnetic field consisting of two high density ionospheric plasma bands placed over tropical regions around the geomagnetic equator.

To minimize the ionospheric delay, the GPS message gives an estimation of the error caused by the ionosphere. This estimation is based on Klobuchar model [4], but this model does not take into account the IEA effects. This implies that new models must be developed in order to have a best fit in the IEA region.

In order to study the IEA, the geomagnetic equator and the lines for ±20º and ±40º geomagnetic were introduced in all maps. It can be seen that the peaks of maximum electron concentration really happen over ±20º magnetic. Although the IEA is a phenomenon that generally occurs near the geomagnetic equator, there have been found periods when the IEA extended to regions over USA, Europe, and Japan

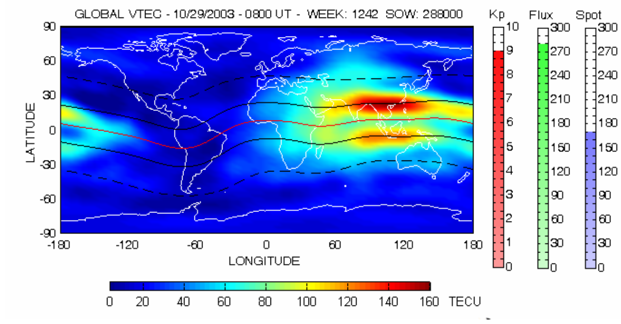

Fig. 2: Global VTEC map during a period of a solar storm at 08:00 (UT) Oct. 29, 2003. The Kp index is 9 (shown on the right), Flux is 280 and the Sun Spot Number 170.

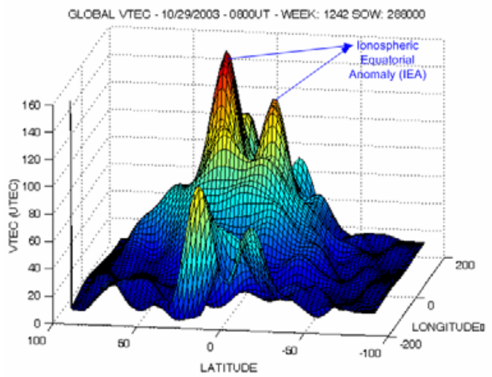

Fig. 3: 3D Global VTEC map during a period of a solar storm at 08:00 (UT) Oct. 29, 2003. It can be seen the Ionospheric Equatorial Anomaly.

The VTEC variation with latitude for March, July, and October (monthly variation) can be seen in Fig. 4, for longitude of 200^0. This figure also shows that during higher solar activity periods (March and October) there are higher VTEC values than during lower Solar activity periods (July).

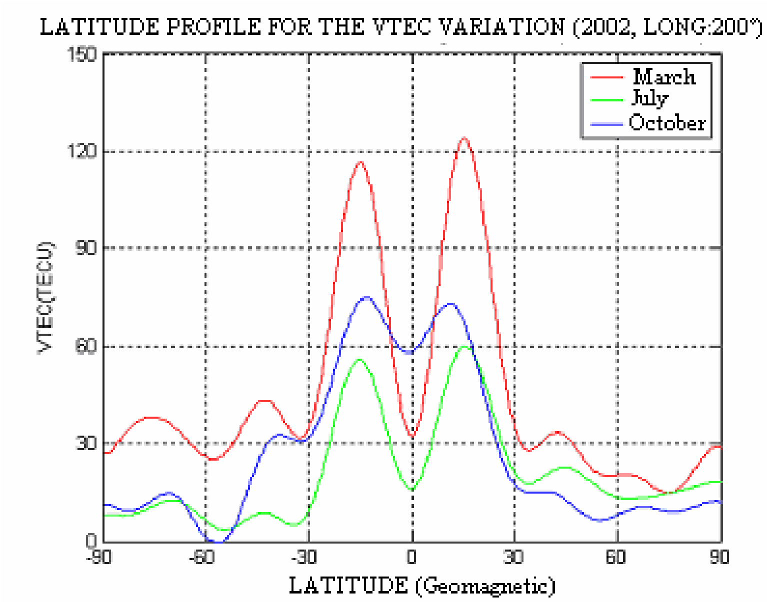

Fig. 4 – Latitude Profiles for the VTEC variation during March, July, and Oct. 2002 (Longitude 200º and 07 UT).

GLOBAL BEHAVIOR OF THE IONOSPHERE

A strong geomagnetic storm occurred on the last days of Oct. 2003 (Fig. 5 to 8). On these days the VTEC has reached extremely high values (>160 TECU) for example, in such regions as California, USA (Fig. 5). The greater the VTEC, the greater are the effects on the GPS signal propagation.

Two peculiar epochs were analyzed (Oct. 29 and 30, 2003). It can be seen (Fig. 5) that at 20:00 UT occurred an extension of the electron concentration that went up to +40º of geomagnetic latitude with high electron density. In this moment the Kp index achieved 8.33 (high geomagnetic activity), the Solar Flux 280 and the Sun Spot Number 170. Two hours later (Fig. 6), the Kp index fell drastically (Kp = 4) making the peaks of IEA to return to ±20º, which is the case of days with low Kp index. Notice that the Solar Flux and the Sun Spot Number practically remain constant over this period. It can be observed that in the same day (Oct. 30, 2003) the IEA peak is around +40º of geomagnetic latitude and the Kp index reached 9. In this way it was observed that the Kp index provides a great correlation with the IEA behavior during solar storms, and this is an important index to be analyzed.

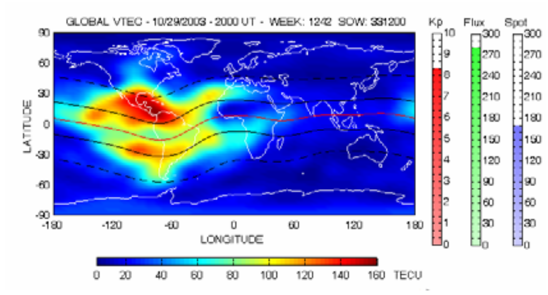

Fig. 5: Global VTEC map at 20:00 (UT) Oct. 29, 2003. The The Kp index is 8.33, Flux is 280 and the Sun Spot Number 170 (shown on the right).

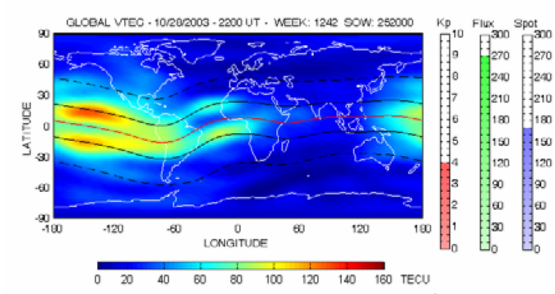

Fig. 6: Global VTEC map at 22:00 (UT) Oct. 29, 2003. The The Kp index is 4, Flux is 270 and the Sun Spot Number 170 (shown on the right).

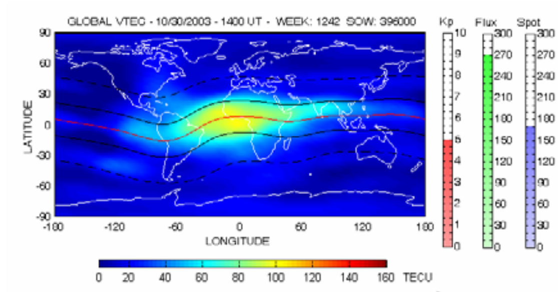

Fig. 7: Global VTEC map at 14:00 (UT) Oct. 30, 2003. The The Kp index is 5, Flux is 270 and the Sun Spot Number 170 (shown on the right).

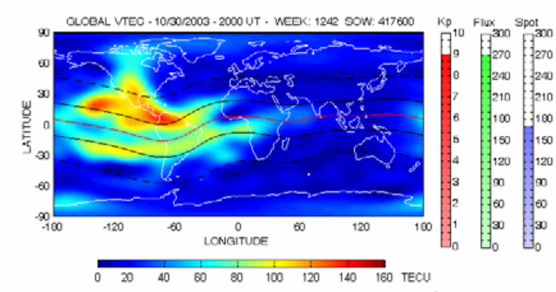

Fig. 8: Global VTEC map at 20:00 (UT) Oct. 30, 2003. The The Kp index is 9, Flux is 270 and the Sun Spot Number 170 (shown on the right).

CONCLUSION

There have been developed tools to study the global ionospheric behavior during solar storms since 1999, mainly over the IEA region. IONEX appears to be a good source of data to study the ionosphere behavior in a global way and its correlation with the Kp, sunspot number, and solar flux index.

Knowing the history of the ionosphere and its correlation with Kp index more accurate predicted VTEC models can be found. Also these data are been used to study the electron density gradients mainly at the IEA since large longitudinal and latitudinal gradients are presented in these regions.

To improve VTEC maps it is suggested to increase the numbers of GPS stations mainly in critical regions, and to have IONEX data available with time intervals less than two hours.

ACKNOWLEDGMENTS

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REFERENCES

[1] A. B. V. Oliveira, T. N. de Morais; F. Walter, "Effects of Equatorial Anomaly in the GPS Signals", ION-GNSS-2003, Portland, OR, 9-11 Sep., 2003.

[2] ICD GPS 200C – 002. Navstar GPS Space Segment/ Navigation User Interfaces. September 25, 1997. pp. 89.

[3] T. N. de Morais, A. B. V. Oliveira; F. Walter,. "Global Behavior of Equatorial Anomaly since 1999 and Effects on GPS Signals". In: IEEE Transactions on Aerospace and Electronic Systems, March 2005.

[4] J. A. Klobuchar, "Ionospheric Time-Delay Algorithm for Single-Frequency GPS users", IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-23, No. 3, pp. 332-338, 1987.