Geofísica Internacional (2002), Vol. 41, Num. 1, pp. 49-55

Variations of total electron content during a magnetic storm

B. F. de Haro Barbás, V. H. Ríos, A. Pérez Gómez and M. Santillán
Laboratorio de Técnicas Satelitales, Depto. de Física, Facultad de Ciencias Exactas y Tecnología,
Universidad Nacional de Tucumán, Argentina

Received: May 02, 2000; accepted: April 24, 2001.

RESUMEN

En este trabajo se analizan las variaciones del Contenido Electrónico Total (CET) durante una tormenta geomagnética, calculado a partir de mediciones del retardo ionosférico sobre las señales de código y fase, transmitidas por los satélites del Sistema de Posicionamiento Global (SPG).

Los datos procesados corresponden a la estación SPG perteneciente al proyecto CAP (Central Andes Project), situada en San Miguel de Tucumán (26° 53' S , 65° 13' W), Argentina.

Las variaciones del CET ocurridas en los días de abril de 1997 presentan valores altos, comparados con valores promedios del mes de abril calculados con mediciones de nuestro banco de datos de años anteriores.

El fenómeno se registró con mayor intensidad en el período comprendido entre los días 9 al 12 de abril de 1997, tomando un valor de Kp=7- (Figure 2) para el día 11.

Además se comparó dichos valores con los obtenidos para días anteriores y posteriores a la tormenta.

Los valores de CET alcanzados durante la tormenta exceden en un 30 % a los valores que se alcanzan para días calmos durante esa época del año, lo cual provoca mayores errores en el cálculo del posicionamiento mediante el sistema SPG.

PALABRAS CLAVES: Ionosfera, SPG, tormenta magnética, CET.

ABSTRACT

The variations of Total Electron Content (TEC) are analysed during a geomagnetic storm, from measurements of ionospheric delay in code and phase, with the satellites of the Global Positioning System (GPS) at Tucumán, Argentina.

The variations of TEC in April 1997 present high values, compared with averages values of previous years, reaching a value of Kp=7 – on April 11, 1997.

The TEC values exceed by 30% the average values for quiet days for the same time of year.

KEYWORDS: Ionosphere, GPS, magnetic storm, TEC.

SYMBOLS

TECO: oblique total electron content.

TEC: vertical total electron content.

L1, L2: frequencies of the carriers.

dt, dT: biases of the receiver and satellite clocks respectively.

$\varphi_{k,1}^{p}$, $\varphi_{k,2}^{p}$: phase observables to the frequencies L1 and L2 free of slip cycles for the satellite p and the station k.

$R_{k,1}^{p}$, $R_{k,2}^{p}$: observables pseudoranges for the frequencies L1 and L2 for the satellite p and the station k.

$\lambda_{1,2}$: the wavelengths of the carrier.

$P_{k,1}^{p}$, $P_{k,2}^{p}$: observables pseudoranges expressed in phase units $P = R / \lambda$.

$I_{k,1,2}^{p}$, T_{k}^{p}: ionospheric and tropospheric delay.

INTRODUCTION

Geomagnetic storms and associated ionospheric storms occur when charged particles with high energy in the solar wind, or from holes in the corona, arrive to the earth causing interferences in the terrestrial magnetic field. The charged particles interacting with the atmosphere excite ions and produce additional electrons. The strong electric fields that are generated cause significant changes in the ionosphere morphology, producing large delay of the propagation of the GPS signals and an advance in the phase of the carrier. These are results of the magnetic storms that produce large changes in the distribution of the electron density, in the TEC and the system of ionspherics streams (González *et al.,* 1994).

The total electron content (TEC) is found from the delay and the advance in phase produced by the ionosphere in the signals broadcast by the GPS satellites (Hartmann *et al.,* 1984; Brunner *et al.,* 1991; Ríos *et al.,* 1998).

By linear combination, the following relationships are obtained:

$$\varphi_{k,3}{}^{p} = \varphi_{k,1}{}^{p} - r * \varphi_{k,2}{}^{p} \qquad (1)$$

for free ionosphere combination, with $r = \lambda_1 / \lambda_2 = 60 / 77$, and

$$\varphi_{k,4}{}^{p} = \varphi_{k,1}{}^{p} - (1/r) * \varphi_{k,2}{}^{p} \qquad (2)$$

for lineal combination free of clock bias.

The phase shift is obtained from

$$\varphi_{k,1,2}{}^{p} = (1/\lambda_{1,2}) \, [\rho_{1,2} - I_{k,1,2}{}^{p} + T_{k}{}^{p} + c\,(dt - dT) + \lambda_{1,2} \, N_{k,1,2}{}^{p}] \qquad (3)$$

where $I_{k,f}{}^{p} = (40.30 / f_{1,2}{}^{2}) \, TECO_{k}{}^{p}$.

Thus we obtain for the lineal combination

$$\varphi_{k,4}{}^{p}(t) = 5.53 * TECO_{k}{}^{p} + N_{k,1}{}^{p} - (1 / r) \, N_{k,2}{}^{p} \qquad (4)$$

where $P_{k',4}{}^{p} = N_{k,1}{}^{p} - (1 / r) \, N_{k,2}{}^{p}$. If $P_{k,4}{}^{p}$ is known for each station. The vertical electron content can be calculated with a high precision because the phase can be observed to the order of ≈0.01 cycle (Gehlich and Hutckuck, 1991).

For receivers that measure pseudo-ranges and phases in the frequencies L1 and L2 we can form the following linear combination of observations:

$$(P_{k,1}{}^{p} - P_{k,2}{}^{p} / r) + (\varphi_{k,1}{}^{p} - \varphi_{k,2}{}^{p} / r) = P_{k,4}{}^{p} \qquad (5)$$

whence we obtain $P_{k,4}{}^{p}$.

ESTIMATING VERTICAL ELECTRON CONTENT (TEC) FROM OBLIQUE ELECTRON CONTENT (TECO)

TECO is the total electron content along the signal path between the satellite and the receiver. The integral is assumed to include the electrons in a column with a cross-section of 1 m^2 and extending from the receiver to the satellite.

Figure 1 shows a first approach where the oblique electron content is related to the vertical electron content by

$$TECO \cong TEC / \cos Z', \qquad (6)$$

where Z' is the zenith angle at point I.

From Figure 1 we may calculate Z' as

$$\sin Z' = (R_T \sin Z) / (R_T + h_I) \qquad (7)$$

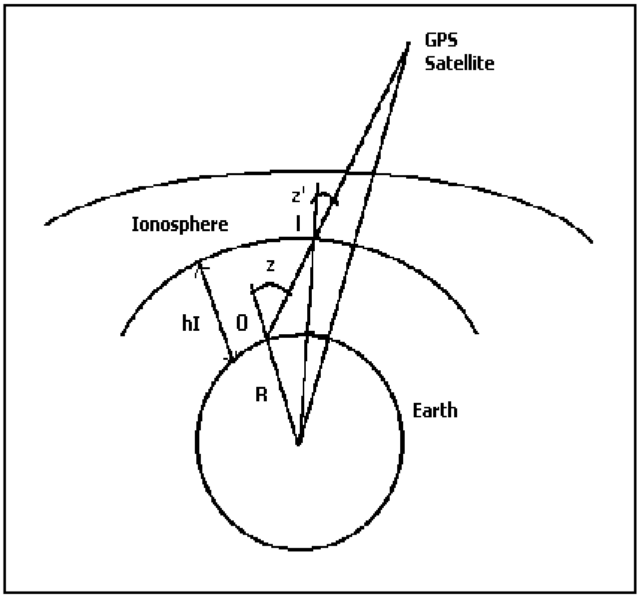

Fig. 1. Geometry for ionospheric path delay.

where R_T is the mean radius of earth, and h_I is the mean height of the ionosphere.

The zenith angle Z can be calculated from the position of the satellite and the approximate coordinates of the localization of the observation point.

OBSERVATIONS

Station Tucumán has a GPS Ashtech Z-XII receiver of 12 channels in parallel (GPS World, January 1997).

The observations are available in

- C/A code in L1
- P code in L1 and L2
- Carrier phase in L1 and L2.

The signal can be acquired each 30 sec but the precise ephemerides of the satellites are obtained every 15 minutes. Therefore the calculation was carried out at intervals for 15 minutes for a total of 96 daily observations (Santillán, 1999).

In Figure 2 the planetary index Kp is plotted every 3 hours starting from 8 April 1997. A major increase was observed on the 11. Alerts are issued when the Kp index is 4 or greater, or when the 24-hour running A index is 20 or greater (J. A. Joselyn). In Figure 3, the magnetic index Dst is plotted. Observe a marked depression during 10 and 11 April 1997 (start at 18 UT April 10 and end at 7 UT April 11), and a recovery starting from the 13.

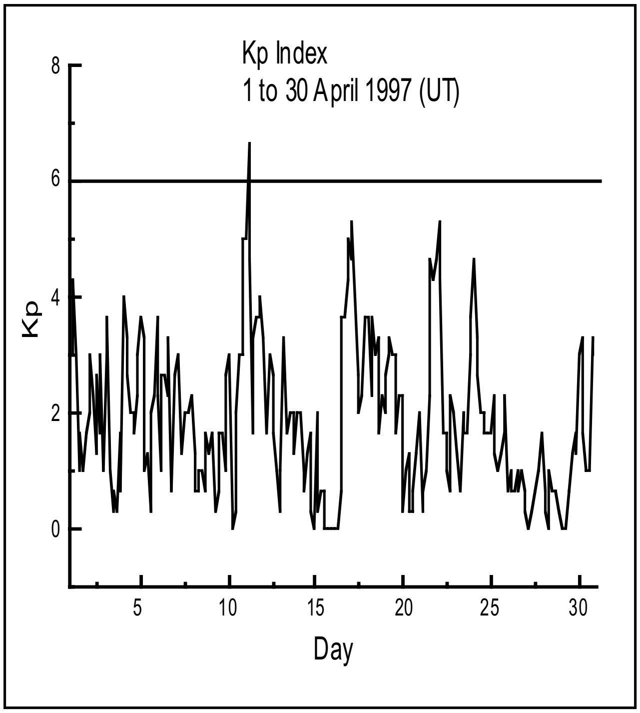

Fig. 2. Kp index every 3 hours.

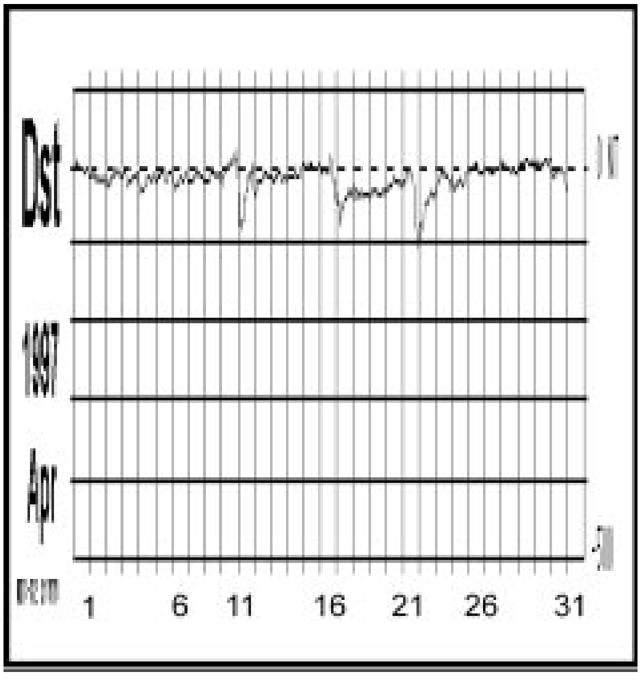

Fig. 3. Magnetic index DST.

The intensity of a magnetic storm is commonly defined by the minimum Dst value during the magnetic storm, which is equivalent to the maximum Dst magnitude at the main phase. The associated Sun-Earth connection to this storm is reported in Berdichevsky *et al.*

The variations of the AE and AU indices are plotted in Figure 4. Observe a marked interference peak intensity on 10 and 11 April 1997.

After each magnetic storm interval (sharp Dst decrease), there are prolonged intervals of intense AE. These AE intensifications are directly correlated with the slow recovery of Dst.

In most events, the Dst index takes 10-20 days to recover near-background values (Kamide; Tsurutani and González, 1997) A comparison with the AE index indicates that there is a good relationship between AE increase and Dst decrease. Possible sources of the ring current are a substorm injection from plasma sheet, and boundary layers.

RESULTS AND DISCUSSION

Figure 5 illustrates the ionospheric response to a storm in April, 1997 and shows the dependence in time (UT) of TEC over Tucumán station. We find that on the days 9 to 13, there is a depression and then a recovery of the TEC. The location is (-25° 26', -3° 47') in magnetic coordinates; behavior is typical of ionospherics storms. In Figure 6 the storm is positive respect to the calm average.

- The values during the storm exceed by 30% the values on quiet days (Figure 6).
- The values during the storm oscillate between 15 and 75 total electron content units (10^{16} m^{-2}), for the Tucumán station.
- In previous and later days density is compressed until recovering the normal values.
- During geomagnetic storms the sign of the GPS system is affected, introducing errors in the calculation of the positioning.

From Figure 7 at the beginning of the storm the values of TEC are smaller than the calms and in the recovery phase the difference becomes positive, that is to say, the perturbed values are larger than the calms, with values about 20 Tecu for the days 11 and 12 of April.

Auroral ionization increases the conductivity of the thermosphere, and together with magnetospheric convection produces Joule heating, which can increase from tens of gigawatts during quiet times, to hundreds of gigawatts during severe geomagnetic disturbances (Lu *et al.,* 1995: Evans *et al.,* 1998). The combined globally integrated rate of energy input from magnetosphere can exceed a terawatt, possibly dumping thousands of terajoules of energy during radiation over the day or so following the storm (Tsurutani *et al.,* 1998).

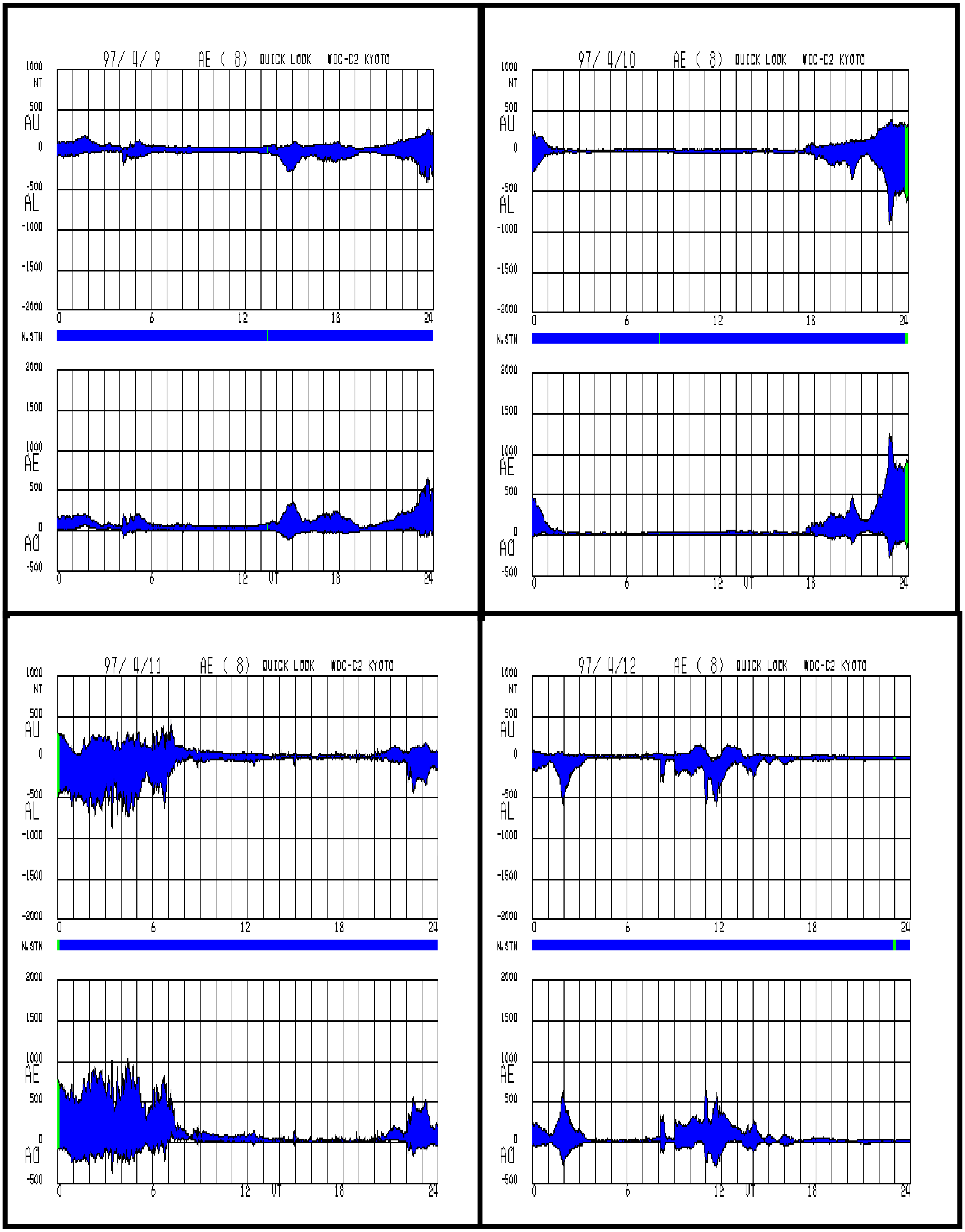

Fig. 4. AU and AE index April 1997.

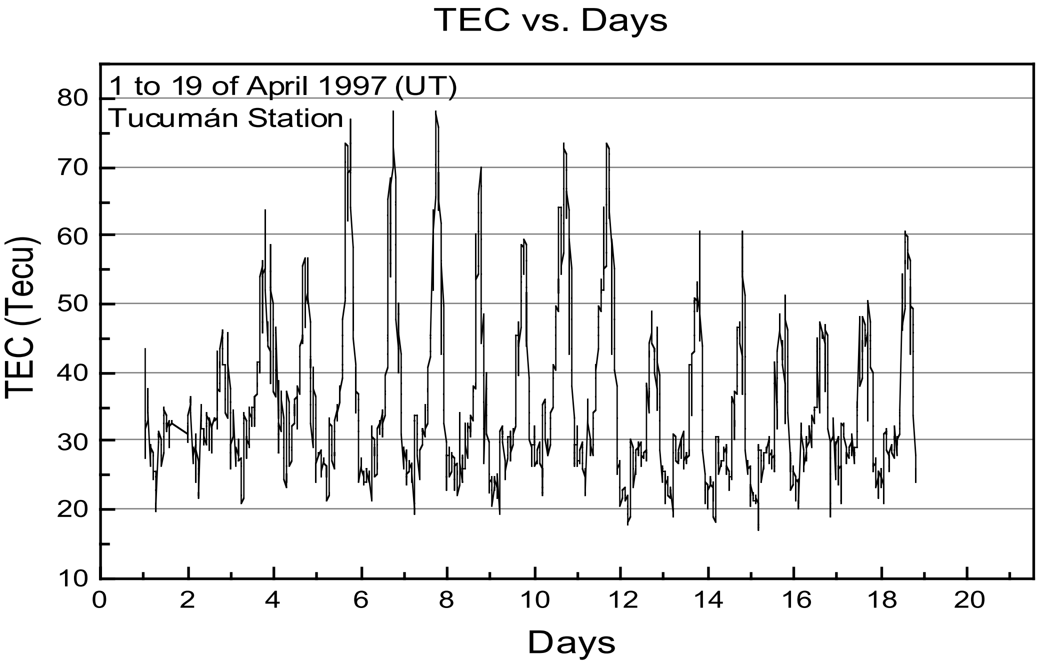

Fig. 5. Variation of TEC, April 1997

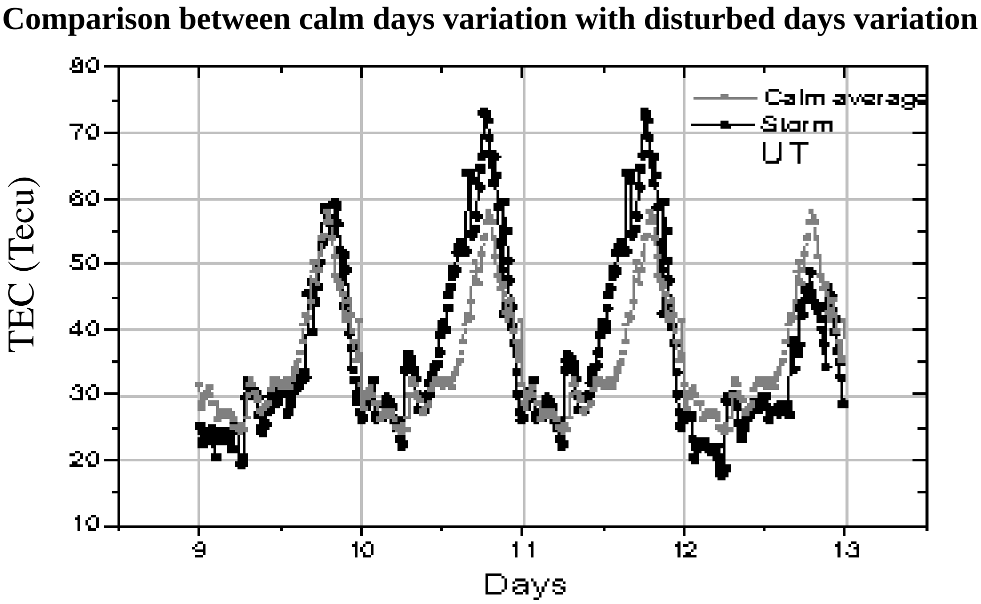

Fig. 6. Comparison between calm day variation with disturbed day variation. The scale is referred to the days of storm.

CONCLUSIONS

The method used for estimation of TEC by GPS gives a good approach to determine the presence of geomagnetic storms.

By means of the processing of the sign we can obtain the lag from crossing the ionosphere and in this way apply a correction factor to the values obtained in the measurements of positioning.

ACKNOWLEDGMENTS

We thank Robert Smalley of the University of Memphis for the data.

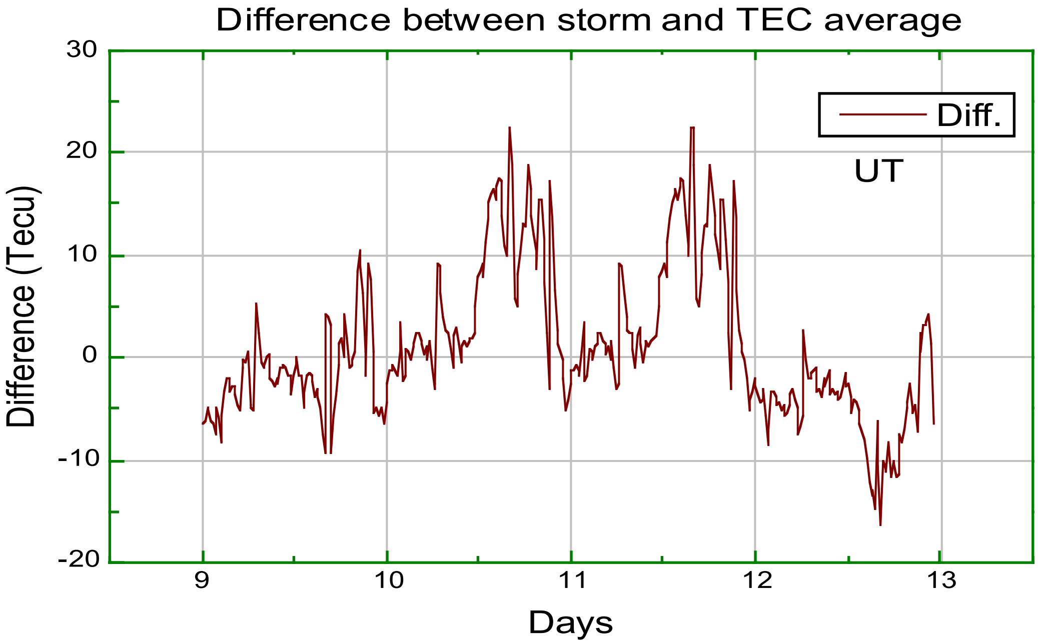

Fig. 7. Difference between TEC values during storm and the average values of calm days.

BIBLIOGRAPHY

BERDICHEVSKY, D., J. L. BOUGERET, J. P. DELABOUDINIERE, N. FOX, M. KAISER, R. LEPPING, D. MICHELS, S. PLUNKETT, D. REAMES, M. REINER, I. RICHARDSON, G. ROSTOKER, J. STEINBERG, B. THOMPSON and T. VON ROSENVINGE, 1998. Evidence for multiple ejecta: April 7-11, 1997 Sun-Earth connection event. *Geophys. Res. Lett., 25,* 2473.

BRUNNER, F. K. and M. GU, 1991. An improved model for the dual frequency ionospheric correction of GPS observations. *Manuscripta Geodaetica 16,* 205-214.

EVANS, D. S., 1988. Specification of the heat input to thermosphere from magnetospheric processes using TIROS/NOAA auroral particle observations. *Adv. Astron. Sci., 65,* 1649-1667.

GEHLICH, U. and H. HUCKUCK, 1991. Automized Preprocessing of GPS Phase-dates, IAG Symp109 Permanent Satellite Tracking Networks for Geodesy and Geodynamics, Vienna.

GONZÁLEZ, W., J. JOSELYN, Y. KAMIDE, H. KROEHL, G. ROSTOKER, B. TSURUTANI and V. VASYLIUNAS, 1994. What is to geomagnetic storm?, *J. Geophys. Res., 99,* 5771-5792.

GPS World, "Receiver Survey", January 1997, pp. 42-60.

HARTMANN, G. K. and R. LEITINGER, 1984. Range errors due to ionospheric and tropospheric effects for signal frequencies above 100 MHz. *Bull. Geod. 58,* 109-136.

JOSELYN, J. A., 1997. System effects – what do users want?, Geophysical Monograph, Series 98, 14-16.

KAMIDE, Y., W. BAUMJOHANN, I. A. DAGLIS, W. D. GONZALEZ, M. GRANDE, J. A. JOSELYN, R. McPHERRON, J. PHILLIPS, E. G. D. REEVES, G. ROSTOKER, A. S. SHARMA, H. J. SINGER, B. T. TSURUTANI and V. M. VASYLIUNAS, 1998. Current understanding of magnetic storms: Storm/substorm relationship, invited review. *J. Geophys. Res., 103* (A8), 17705-17728.

KLOBUCHAR, 1977. Ionospheric Time Delay Corrections for Advanced Satellite Ranging System, AGARD-CP-209.

LU, G., A.D. RICHMOND, B.A. EMERY and R.G. ROBLE, 1995. Magnetosphere-Ionosphere-Thermosphere coupling: Effects of neutral winds on energy transfer and field-aligned currents. *J. Geophys. Res., 100,* 19643-19659.

RÍOS V. H., A. PÉREZ GÓMEZ and A. BASCOLO, 1998. TEC determination from GPS phase and code observation over two Argentina station, COSPAR, Nagoya, Japan.

SANTILLÁN, M., 1999. “Análisis No Lineal de la Ionosfera de Bajas Latitudes“, Private Communication.

TSURUTANI, B. and W. GONZÁLEZ, 1997. The interplanetary causes of magnetic storms: a review. *Geophys. Monograph 98,* 77-87.

TSURUTANI, B., W. GONZÁLEZ, Y. KAMIDE and J. ARBALLO. “Magnetic Storms”. Geophysical Monograph 98.

B. F. de Haro Barbás, V. H. Ríos, A. Pérez Gómez and M. Santillán

Laboratorio de Técnicas Satelitales, Departamento de Física, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucumán, Argentina.
e-mail: bdeharo@herrera.unt.edu.ar