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Magnetic Storms Effects on the Ionosphere TEC through GPS Data

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Abstract: A method for monitoring the magnetic storm effects on the ionosphere using GPS network measurements is proposed. This method consists of determining the ionosphere Total Electrons Content (TEC) for a given region and a given period of time, using the GPS measurements data obtained by a permanent station from IGS (International GPS Geodynamics Service) network for the same region and the same period and an ionosphere model. It is known that the variation of the ionosphere TEC is directly related to the sun spot activities (approximately 11 years cycle), its seasonal and diurnal variations. These sun activities can be represented by the magnetic indexes of the geomagnetic activities (A_p, K_p), which are continuously obtained by geophysics observatories. It is shown in this article that the variation of both the TEC and the magnetic index A_p are closely related. Based on this result one may monitor the magnetic storms, which are caused by the different solar activities by simply monitoring the TEC using the GPS measurements. Although the GPS permanent stations IGS network does not cover all world regions, like North Africa and other regions in Asia and southern America, any other station not far away than 2000 km from a IGS permanent one can be used. The present results are obtained for the region of Oran city in Algeria for the period of the month of January 2004.

Key words: Magnetic storms, ionosphere TEC, GPS measurements, ionosphere modelling

INTRODUCTION

The Global Positioning System (GPS) is today the privileged tool for positioning with a high degree of accuracy and is also useful as a temporal reference. It is usually used for the positioning and the synchronization of measurements. Recent studies (Calais and Minster, 1995; Calais and Amarjargal, 2000; Chuo *et al*., 2000, Jann *et al*., 2000) have used the Global Positioning System (GPS) in studying the earth surface deformation and have shown the existence of some relationship between some earthquake events and the Total Electron Content (TEC) disturbances. In order to have a better understanding of the possible relationships between the solar activity or the geomagnetic storms and the earth deformation, one should have a dense GPS permanent stations network recording the maximum possible of data. The objective of this study is firstly to point out the close relationship between the magnetic storms and the TEC variation and secondly to show the possibility of studying or monitoring the earth surface deformation and eventually estimating the earthquake hazard using GPS measurements. This can be accomplished by observing the main ionospheric parameter (TEC) through GPS data collected on a region which has no GPS permanent stations, but not far away than 2000 km from an IGS permanent station (Schaer, 1997).

IONOSPHERE AND TROPOSPHERE

The ionosphere is the upper layer of the earth atmosphere (Fig. 1); it extends from 50 km up to 2000 km. The ionosphere is often spread into two layers:

The low layer shown as layer E (alone times called Kennelly Heaviside layer), it is included between 80 and 113 km above the earth surface and it reflects radio waves of low frequencies; and an upper layer called F layer (or Appleton Layer), which reflects higher radio waves (Boutiouta, 1994). It is divided into two layers: Layer F_1 which is beyond 180 km above the earth-surface and layer F_2 which is beyond 300 km above earth-surface, this layer is permanent in day time as well as during the night, despite the lack of the production term (Al'pert, 1973). It is maintained by vertical movement and mainly horizontal movement of the ionisation. The ionisation is

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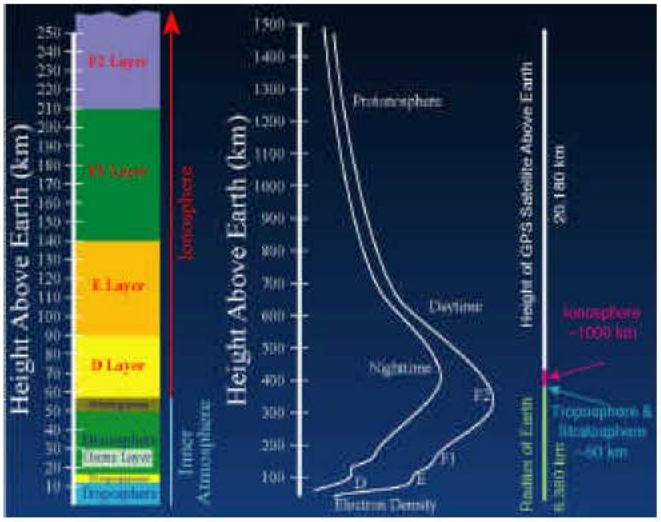

Fig. 1: Earth atmosphere

mainly caused by solar radiation (Belbachir, 1981). It is therefore dependant on location and time of day as well as season and on the 11 years sun spot cycle. This leads to a change of the atmosphere characteristics, the ionosphere refraction effect on the GPS satellites emitted signals depend on the TEC (Total Electron Content) (Richard, 2000); in other words the number of free electrons encountered by these signals when their traveling into the ionosphere. The concentration of free electrons depends somehow on the solar activity, i.e., the solar radiation quantum intercepted by the ionosphere. The ionosphere delay (path-time prolongation satellite-receiver) is included between zero and 50 m and varies in function of the ionosphere agitation.

Contrarily to the troposphere, it is not possible to model correctly this effect. The ionosphere has otherwise, a momentous property; it is a depressive medium for frequencies, which interest us. The electronic delay depends on the frequency and so the utilization of two GPS signals in L band, of frequencies ($f_1 = 1575.42$ Mhz and $f_2 = 1227.6$ MHz), with waves length: ($\lambda_1 = 19$ cm and $\lambda_2 = 24.4$ cm) undergo different perturbations will enable the elimination of the ionosphere delay (Klobuchar, 1996). To compute the ionosphere effects, the free electrons density along the satellite–receiver propagation path should be taken into account (Total Electron Content Unit), 1 TECU = 10^{16} el m $^{-2}$).

The troposphere is the lower atmospheric layer; it extends above ground upto 8 or 15 km high. It produces a variable reduction of the transmitted wave speed, which extends the path time; it is the troposphere delay (Boutiouta, 1994). The troposphere refraction effect on GPS signals depends somehow on weather conditions: Humidity (water drops, Temperature and pressure as well as on the satellite elevation).

The error is minimum at the zenith. The troposphere is a non-depressive medium; the troposphere delay does not depend on the frequency. Contrary to the ionosphere this error cannot be annulled by the measure of the two frequencies. In case where the receiver position would be known with a good precision, the GPS measures can be used to compute the atmospheric refraction effect on the GPS signals. In this case, the unknown to be resolved is not anymore the position of the observer but the atmospheric perturbation, which itself depends on some parameters, such as the TEC of the ionosphere or on the quantities of water vapour in the troposphere.

IONOSPHERE MODELLING

In practice the ionosphere is modulated as a spherical layer with a dual dimension thickness, or in other words, as a spherical shell, located at a height of h_{iono}, eagle 355 km (Fig. 2). The cross between the line of sight of the satellite and this spherical shell is named ionosphere point (IP), some times called Ionosphere Pierce Point or (IPP). The projection of the ionospheric Point on the earth surface is called SIP (Sub-Ionospheric Point). On the Fig. 2, Z_{rec} and Z_{IP} represent respectively the zenith angles of the GPS satellite such as it is seen by the receiver at a given site and the ionosphere point, R_T represents the ground radius.

Because this satellite is not found at the vertical of the observation site, the TEC measured along of this line of site is brought to the vertical with the aide of the function $(\mathrm{Cos}\,(z_{IP}))^{-1}$. The ionospheric refraction effect on GPS signals is explained by the propagation delay of the modulations, which result in an apparent propagation

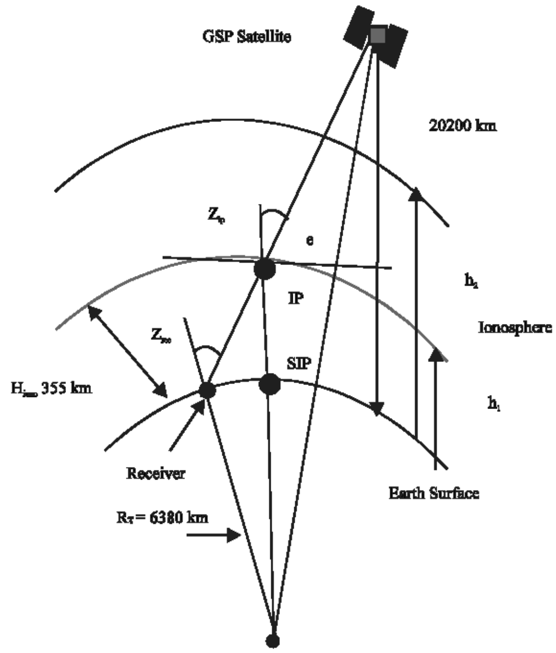

Fig. 2: Sub-ionosphere and ionosphere point

path, $I^i_P(t)$. On the other hand the ionospheric refraction causes an advance in the carrier phase propagation, or else, an apparent straightening in their path eagle to $-I^i_P(t)$.

Phase and group velocity: A single electromagnetic wave propagating, the velocity of phase is given for GPS L_1, L_2 by:

$$v_{ph} = \lambda f \tag{1}$$

A group of waves with slightly different frequencies, the group velocity for GPS code measurement is:

$$v_{gr} = \frac{df}{d\lambda}\lambda^2 \tag{2}$$

The relation between phase and group velocity

$$dv_{ph} = fd\lambda + \lambda df \tag{3}$$

The differentiation implicitly contains the dispersion, which is defined as a dependence of the phase velocity on the wavelength or the frequency.

$$v_{gr} = v_{ph} - \frac{dv_{ph}}{d\lambda}\lambda \tag{4}$$

The wave propagation in a medium depends on the refractive index n.:

$$v = \frac{C}{n} \tag{5}$$

$$C = \lambda f \tag{6}$$

The relationship between refractive index and frequency is:

$$n_{gr} = n_{ph} + f\frac{dn_{ph}}{df} \tag{7}$$

Refraction index: The ionosphere, extending in various layers, it is a depressive medium with respect to the GPS radio signal. The following series of approximates the phase and group refractive index.

$$n_{ph} = 1 + \frac{C_2}{f^2} + \frac{C_3}{f^3} + \frac{C_4}{f^4} + \ldots \tag{8}$$

$$n_g = 1 + \frac{C_2}{f^2} - \frac{C_2}{f^3} = 1 - \frac{C_2}{f^2} \tag{9}$$

C_2, C_3, C_4 do not depend on frequency but on the quantity N_e denoting the number of electrons per cubic meter (i.e., the electron density) along the propagation path. Refractive Index for single and group wave are:

$$n_{ph} = 1 + \frac{C_2}{f^2} \text{ and } n_{gr} = 1 - \frac{C_2}{f^2} \tag{10}$$

The group and the phase refractive indices deviate from unity with opposite sign. The relation: $n_{gr} > n_{ph}$ and, thus, $v_{gr} < v_{ph}$ because the electron density N_e is always positive. With different velocities, a group delay and a phase advance. Thus, GPS code measurements are delayed and the carrier phases are advanced. The code pseudoranges are measured too long and the carrier phase pseudoranges are measured too short compared to the geometric range between the satellite and the receiver.

The refraction index for the ionosphere (Sardon *et al.*, 1994; Davies, 1990) is given by:

$$n = 1 - \frac{X}{2} = 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2} = 1 - \frac{C}{f^2}N_e \tag{11}$$

where:

$$X = \frac{\omega_p^2}{\omega^2}; \omega_p^2 = \frac{e^2 N_e}{M\varepsilon_0}$$

$$C = \frac{e^2}{(8\pi^2 M\varepsilon_0)} \approx 40.3 [m^3/s^2]$$

e = electron charge
M = electron mass,
ε_0 = diélectrique constante (vacuum),
N_e = electron density $/m^3$
ω_p = plasma frequency (6 to 60 Mhz)

Finally and after all calculation the refraction index is:

$$n = 1 - \frac{C}{f^2} N_e = 1 - \frac{40.3}{f^2} N_e \quad (12)$$

The ionosphere refraction for the two cases (phase carrier and group «modulations») is:

$$I_{phase}(t) = -\frac{40.3}{f^2} \int_{path(sat-rec)} N_e ds$$
$$I_{groupe}(t) = \frac{40.3}{f^2} \int_{path(sat-rec)} N_e ds \quad (13)$$

In fact the absolute value of the ionospheric refraction is similar to the carriers as to modulations, but its singe is different. For a vertical propagation:

$$I_{rec}^{sat}(t) = \frac{40.3}{f^2} \int_{path(sat-rec)} N_e ds \quad (14)$$

The TEC along the receiver(j) line of sight to GPS satellite(i) is:

$$TEC_j^i = \int_{path(sat-rec)} N_e ds$$

The which affords the ionospheric refraction effect: TEC brought to the vertical is :

$$TEC_{j,vertical}^i = VTEC \quad (15)$$

The relationship between ionospheric refraction and TEC is :

$$I_{phase}(t) = -\frac{40.3}{f^2} TEC; \; I_{group}(t) = \frac{40.3}{f^2} TEC \quad (16)$$

So :

$$TEC_j^i = \int_{path(sat-rec)} N_e ds$$

It represent the slant total electrons for the line of sight, (the Slant Total Electrons Content « STEC») electrons/m², between the terrestrial receiver (j) and the satellite (i).

$$TEC_j^i = \int_{path(sat-rec)} N_e ds = STEC \quad (17)$$

Therefore:

$$I_j^i(t) = \frac{40.3}{f^2}.STEC \quad (18)$$

TEC brought to the vertical is: $TEC_{j,vertical}^i$. At the vertical and with the aide of function $(Cos\,(z_{IP}))^{-1}$, It will be:

$$I_j^i(t) = \frac{40.3}{f^2 Cos(z_{ip})}.VTEC \quad (19)$$

This manner of processing neglects the horizontal gradients effects in the ionosphere.

It is worth to mention in practice that the function becomes less and less realistic, when the Z_{ip} angle is increased. For this reason all measures corresponding to the zenithal angles Z_{rec} superior to 70° are rejected in calculations. It is to be noted that the TEC obtained by this way is not representative of the ionosphere above the GPS receiver site, but of the ionosphere situated at the vertical of the sub-ionospheric point (SIP).

METHODOLOGY

One of the important characteristics of the ionosphere is that is spread the electromagnetic power (Boutiouta, 1994) of the radio electrics signals in L band, for this raison GPS signals of frequencies L_1 and L_2 undergo different perturbations. This ionosphere property can be exploited to determine this error using receiver double frequencies measures.

The TEC calculations are biased by the receiver and satellite clocks offsets as well as by troposphere propagation errors and the multi-paths. Satellite precise positioning systems function mainly with two frequencies in order to be able to determine the ionosphere delay. The two types of the following measures are used:

The pseudo-range P^i_j and the phase carriers L^i_j. The pseudo-range P^i_j and the phase carriers L^i_j for the GPS frequencies f_1 and f_2, in the units of distance, can be expressed (Al'pert, 1973; Klobuchar, 1996; Jann *et al.*, 2000; Gao and Liu, 2002) by:

$$P^i_{1,j} = \rho^i_j + I^i_{ion,1,j} + I^i_{trop,j} + C(\tau_i - \tau_j) + d^i_{ins,1} + d_{ins,1,j} + d^i_{orb,j} \quad (20)$$

$$P^i_{2,j} = \rho^i_j + I^i_{ion,2,j} + I_{trop,j} + C(\tau_i - \tau_j) + d^i_{ins,2} + d_{ins,2,j} + d^i_{orb,j} \quad (21)$$

$$L^i_{1,j} = \lambda_1\phi^i_{1,j} = \rho^i_j - I^i_{ion,1,j} + I^i_{trop,j} + C(\tau_i - \tau_j) + -\lambda_1 b^i_{1,j} \quad (22)$$

$$L^i_{2,j} = \lambda_2\phi^i_{2,j} = \rho^i_j - I^i_{ion,2,j} + I^i_{trop,j} + C(\tau_i - \tau_j) + -\lambda_2 b^i_{2,j} \quad (23)$$

Where the indices i and j represent the GPS satellite and the receiver, respectively:

ρ^i_j : The true distance between receiver and satellite;
I_{ion} : The ionosphere effects ;
I_{trop} : The troposphere effects;
c : Light speed on a vacum ;
τ : Clock offset receiver or satellite;
d_{ins} : Satellite or receiver instrumental biases;
d_{orb} : Orbit-error ;
λ : Carrier waves length;
ϕ : Carrier phase between receiver and satellite;
b : Cycle slip of the carrier phase .

The troposphere effect in the carrier phase and the pseudo-range measures can be eliminated by substraction 20 of the 21 and 22 of the 23, respectively. The ionosphere effects in terms of oblique TEC along the line of sight, STEC in electrons/m², between terrestrial receiver R_j and satellite T_i can be expressed as:

$$I_{ion} = \rho^* - \rho_0 = \int_j^i (n_g - 1)ds = \frac{40.3}{f^2}\int_j^i N ds = \frac{40.3}{f^2} STEC \quad (24)$$

Where:

ds : The infinitesimal length of path propagation of the radio wave ;
ρ^* : The vertical distance between receiver and satellite;
ρ_0 : The real distance between receiver and satellite;
N : The electrons density (electrons concentration. m^{-3});
f : The radio wave frequency in Hz;
STEC : Slant total electronics content;

Using Eq. 24 in Eq. 20, 21, 22 and 23 we can obtain (16):

$$STEC = \frac{1}{40.3}\frac{f_1^{\,2} f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}}(P^i_{2,j} - P^i_{1,j} - k^i - k_j) \quad (25)$$

$$STEC = \frac{1}{40.3}\frac{f_1^{\,2} f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}}(\lambda_1\phi^i_{2,j} - \lambda_2\phi_{2,J} + A^i_j) \quad (26)$$

where: $K^i = d^i_{ins,2} - d^i_{ins,1}$, $K_j = d_{ins,2,j} - dins_{,1,j}$ and

$$A^i_j = (P^i_{2,j} - P^i_{1,j}) + (\lambda_2\phi^i_{2,j} - \lambda_1\phi^i_{1,j}) - (k^i - k_j) \quad (27)$$

Though Eq. 24 can give us directly the TEC, because of the length of the pseudo-range, the STEC precision is relatively weak. The alternative way is to combine the Eq. 24, 25 to obtain the mean square value A^i_j and then we use Eq. 25 to obtain a better precision of STEC.

The STEC can be obtained as shown previously, however it has been proved that is preferable to adjust mathematically the STEC to TEC observed at the sub-ionosphere point (SIP), the reference point for the vertical total electrons content (VTEC).

$$VTEC = STEC \cdot S(e) \quad (28)$$

S(e) is the function given by Sover and Fanselow (1987):

$$S(e) = \frac{\sqrt{R^2_T Sin^2 e - R^2_T + (R_T + h_1)^2} - \sqrt{R^2_T Sin^2 e - R^2_T + (R_T + h_2)^2}}{h_1 - h_2} \quad (29)$$

Where:

e: is the satellite elevation;
h_1 and h_2: are respectively the lower and upper heights of the ionosphere;
R_T: is the principal radius of the earth.

It is interesting to note that the function S(e) depends mainly on the height of the mean layer of the ionosphere : $h_m = (h_1+h_2)/2$.

Davies (1990) has shown that h_m varies between 300 and 450 km, however, other researchers consider that is limited between 300 and 400 km. Sardon *et al.* (1994, 1997) have simply assumed that h_m is of 355 km. The cut-off elevation angle for each GPS receiver was 20°, in order to minimize theirs offset and to neglect undesirable errors.

DATA PROCESSING AND RESULTS ANALYSES

We have used the ionosphere model coefficients (CODE), (Schaer, 1997) (Centre for Orbit Determination in Europe) modelling approach of TEC from IGS permanent stations network (Fig. 5). We have taken the Rabat (Morocco) GPS permanent station measures; we were in need of the almanacs to calculate satellites position and sub-ionospheric points to develop a regional model limited around the station.

It is interesting to note that presently (2005), the analysis centre CODE, processes data about 200 stations, globally distributed throughout the world (Fig. 3) IGS global network.

The circles indicate places where TEC have been determined. The CODE GIM (CODG) is based on one layer model, or thin layer. This model assumes that the electrons are concentrated in a spherical scale with a thin infinitesimal layer (Fig. 3).

The diameter of each cell surface is more than 2000 km, whereas the cut-off angle is less than 20°.

The total slant electrons content is then converted to vertical total electrons content STEC to VTEC.

In present study we have taken the case of a zone near the city of Oran (ALGERIA) which has the geographical position (latitude 35° 39' 50'' and longitude 0° 38' 08'') for a period of one month (January, 2004). After having loaded the measures concerning this period, the calculation of the TEC can be performed according to the following procedure (Fig. 4).

For data processing and in order to obtain the TEC, we have proceeded in the following manner:

- Downloading measures data of GPS permanents stations (IGS network)
- Decoding the raw observations data files « RINEX)» (Receiver Independent Exchange (format) and almanacs files (files: Yuma.txt).

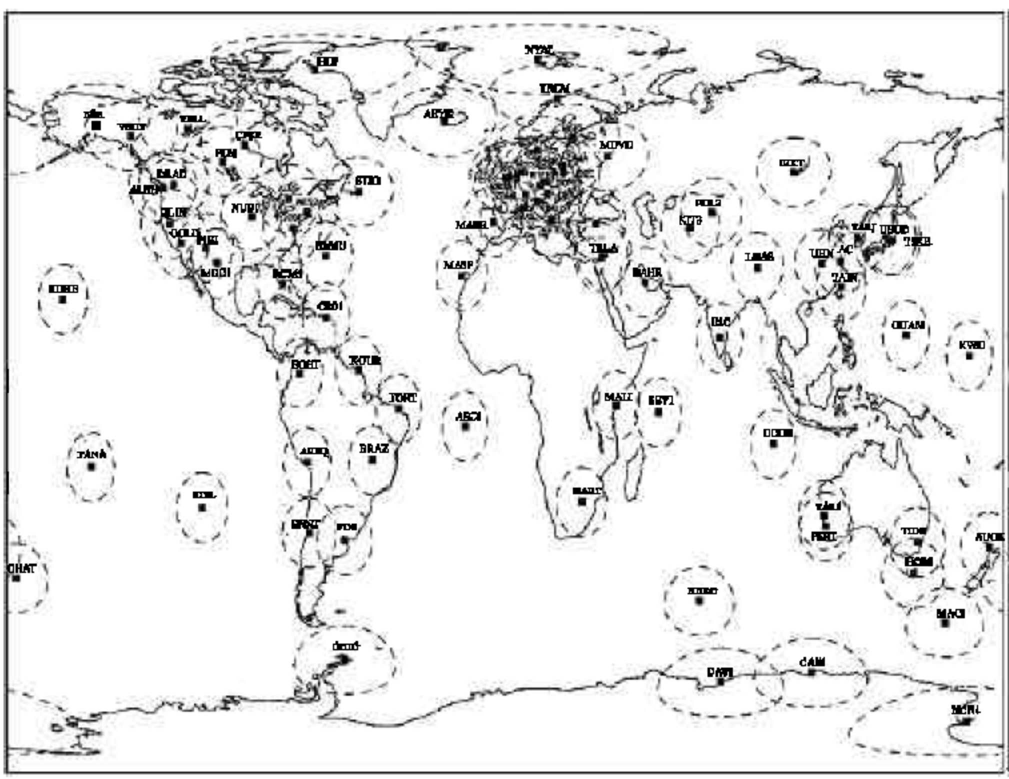

Fig. 3: GPS stations considered by CODE

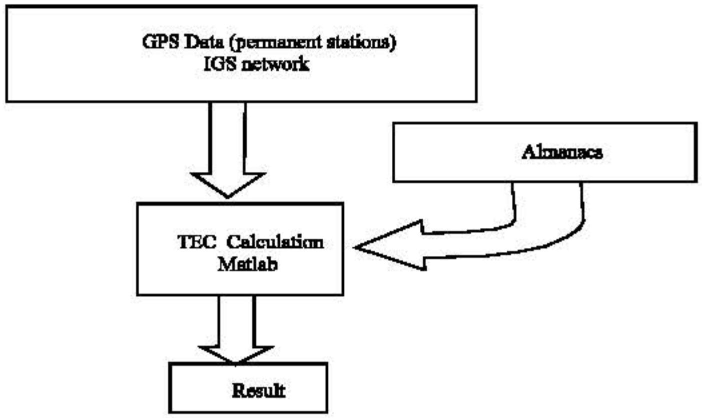

Fig. 4: TEC procedure calculation

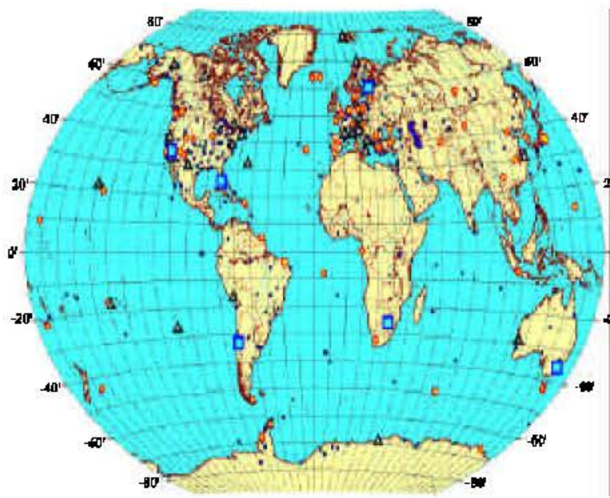

Fig. 5: IGS permanent stations network

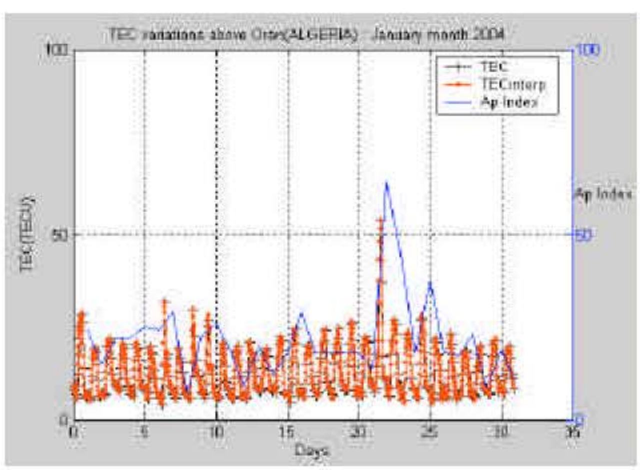

Fig. 6: TEC variation for Oran, (January, 2004)

Table 1: TEC variations

Days	Index A_p	TEC Values (TECU)
1	24	29
7	29	32
9	23	30
10	26	28
20	18	27
22	64	54
23	43	27
25	38	28

Table 2: Indexes K_p and A_p

Index K_p	Index A_p	Geomagnetic field state
<4	<10	Calm
4	>10 et <20	Unstable
>4	>20 et <40	Geomagnetic storm (bore ales auroras apparition)

A small programme under matlab treats the data of Rinex and «yuma.txt» files. The result for the treated period shows well a particular activity. The obtained result for the TEC variation is given in Fig. 6. In order to interpret TEC evolution, we have plotted the magnetic index A_p on the same Fig. 6. As it can be seen from this figure both the magnetic index Ap and the TEC are more important for the days: 1, 7, 9, 10, 20, 22, 23 and 25. Therefore the TEC variations depend on the magnetic storms activity, which is it self related to the solar activity. The most recent solar activity pick took place in December 2001 and 2004 corresponds to the decreasing phase of solar activity.

To quantify the geomagnetic activity, two indexes are defined: Index A and Index K, they represent the perturbations of the magnetic field measured each three-hour time. For our concern we use index K_p (planetary) and index A_p (planetary), (NOAA Web Site) to make the interpretation of present results.

For the geomagnetic condition, in function of indexes K_p and A_p we have drawn Table 1 and 2.

A geomagnetic storm affects the earth magnetic field, whereas an ionosphere storm affects the ionised ionosphere conditions of the layers and finally causes perturbations to signals of « GPS, GLONASS and GNSS».

CONCLUSIONS

This study deals with magnetic storms on the GPS observations; it represents the TEC variations above the area of Oran city, from GPS data collected by IGS permanent stations network during January 2004.

Figure 6 shows the close relationship between the geomagnetic index A_p and the ionosphere TEC. Space climate and associated perturbations in the magnetic field can cause large gradients in the TEC at average altitudes. The large gradients in the TEC are frequently associated with events of ionosphere scintillations with hard conditions. These fluctuations can produce link failure (receiver-satellites links) of GPS receivers. So, the knowledge of this gradient is important for different GPS users. The GPS can be used for the study of magnetic storms; otherwise it is a comprehension tool for the earth-solar environment.

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