

Estimated Impacts Induced by The Magnetic Activity Index (Dst) on the Local Total Electronic Content (TEC) in Africa Equatorial Zone

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ABSTRACT

The state of equatorial ionosphere has been studied from the determination of the Total Electron Content (TEC) based on the correction of errors propagation of GPS signals due to ionospheric disturbances using the dual frequency method. In our study, we considered three stations of the equatorial area (adis, bjco and nklg) in January 2012. Firstly, the monthly survey of the TEC has revealed that the magnetic storm days coincide with the days that the TEC RINEX around 70 UCET. Secondly, the daily survey of the TEC reveals two TEC (TEC/RINEX and the TEC/CODG) has revealed that during magnetic storms days, the interval between curves of TEC observed between 10: 00PM to 16:00PM (UT) is more important (around 10 UCET) when the Dst is strongly negative whatever the nature of the magnetic storm, and the interval between curves of TEC observed between 17:00 to 20:00PM (UT) is function of the nature of the magnetic storm.

Keywords: Total Electron Content, magnetic storm, Ionosphere and equatorial zone.

INTRODUCTION

This study falls within the context of the influence of magnetic storms on the ionosphere in the equatorial region. Indeed, the Sun ejects a flow of particles called solar wind which interacts with the magnetic field of the Earth. Part of this solar wind can penetrate the magnetosphere and reach the ionosphere causing several effects including geomagnetic activity. This activity greatly disturbs the ionosphere which in turn disturbs the propagation of radio waves. A number of magnetic indices have been defined to quantify this activity [1]. Only the Dst (Disturbance Storm Time) index will be used in this study. The Dst describes the effect of geomagnetic activity on the ionosphere. It is obtained by a network of geomagnetic observatories near the equator, which globally measure the intensity of the equatorial electrojet [2]. The electrojet is a strong electronic and ionic current located in the E region of the ionosphere and whose maximum intensity is at an altitude of 105 km [3]. The ionosphere is the layer of the upper atmosphere permanently subject to the influence of solar activity. This is the ionized region of the Earth's atmosphere. According to Gauss, the ionosphere is the seat of currents responsible for variations in the Earth's magnetic field [4]. The ionosphere is composed of several layers of different thicknesses in which the ionization varies according to the day, the season, the latitude and the solar activity [5]. Particularly, we limited our study to the equatorial ionosphere characterized by a high electron density. The diagnosis of the equatorial ionosphere consists of studying the phenomena that govern and disturb the sun-earth system, including equatorial magnetic disturbances.

Numerous studies have shown that disturbances in the ionosphere, regardless of the cause, affect the propagation of GPS (Global Position System) signals [6]. The GPS is an effective tool for the study of the ionosphere in the measurement of the Total Electronic Content (TEC) along the satellite-earth path that we note TEC (Total Electron Content). TEC is the number of free electrons in the ionosphere encountered by signals from GPS satellites along their path to the GPS receiver.

Similarly, it is well known that the effects of magnetic storms on the ionosphere are very significant, but these effects on the TEC are very weak [7]. In this study, the scientific question that arises is whether the variation of the local TEC over the equatorial region is strongly dependent on the Dst.

The data we have to study this aspect is a temporal model of the free electron content of the ionosphere on a global scale. This model was built by Rolland Fleury of the Institut Télécom-Bretagne [8] based on ionospheric data from GPS. These data were obtained thanks to the Research Group in Exact and Natural Sciences (GRSEN) in collaboration with the International Research Group in Geophysics Europe Africa (GIRGEA). We apply this model to the ionospheric measurements of the three GPS stations located in equatorial Africa. For technical reasons, we used GPS data from nklg stations in Gabon, bjco stations in Benin and adis stations in Ethiopia throughout January 2012.

To answer our concern, we propose to show that using the calculation of the TEC, the variation of the local TEC noted TEC RINEX is a function of the Dst index in the equatorial zone. Achieving our main objective requires three specific objectives:

- determine the TEC by the local model TEC RINEX from the RINEX format file (ReceiverIndependent Exchange) and the TEC by the global TEC model CODG (Center for OrbitDetermination in Europe for Global IonosphereMaps) from the IONEX format file (Ionosphere Exchange);
- carry out a comparative study between the results of the local TEC RINEX treatment and those of the global TEC CODG treatment.
- examine the differences ($\Delta\text{TEC} = \text{TEC RINEX} - \text{TEC CODG}$) between the curves of the TEC (TEC RINEX and TEC CODG) to the variation of the Dst during the same period.

Site Description

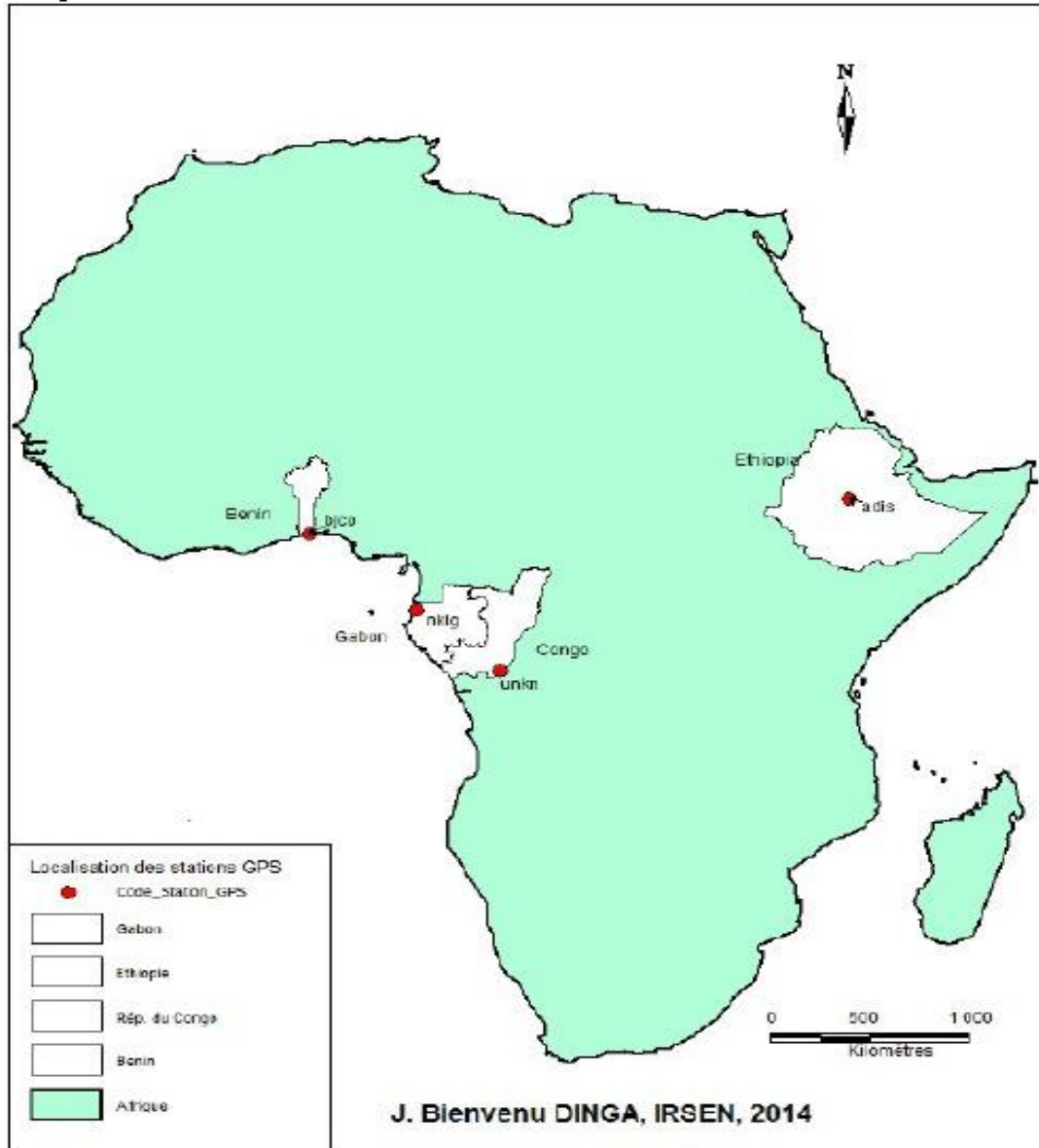


Fig. 1: Location map of GPS stations in the study area

Our study is focused on the ionosphere above Africa in the equatorial region. The equatorial region is located 30° latitude on either side of the magnetic equator. In the equatorial zone of

Africa, we used GPS data from three stations between 10° north latitude and 10° south latitude with respect to the geographical equator. The three stations are:

1. the “adis” station: located in Ethiopia at 9.035° north latitude above the geographic equator and at 38.766° longitude;
2. la station « bjco »: située au Bénin à 6,385° de latitude nord au-dessus de l'équateur géographique et à 2,450° de longitude;
3. the “nklg” station: located in Gabon at 0.354° north latitude above the geographic equator and at 9.672° longitude.

MATERIAL AND METHOD

Material

We detail in this section how we conducted our study.

At first, we did bibliographic research, on studies on the ionosphere and in particular on the equatorial ionosphere. The bibliographical research allowed us to clearly define the context of our theme.

Secondly, we used GPS data from the cooperation between GIRGEA and the SCINDA GPS Data Collection System station, obtained through cooperation with AFRL (Air Force Research Laboratory), located in Brazzaville under the responsibility of IRSEN, which we store on a computer. We then used for the processing, the MATLAB and EXCEL software and the “tec_notigs.m” program and a “vtec_time_1_month.m” sub-program for the calculation of the TEC.

Satellite data used

1. RINEX format file: the RINEX file (ReceiverIndependent Exchange) contains the observations which make it possible to determine the local TEC or experimental TEC that we have denoted TEC RINEX. We retrieved our RINEX files from the “SOPAC” GPS measurement site [25].
2. IONEX format file: the IONEX file (Ionosphere Exchange) contains the observations which make it possible to determine the global TEC or theoretical TEC that we have denoted TEC CODG. It is retrieved from the CODG site (University of Bern, Switzerland) [26].
3. Almanac file (fichieryuma): the GPS almanac is the set of parameters allowing a priori the state, the trajectory and the clock biases of one or more satellites. Each almanac is linked to a GPS week number. It is valid for all GPS stations. It is retrieved from the “celestrak” GPS measurement site [27].
4. DCB (Differential Code Bias) file: it gives all the satellite and receiver biases. It is valid for one month and for all GPS stations, and is retrieved from the same site as the IONEX file.

Methodology

There are three techniques for measuring the total electronic content (TEC), namely: ionospheric soundings, radars and the GPS technique. There are two main approaches with the GPS technique: the single-frequency method proposed by Smith in 1987 [28] and the dual-frequency method proposed by Warrant in 1996 [29]. As part of this study, the dual-frequency method using two GPS signals of frequencies f_1 and f_2 was used.

The bi-frequency method is the most effective method for determining the TEC. The various disturbances undergone by the GPS signals constitute the errors of determination due to the disturbances of the ionosphere. These errors are corrected by the method for determining the TEC. For reasons of simplicity, we have used in our case the measure of the pseudo-distance (code) defined as:

$$P_j^i(f) = \rho_j^i + c [b_i(f) - b_j(f)] + \Delta_j^{Tropo,i} + \Delta_j^{Iono,i}(f) + \alpha_j^i(f) \quad (3)$$

With:

c : the speed of light; i and j represent the satellite and the receiver respectively;

ρ_j^i : the true distance between the satellite and the receiver;

b_i : represents the sum of the receiver bias and the receiver clock offset (unknown);

b_j : represents the sum of the satellite bias and the clock offset “known: modeled and contained in the GPS navigation message”;

$\Delta_j^{Iono,i}$: represents the effect of ionospheric refraction;

$\Delta_j^{Tropo,i}$: la contribution troposphérique;

α_j^i : other contributions (relativistic effects, multipath errors).

The determination of the ionospheric refraction $\Delta_j^{Iono,i}$, was inspired by the thesis of Muhammad [30], the ionospheric refraction has the effect of curving the direction of propagation of the signal, of causing an advance (or a delay) in carrier propagation. The GPS code measurements propagate as a group. And the determination of the group index depends above all on knowing the phase index, simplified by:

$$n_{ph} = 1 + \frac{C_2}{f^2} + \frac{C_3}{f^3} + \frac{C_4}{f^4} + \dots \quad (4)$$

Where the coefficients C_2 , C_3 , C_4 do not only depend on the frequency but on the concentration of free electrons N_e (The number of electrons in a cubic meter which reflects the density of electrons along the path of propagation). Neglecting the 3rd order terms, we get:

$$n_{ph} = 1 + \frac{C_2}{f^2} \quad (5)$$

By differentiating this equation

$$dn_{ph} = -\frac{2C_2}{f^3} df, \quad (6)$$

Knowing that the group index has the expression:

$$n_{gr} = n_{ph} + f \frac{dn_{ph}}{df} \quad (7)$$

Substituting equations (5) and (6) into (7) we get:

$$n_{gr} = 1 - \frac{C_2}{f^2} \quad (8)$$

By comparing equations (5) and (8) we deduce that they differ by the sign of the coefficient C_2 . The estimate of C_2 is given by Hartmann and Leitiger [30] as: $C_2 = -40.3 N_e \text{ [Hz}^2\text{]}$ where N_e is the electron density in the ionosphere (electrons/m³). As a result, the code measurements are late while the phase measurements are ahead. In other words the pseudo-distance of this code is longer, that of phase is shorter compared to the geometric distance between the satellite and the receiver. The absolute value of the difference is the same in both cases.

By applying the fermat principle, the measured distance S is defined by:

$$S = \int n. ds \quad (9)$$

The integral must be calculated over the entire propagation path. The geometric distance S_o on the straight line between the satellite and the receiver is obtained by replacing n by 1:

$$S_o = \int ds_o \quad (10)$$

The difference Δ^{Iono} between the measured pseudo-distance and the geometric distance is the ionospheric refraction, such that:

$$\Delta^{Iono} = \int n. ds - \int ds_o \quad (11)$$

Which can be written as a function of the phase refractive index n_{ph}

$$\Delta_{ph}^{Iono} = \int \left(1 + \frac{C_2}{f^2}\right). ds - \int ds_o \quad (12)$$

And depending on the group refractive index n_{gr}

$$\Delta_{gr}^{Iono} = \int \left(1 - \frac{C_2}{f^2}\right). ds - \int ds_o \quad (13)$$

Assuming that ds is equal to ds_o , we can write:

$$\Delta_{ph}^{Iono} = \int \frac{C_2}{f^2} ds_o \text{ et } \Delta_{gr}^{Iono} = - \int \frac{C_2}{f^2} ds_o \quad (14)$$

We can write by substituting the value $C_2 = C_2(N_e)$, it comes that:

$$\Delta_{ph}^{Iono} = - \frac{40,3}{f^2} \int N_e ds_o \text{ et } \Delta_{gr}^{Iono} = \frac{40,3}{f^2} \int N_e ds_o \quad (15)$$

Knowing that:

$$TEC = \int N_e ds_o \quad (\text{measured in } e^-/\text{m}^2) \quad (16)$$

The expressions of equation (15) become:

$$\Delta_{ph}^{Iono} = -\frac{40,3}{f^2} TEC_{ene} / m^2 \text{ et } \Delta_{gr}^{Iono} = \frac{40,3}{f^2} TEC \text{ in } e^- / m^2 \quad (17)$$

For code observations, the ionospheric refraction will have the expression:

$$\Delta_i^{Iono} = \frac{40,3}{f_i^2} TEC \quad (18)$$

With

Δ_i^{Iono} : the ionospheric delay of frequency i in meters.

f_i : The carrier signal frequency (1575.42 MHz for L₁, 1227.60 MHz for L₂)

+ : code observations sign / - : phase observations sign

By considering the model of a spherical thin layer (Singel-Layer Model, denoted SLM) in order to model the TEC of the ionosphere [30] as shown in Figure 14.

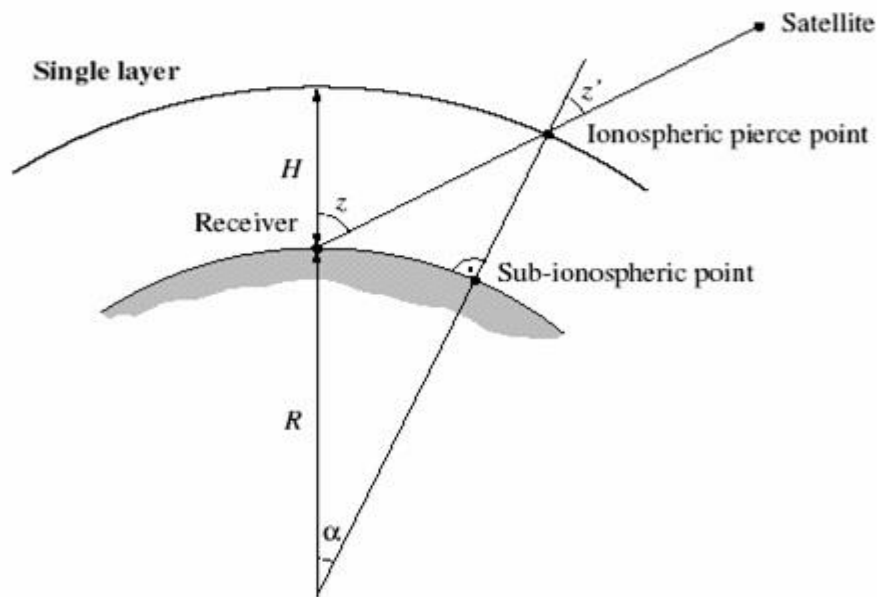


Fig. 14: Ionospheric layer for modeling [30]

The effect of ionospheric refraction becomes:

$$\Delta_i^{Iono} = \frac{40,3}{f_i^2} STEC \quad (19)$$

Where STEC represents the TEC oblic absolu in Anglais « AbsoluteSlant TEC »

Détermination de TEC Oblic (STEC)

It is determined from the code measurement (pseudo-distance: $P_j^i(f)$)

Equation (3) depending on the STEC becomes:

$$P_j^i(f) = \rho_j^i + c [b_i(f) - b_j(f)] + \Delta_j^{Tropo,i} + \frac{40,3}{f_i^2} STEC + \alpha_j^i(f) \quad (20)$$

By applying the dual frequency method, we will have:

$$P_j^i(f_1) = \rho_j^i + c [b_i(f_1) - b_j(f_1)] + \Delta_j^{Tropo,i} + \frac{40,3}{f_1^2} STEC + \alpha_j^i(f_1) \quad (21)$$

$$P_j^i(f_2) = \rho_j^i + c [b_i(f_2) - b_j(f_2)] + \Delta_j^{Tropo,i} + \frac{40,3}{f_2^2} STEC + \alpha_j^i(f_2) \quad (22)$$

The tropospheric contribution does not depend on frequency, so will remain constant. By making the difference between equations (21) and (22), we will have:

$$P_j^i(f_1) - P_j^i(f_2) = c[b_i(b_i(f_1) - b_i(f_2))] - c[b^j(f_2) - b^j(f_1)] + 40,3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC + \alpha_j^i(f_1) - \alpha_j^i(f_2) \quad (23)$$

We put:

$$P_j^i(f_1) - P_j^i(f_2) = P_1 - P_2;$$

$$b_i(f_1) - b_i(f_2) = \Delta b_i;$$

$$b^j(f_2) - b^j(f_1) = \Delta b^j;$$

$$40,3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC = C_I$$

The expression $\alpha_j^i(f_1) - \alpha_j^i(f_2)$ is negligible for the elevation of the satellite greater than 10° (in the case of our study concerning the equatorial ionosphere this elevation $z' > 10^\circ$), d where the expression:

$$P_1 - P_2 = c[\Delta b^j - \Delta b_i] + C_I \cdot STEC \quad (24)$$

From expression (24), we determine the expression of the oblique TEC (STEC) such that:

$$STEC = \frac{1}{C_I} [(P_1 - P_2) - c(\Delta b^j - \Delta b_i)] \quad (25)$$

The first term is given by the RINEX file, and the second term is given by the DCB file

Détermination of TEC Vertical: VTEC

Since the satellite is not vertical to the observation location, the concentration of free electrons measured along this sighting is brought back to the vertical. We then model the total vertical content of VTEC electrons.

We denote the total electronic content brought to the vertical by:

$$TEC_j^i = VTEC \quad (26)$$

Using the secant law:

$$STEC = \frac{VTEC}{\cos z'} \text{avec} \sin z' = \frac{R_e}{R_e + H} \sin z \quad (27)$$

Where : $R_e = 6371,2$ Km (earth radius);

H represents the reference radius and approximately equal to 350km [31] ;

z' et z are the zenith angles at the ionospheric point IP and the observation site.

From the expressions of equation (27), we derive the expression for the vertical TEC VTEC such that:

$$VTEC = STEC \sqrt{1 - \left(\frac{R_e}{R_e + H} \sin z\right)^2} \quad (28)$$

We put $\sin z = \cos \beta$; with β : the elevation of the satellite. Hence the relationship:

$$VTEC = STEC \sqrt{1 - \left(\frac{R_e}{R_e + H} \cos \beta\right)^2} \quad (29)$$

By substituting equation (25) into equation (28), the expression for VTEC becomes:

$$VTEC = \frac{1}{c_I} [(P_1 - P_2) - c(\Delta \mathbf{b}^j - \Delta \mathbf{b}_i)] \sqrt{1 - \left(\frac{R_e}{R_e + H} \cos \beta\right)^2} \quad (30)$$

Where the skew ratio $\sqrt{1 - \left(\frac{R_e}{R_e + H} \cos \beta\right)^2}$ is given by the YUMA file

RESULTS

Impact of Dst on the TEC obtained from the “adis” station in Ethiopia

1. Day of January 01, 2012

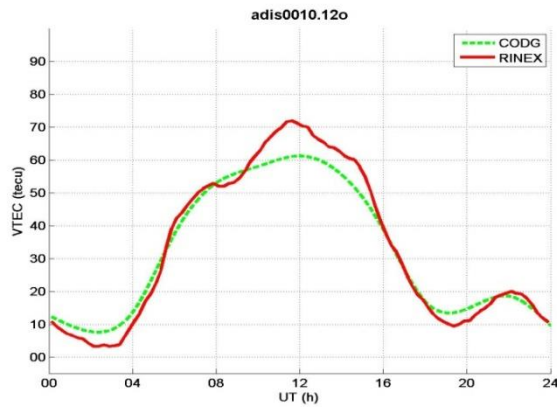


Fig. 24: TEC of January 01, 2012

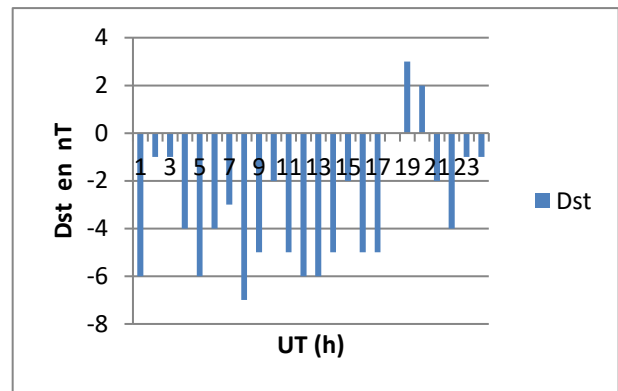


Fig. 25: Dst of January 01, 2012

2. Day of January 03, 2012

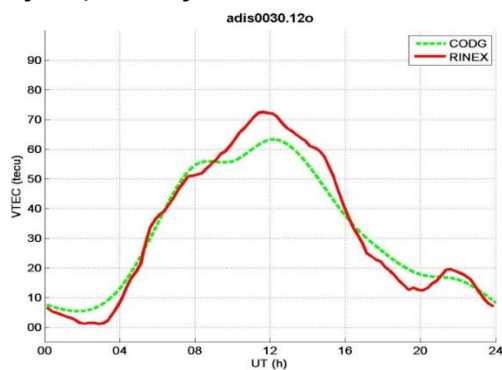


Fig. 26: TEC of January 03, 2012

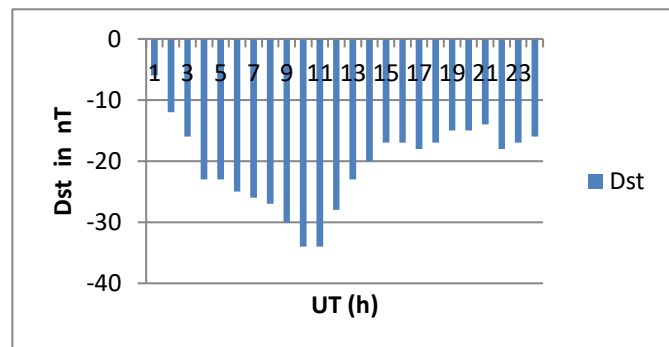


Fig. 27: Dst of January 03, 2012

3. Day of January 04, 2012

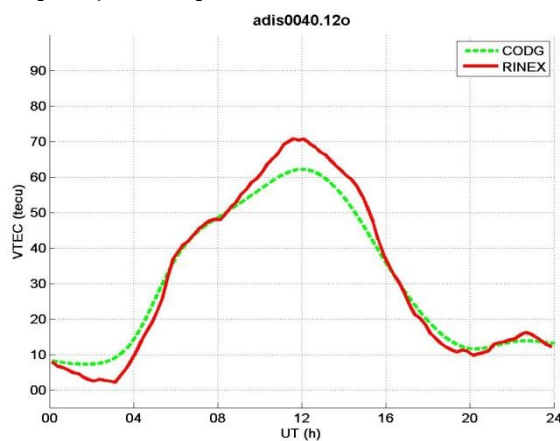


Fig. 28: TEC of January 04, 2012

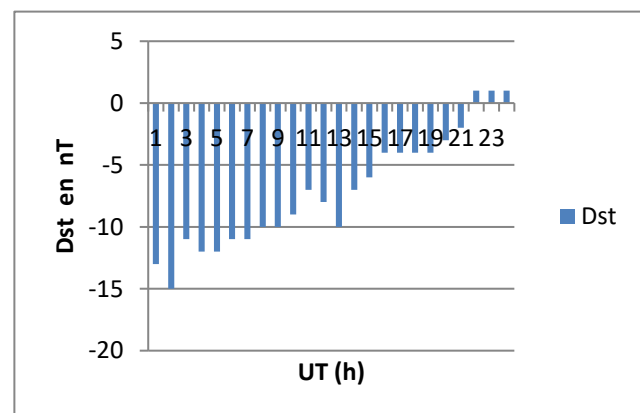


Fig. 29: Dst of January 04, 2012

4. Day of January 23, 2012

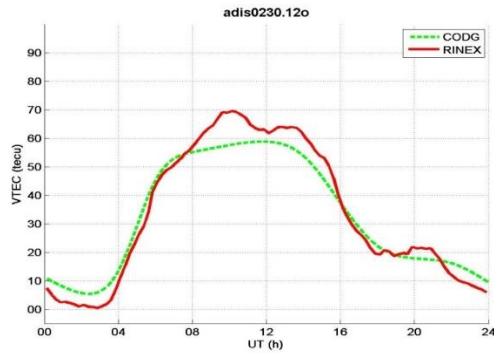


Fig. 30: TEC of January 23, 2012

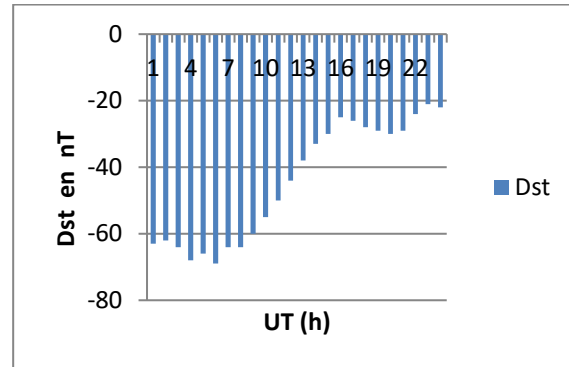


Fig. 31: Dst of January 23, 2012

5. Day of January 24, 2012

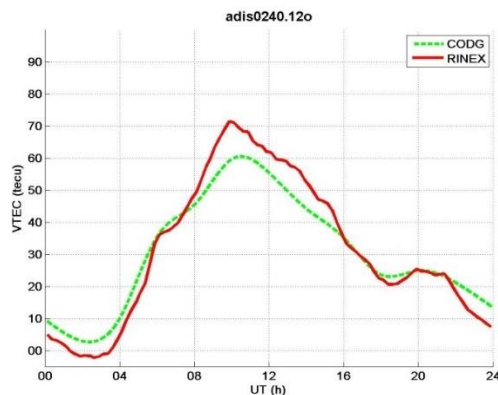


Fig. 32: TEC of January 24, 2012

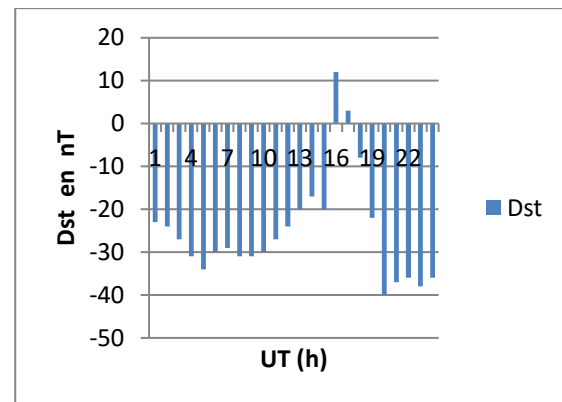


Fig. 33: Dst of January 24, 2012

We observe from these results the same phenomena:

- between 00h and 05h (UT), the TEC RINEX is below the TEC CODG and the difference between the curves of the TECs is on average about 5 UCET regardless of the variation in Dst.
- between 10 a.m. and 4 p.m. (UT), around 10 a.m., when the Dst is strongly negative regardless of the nature of the magnetic storm, the TEC RINEX is above the TEC CODG and the difference between the TEC curves is significant of about 10 UCEUs.
- between 5 p.m. and 8 p.m. (UT), the RINEX TEC is below the CODG TEC and the gap between the TEC curves varies according to the nature of the magnetic storm. Indeed the results obtained showed us that, when the magnetic storm is very weak or weak the difference between the curves of the TECs is very weak or weak, and when the magnetic storm is moderate the difference between the curves of the TECs is important by about 9 UCET.

Impact of Dst on the TEC obtained from the “nklg” station in Gabon

1. Day of January 16, 2012

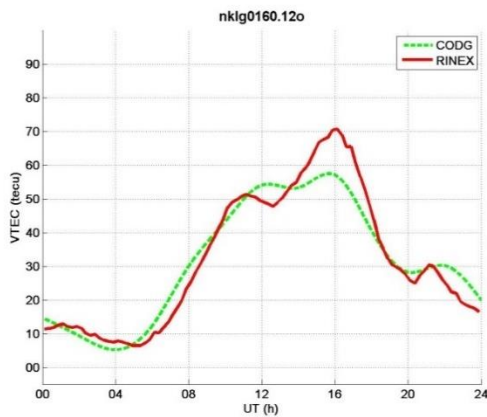


Fig. 34: TEC of January 16, 2012

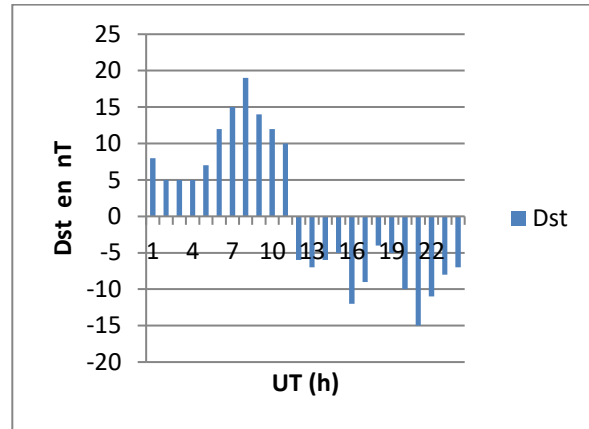


Fig. 35: Dst of January 16, 2012

2. Day of January 25, 2012

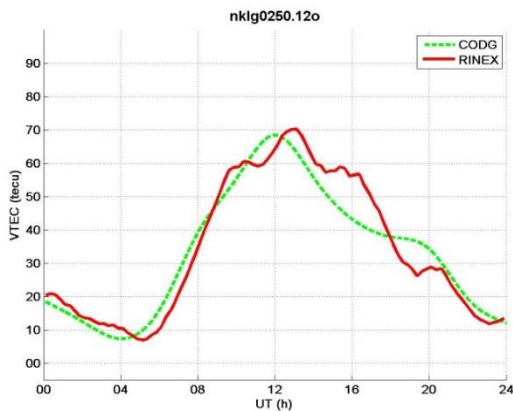


Fig. 36: TEC of January 25, 2012

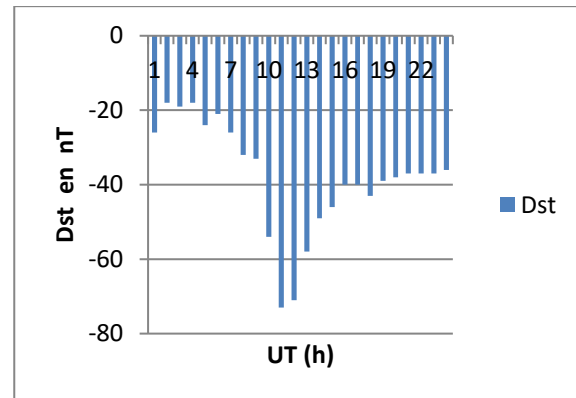


Fig. 37: Dst of January 25, 2012

- between 00h and 05h (UT), the TEC RINEX starts everywhere below the TEC CODG and creates a smaller gap between the curves of the TECs regardless of the value of the Dst and the nature of the magnetic storm.
- between 10 a.m. and 4 p.m., when the Dst is strongly negative, the RINEX TEC is maximum so that the difference between the TEC curves is very large. For the day of January 25, 2012, the maximum difference between the curves of the TEC and the maximum value of the TEC are not observed at the same time.
- between 5 p.m. and 8 p.m. (UT), we found that on January 16, 2012 when the magnetic storm is weak, the difference between the TEC curves is less important by about 2 UCET, and on January 25, 2012 the difference between the TEC curves becomes significant (about 9 UCET) and the magnetic storm becomes moderate ($-50 \text{ nT} < \text{Dst} < -30 \text{ nT}$).

Impact of Dst on the TEC obtained from the “bjco” station in Benin

1. Day of January 23, 2012

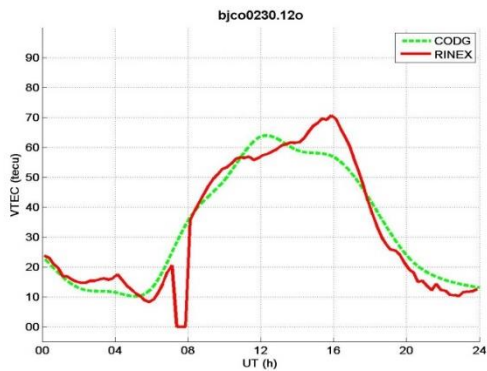


Fig. 38: TEC of January 23, 2012

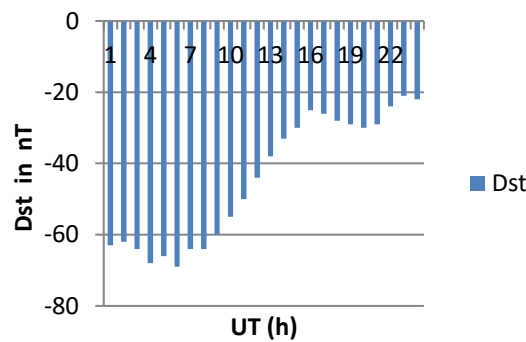


Fig. 39: Dst of January 23, 2012

We observe the same phenomena as those observed on January 16, 2012 in Gabon at the “nklg” station in Gabon, namely:

- between 00h and 05h (UT), the TEC RINEX begins its course above the TEC CODG before its ascent, thus creating a small gap between the curves of the TECs regardless of the value of the Dst and the nature of the magnetic storm.
- between 10 a.m. and 4 p.m. (UT), the greatest difference between the TEC curves ($\Delta\text{TEC} \geq 10 \text{ UCET}$) is observed around 4 p.m. (UT) while the Dst is negative ($\text{Dst} = -25 \text{ nT}$). When the Dst is strongly negative, the CODG TEC is above the RINEX TEC, but the difference between the TEC curves is less important.
- between 5 p.m. and 8 p.m. (UT), the TEC RINEX is below the TEC CODG and the gap between the TEC curves varies according to the nature of the magnetic storm.

To properly explain the impact of Dst on the TEC, we have summarized using tables 2, 3 and 4, our most expected results.

Table 2 summarizes the differences between the TEC curves observed between 00h and 05 (UT).

Station	Day	Time Interval (UT)	Dst value in nT	Nature of the geomagnetic activity	Position of the RINEX TEC in relation to the CODG TEC	Value of the average deviation between the TEC curves in UCET	Latitude
Adis	1	00h-05h	$-7 < \text{Dst} \leq -1$	Low	Below	5	09,035°
	3	00h-05h	$-27 < \text{Dst} \leq -6$	Low	Below	5	
	4	00h-05h	$-15 \leq \text{Dst} < -11$	Low	Below	5	
	23	00h-05h	$-69 \leq \text{Dst} \leq -62$	Elevée	Below	5	
	24	00h-05h	$-34 \leq \text{Dst} \leq -23$	Low	Below	5	
Nklg	16	00h-05h	$5 \leq \text{Dst} < 19$	Very low	Above	2	0,354°
	25	00h-05h	$-26 \leq \text{Dst} \leq -18$	Low	Above	2	
Bjco	23	00h-05h	$-69 \leq \text{Dst} \leq -62$	High	Above	2	06,385°

Table 2: Statistical table summarizing the deviations observed between the TEC curves between 00h and 05h

Table 3: Summarizes the differences between the TEC curves observed between 5 p.m. and 8 p.m. (UT).

Station	Day	Time Interval (UT)	Dst value in nT	Nature of the geomagnetic activity	Average difference between TEC curves (Δ TEC) in UCET	Latitude
adis	01	18h-20h	$0 < \text{Dst} < 2$	Very Low	5	09,035°
	03	17h-20h	$-17 < \text{Dst} < -15$	Low	4	
	04	17h-20h	$-4 < \text{Dst} < -3$	Low	3	
	23	Vers 18h	$-30 < \text{Dst} < -25$	Low	3	
	24	Vers 18h	$\text{Dst} = -8$	Low	3	
nklg	16	Vers 20h	$\text{Dst} = -10$	Low	2	0,354°
	25	18h-20h	$-43 < \text{Dst} < -38$	Moderate	9	
bjco	23	18h-20h	$-30 < \text{Dst} < -25$	Low	3	06,385°

Table 3: Statistical table summarizing the differences between the TEC curves observed between 5 p.m. and 8 p.m. (UT).

Table 4 below summarizes the differences between the TEC curves observed between 10 a.m. and 4 p.m. (UT).

Station	Day	Time (UT)	Average value of the difference between the TEC curves (Δ TEC) in UCET	RINEX TEC value (local TEC) in UCET	Dst value in nT	Nature of the geomagnetic activity	Latitude
adis	1	12	10	71	-6	Low	09,035°
	3	11	10	73	-28	Low	
	4	12	10	71	-10	Low	
	23	10	10	70	-55	High	
	24	10	10	72	-30	Moderate	
nklg	16	16	12	71	-12	Low	0,354°
	25	13	5	70	-58	High	
		16	14	58	-40	Moderate	
bjco	23	12	5	58	-44	Moderate	06,385°
		16	12	71	-25	Low	

Table 4: Statistical table summarizing the differences between the TEC curves observed between 10 a.m. and 4 p.m. (UT)

Several questions arise with regard to the difference observed between the TEC curves, between midnight and 5 a.m., between 10 a.m. and 4 p.m. (UT), then between 5 p.m. and 8 p.m. (UT):

- is it due to the latitude of the station?
- is it due to the effects of geomagnetic activity through its Dst index?

Li Feng [2] demonstrated that the effects of magnetic storms on the ionosphere are significant, but these effects on the TEC are very weak. Jakowski [32] also showed that during the magnetic storm of January 10, 1997, the local TEC values are high and do not exceed 200 UCET.

DISCUSSION

Remember that the TEC RINEX is obtained from a local model (experimental model) and the TEC CODG measured from the global model (theoretical model).

The local model reveals days of high electron densities (TEC) which are not observable on the global model.

We have observed that the TEC RINEX is practically different from the TEC CODG. Indeed, the TEC RINEX is either below the TEC CODG or above the TEC CODG. In general, we considered the differences between the TEC curves observed in the morning between midnight and 5 a.m. (UT), around noon between 10 a.m. and 4 p.m. (UT), and in the evening between 5 p.m. and 8 p.m. (UT).

In this part we will examine the impact of Dst on TEC RINEX from the differences observed between the curves of the TEC.

For the "adis" station in Ethiopia, the results in table 2 confirm that, regardless of the nature of the magnetic storm or the value of the Dst, between 00h and 05h, when the station is very close to the magnetic equator ($9^{\circ} < \text{latitude} < 10^{\circ}$), the TEC CODG is above the TEC RINEX (TEC RINEX < TEC CODG) such that a less significant gap between the TEC curves of about 5 UCET is observed. We can therefore say that, in Ethiopia, in January 2012, between 00h and 05h (UT) the difference between the TEC curves depends on the latitude of the station considered.

Between 10 a.m. and 4 p.m. (UT), the results in table 4 show us that: when the Dst is strongly negative, regardless of the nature of the magnetic storm, regardless of the latitude of the station, the TEC RINEX believes more faster than the TEC CODG (TEC RINEX > TEC CODG) and is close to 70 UCET so that the difference between the curves of the TEC is very large at around 10 UCET. We can therefore say that, in Ethiopia, in January 2012, between 10 a.m. and 4 p.m. (UT) the difference between the TEC curves varies according to the Dst.

Between 5 p.m. and 8 p.m. (UT), the difference between the TEC curves is less important, this is explained by the fact that between 5 p.m. and 8 p.m. (UT) the geomagnetic activity is weak or very weak. We can therefore say that, in Ethiopia, in January 2012, between 5 p.m. and 8 p.m. (UT) the difference between the TEC curves varies according to the nature of the magnetic storm.

For the "nklg" station in Gabon, between 00h and 05h, table 2 shows us that: whatever the Dst and the nature of the magnetic storm, the TEC RINEX is above the TEC CODG, and the deviation observed between the TEC curves is positive and less important (about 2 UCET). This result

would be due to the remoteness of the nklg station from the magnetic equator ($0 < \text{latitude} < 06.5^\circ$).

Between 10 a.m. and 4 p.m. (UT), around 4 p.m. when the Dst is strongly negative, the TEC RINEX reaches the maximum value of about 70 UCET, is placed above the TEC CODG in such a way that the difference observed between the curves of the TEC is very important about 10 UCET. We can therefore say that, in Gabon, in January 2012, between 10 a.m. and 4 p.m. (UT) the difference between the TEC curves varies according to the Dst.

Between 5 p.m. and 8 p.m. (UT), the difference between the TEC curves is less important when the geomagnetic activity is weak, and is important (about 9 UCET) when the geomagnetic activity is moderate. We can therefore say that, in Gabon, in January 2012, between 5 p.m. and 8 p.m. (UT) the difference between the TEC curves varies according to the nature of the magnetic storm.

For the "bjco" station in Benin, we note the same behavior as for the "nklg" station in Gabon observed on January 16, 2012. Figures 38 and 39 as well as tables 2, 3 and 4, confirm the previous observations to us. to know:

- in the morning, between 00h and 05h (UT), for the bjco station far from the magnetic equator ($0 < \text{latitude} < 06.5^\circ$), whatever the nature of the magnetic storm and the value of the Dst, the TEC RINEX is above the TEC CODG ($\text{TEC RINEX} > \text{TEC CODG}$), such as the difference between the curves of the TECs is less important of approximately 5 UCET.
- between 10 a.m. and 4 p.m. (UT), when the Dst is strongly negative, the TEC CODG is above the TEC RINEX ($\text{TEC RINEX} < \text{TEC CODG}$); but the very significant difference between the curves of the TEC ($\Delta\text{TEC} \geq 10 \text{ UCET}$) is observed around 4 p.m. when the Dst is negative ($\text{Dst} = -25 \text{ nT}$), this is due to the latitude of the "bjco" station (far from the magnetic equator).

We can therefore say that, in Benin, in January 2012, around 4 p.m., when the Dst is negative, the difference between the TEC curves is significant and around 10 UCET.

- between 5 p.m. and 8 p.m., in the presence of weak geomagnetic activity, the difference observed between the TEC curves is less significant by about 3 UCET. We can therefore say that, in Benin, in January 2012, between 5 p.m. and 8 p.m. (UT) the difference between the TEC curves varies according to the nature of the magnetic storm.

CONCLUSION

The work carried out in this article first concerned in a first step the study of electron density in the equatorial ionosphere and particularly the total electronic content (TEC). A method for modeling the TEC has been developed.

TEC is measured by its effect on the signal travel time between the satellite and the receiver. The expression of the TEC was given by clearly presenting the algorithm allowing its determination. This algorithm was used in the processing of TEC data for the month of January 2012 from the stations "adis" in Ethiopia, "nklg" in Gabon and "bjco" in Benin, located in Africa at latitudes between 0 and 10° de either side of the geographic equator. We based our study on a one-month analysis of regular measurement data. For more precision in the knowledge of the

evolution of the TEC in the equatorial zone, a study of the diurnal cycle of the TEC from the measurements of three stations, was made. The daily TEC reveals two patterns: local pattern and global pattern. The local model reveals at times high TEC values, double TEC peaks and small nighttime maxima that characterize the equatorial region [33].

In a first step, we carried out a monthly study (TEC for the month of January 2012) of the TEC above each equatorial region considered by comparing it to the Dst for the month of January 2012. We noticed that in Africa, in the zone equatorial, in January 2012:

- magnetic storm days (negatively low Dst) correspond to days of high electron density values (local TEC ≥ 70 UCET);
- the closer the station is to the magnetic equator ($9^\circ < \text{latitude} < 10^\circ$), the more days there are disturbed by geomagnetic activity.

In a second step, we carried out a daily study of the TEC. This daily TEC allowed us:

1. to carry out a comparative study between the RINEX TEC (local TEC) obtained from in situ data (RINEX file) and the CODG TEC (global TEC) obtained from the CODG model (IONEX files). It appears that, in Africa, in the equatorial zone and in January 2012:
 - the local model is more acceptable than the CODG model in the equatorial zone in Ethiopia, Benin and Gabon; because it integrates several phenomena among which, magnetic storms;
 - the TEC is higher during the day than at night;
 - a day is said to be disturbed by the magnetic storm when the maximum value of the local TEC is around 70 UCET.
2. to link the differences observed between the TEC curves to the variation of the Dst characterizing the geomagnetic activity. For this, a statistical study of the disturbance of the CET over three regions (Ethiopia, Gabon and Benin) throughout the month of January 2012 were made (see tables 2, 3 and 4). The main points that emerge from this study are:
in January 2012, in Africa and in the equatorial zone:
 - the difference observed between the curves of the TECs in the morning between 00h and 05h (UT), is independent of the geomagnetic activity, that is to say of the Dst, but depends on the latitude of the station;
 - between 10 a.m. and 4 p.m. (UT), when the Dst is strongly negative, the TEC RINEX grows faster than the TEC CODG (TEC RINEX > TEC CODG) so that simultaneously the TEC RINEX approaches 70 UCET and the gap widens between the TEC curves is positive and very important
 - ($\Delta\text{TEC} \geq 10$ TECU);
 - between 5 p.m. and 8 p.m. (UT), the variation in the difference between the TEC curves depends on the nature of the magnetic storm.
 - in general, when the station is far from the magnetic equator, the difference between the TEC curves of about 10 UCET is observed around 4 p.m. when the Dst is negative; and when the station is very close to the magnetic equator, the difference between the TEC curves of about 10 UCET is observed around noon when the Dst is negative.
 - in general, the maximum value of the TEC RINEX and the very large difference between the TEC curves are observed at the same time (UT);

- the time difference observed between the peak of the TEC and the greatest difference between the curves of the TEC observed on January 25, 2012 at the “nklg” station in Gabon can be the subject of a study.
- Beyond 8 p.m. (UT), the variation of the TEC is independent of the variation of the Dst, only the nocturnal ionization is responsible for the variation of the Dst.

References

- [1] Sandrine Grimald. Etude de l'émission et de la propagation du Continuum terrestre à partir des données des satellites Cluster. Thèse de Doctorat de l'Université d'Orléans (2007).
- [2] Li Feng. Etude dans l'ionosphère de la densité électronique et de la turbulence électrostatique en fonction de l'activité. Thèse de doctorat de l'Université d'Orléans (2007).
- [3] Thomas Farges. Traitement et analyse de données radar HF : Etude des perturbations ionosphériques détectée à l'équateur magnétique avec le radar LDG et à moyenne latitude avec le réseau de Francourville. Thèse de doctorat de l'Université de Paris-Sud U.F.R Scientifique d'Orsay (2000).
- [4] Gauss, F.K., General Theory of Terrestrial Magnetism, 1939.
- [5] Ephrem Sambou. Contribution à l'étude de l'ionosphère équatoriale : Variation du maximum d'ionisation de la region F 2 en fonction des processus électrodynamiques agissant à grande échelle. Thèse de doctorat de l'Université Cheik Anta Diop de Dakar (1993).
- [6] Boutiouta, S., Belbachir A.H., Dekkiche, H. (2006). Contrôle de l'activité ionosphérique à partir des données GPS. Télédétection, vol.5, n 4, p.325-338
- [7] Codrescu, M.V., S. E Palo, X. Zhang, T.J Fuller-Rowell., C.Pope.(1999). CET: Climatology derived from TOPEX/POPSEIDON measurements, J. Atmos.Sol. Terr.Phys., 61, 281-298.
- [8] P. Lassudrie-Duchesne., R.Fleury. GPS : Ionosphère. Ecoled'ETE Brest Novembre 2012.
- [9] Guy.P, Brasseur and Susan Solomon, Chemistry and Physics of the Stratosphere and mesosphere, Atmospheric and Oceanographic Sciences Library, Springer, Vol.32 <http://sidstation.loudet.org/ionosphere-fr.xhtml>
- [11] Davies K., Watts J.M. et Zacharisien, , 1962, A study of F 2 layer effects as observed with Doppler techniques, Journal of Geophysic, (67) : 601-609
- [12] Xavier Vallieres, 2002, Les échelles de la turbulence dans l'ionosphère des hautes latitudes et leurs signatures sur les échos des radars HF du réseau SuperDARN, Thèse de doctorat de l'Université d'Orléans
- [13] Knight, M., Cervera M. and A. Finn., A comparaison of predicted and measured GPS performance in an ionospheric scintillation environment, Proceedings of ION GPS, Nashville, Tennessee, 1437, September 1999.
- [14] Chapman, S., The absorption and dissociative on ionozing effect of monochromatic radiation in an atmosphere on a rotating Earth, Proc.Phys. Soc., 43, 46-45, 1931 <http://spaceweather.com/>
- [16] www.f6krk.org
- [17] Gold T., Plasma and Magnetic Fields in Solar System, J. Geophys. Res., 64, 1664-1674, 1959
- [18] <http://sohowww.nascom.nasa.gov/spaceweather>

- [19] [http: //www.nasa.gov](http://www.nasa.gov)
- [20] [http: //french.ruvr.ru/](http://french.ruvr.ru/)
- [21] F.El-LemdaniMazouz. Etudes des émissions naturelles dans la plasmasphère, reliées à la gyrofréquence électronique, à l'aide des données de la mission multi-satellites CLUSTER. Thèse de doctorat de l'Université d'Orléans (2008).
- [22] Erwan Thébaut. Modélisation régionale du champ magnétique terrestre. Thèse de doctorat de l'Université Louis-STRASBOURG I (2003).
- [23] M. A. Abdu, I. S. Batista, F. Bertoni, B. W. Reinisch, E.A. Kherani, and J.H.A. Sobral. Equatorial ionosphere responses to two magnetic storms of moderate intensity from conjugate point observations in Brazil. *Journal of Geophysical Research*, Vol. 117, A05321, doi : 1029/2011JA017174, 2012
- [24] [http: //spider.ngdc.noaa.gov](http://spider.ngdc.noaa.gov)
- [25] [http:// sopac.ucsd.edu](http://sopac.ucsd.edu)
- [26] <ftp.unibe.ch/aiub/CODE/2012>
- [27] [ft : //celestrak.com/GPS/almanac/Yuma/](ft://celestrak.com/GPS/almanac/Yuma/)
- [28] C. A Smith. Ionospheric TEC Estimation with a single-frequency GPS receiver. The effect of ionosphere on communication, navigation and surveillance systems, Ionospheric effect symposium, 5-7 May 1987, pp. 145-150, Naval Reserch Laboratory.
- [29] Warnant, R. Etude du comportement du contenu électronique total et des ses irrégularités dans une région de latitude moyenne. Application aux calculs de position relatives par le GPS. Thèse de doctorat de l'Observatoire Royal de Belgique (1996).
- [30] S,Muhammad Ali. Contribution au positionnement en temps réel par GPS. Prédiction de la correction ionosphérique. Thèse de doctorat de l'Université de l'observatoire de Paris (2003).
- [31] Ben D. L. Opperman, Pierre J. Cilliers, Lee-Anne McKinnell and Ray Haggard. Development of a regional GPS-based ionospheric TEC model for South Africa.
- [32] Jakowski, N., S. Schluter, E. Sardon (1997). Total electron Content of the ionosphere during the geomagnetic storm on 10 January. *Journal of Atmospheric and Solar-Terrestrial Physics*. Vol. 61, p 299-307.
- [33] Appelton, E. V., Two anomalies in the ionosphere, *Nature* 157, 691, 1946