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Equatorial ionospheric irregularities using GPS TEC derived index

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A B S T R A C T

We have used the rate of change of TEC (*ROT*) derived fluctuation index to study irregularities in the ionosphere at Franceville in Gabon (Lat.= −1.63°, Long.=13.55°, Geomag. Lat.= −0.71°), an equatorial station in the African sector. Based on a preliminary study at two equatorial stations at different longitude an average *ROTI* index which gives the fluctuation level over half an hour at a particular station was put forward. This index eliminates the noise spikes or extreme value usually present in *ROTI* index estimate. The new index $ROTI_{AVE}$ was used to study ionospheric irregularity occurrence at Franceville. As far as we know, this is the first time irregularity occurrence study is being done at this station using GNSS data. The results obtained showed that ionospheric irregularity season at Franceville is from March to November and that there is a kind of minimum around June. Very low irregularities activity is also observed around January. Pre-midnight fluctuation is observed to be more pronounced at Franceville during the period studied.

1. Introduction

Ionospheric scintillation is a rapid fluctuation in amplitude and phase of a radio signal that passes through the earth's ionosphere containing plasma density irregularities. The irregularities in the ionosphere that causes scintillation of radio wave are being studied using data from digisonde, scanning photometers/imager (optical technique), and VHF monitors among others. Ionospheric scintillation is a common occurrence at the equatorial region essentially at night, shortly after local sunset, around solar maximum. Ionospheric scintillation can cause fading and degrading of GNSS L-bands frequencies (e.g. GPS L1, L2, L5 and Galileo E1, E5, E6) and this could lead to loss of lock on these frequency bands. Degrading occurs when phase scintillations introduce tracking errors or when loss of tracking and failure to acquire signals increases the geometry errors (Kintner et al., 2007). Loss of lock of signal limits the availability of both pseudorange and carrier phase measurements for positioning and this could be worse on GPS L2 frequency. Previous studies have showed that strong or severe scintillation activity could lead to limited availability of carrier phase observations with significant impact on precise positioning applications (Skone et al., 2001; Knight et al., 1999; Doherty et al., 2004).

Because of its temporal and spatial availability, GPS has been considered as an ideal system for studying ionospheric scintillation (Basu et al., 1998; Kintner et al., 2007). To this end, specially modified ground-based GPS receivers (e.g. Van Dierendonck et al., 1993) are been used to obtain values of the scintillation parameters. This kind of receivers has been deployed to different regions of the earth, especially equatorial region, for scintillation monitoring (SCINDA-SCIntillation Network Decision Aid).

The metric being used for phase scintillation is σ_ϕ index which is defined as the standard deviation of the detrended phase of the carrier frequency over a certain interval-typically over 60 s. Higher interval can as well be used depending on the GPS data rate or sampling rate.

Different researchers have derived or used different forms of σ_ϕ index to study ionospheric phase scintillation using GNSS data (Forte, 2005; Kintner et al., 2007; Mushini et al., 2011). For example Forte's scintillation index (σ_{Forte}) after Forte (2005) is

$$\sigma_{Forte} = \sqrt{\left\langle \frac{\partial \phi}{\partial t} \right\rangle^2} \quad (1)$$

And CHAIN scintillation index (σ_{CHAIN}) after Mushini et al. (2011) is

$$\sigma_{CHAIN} = \sqrt{\left\langle \left(\frac{\partial \phi}{\partial t}\right)^2 |\phi| \right\rangle} \quad (2)$$

where ϕ is signal phase, and $\langle . \rangle$ is average over 60 s.

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Similarly, time rate of change of TEC (*ROT*) has been used by different authors as a measure of fluctuation level (e.g. Wanninger, 1993; Pi et al., 1997; Mendillo et al., 2000). TEC is computed by leveling of phase to code measurement of the GPS signals. Therefore ROT and its derived parameters are good proxy for the phase fluctuation. Different authors have used time variation of TEC also known as *ROT* to derive phase fluctuation parameters.

Wanninger, 1993 used rate of change of TEC I_{ROT} computed over a 15 min period.

$$I_{ROT} = 10 \times rms\left(\frac{\Delta TEC}{\Delta t}\right) \tag{3}$$

where ΔTEC is defined by subtracting each TEC from its previous value, Δt is the change in time in minute, I_{ROT} is in *TECU* per minute ($1\ TECU = 10^{16}$ electrons per square meter).

Pi et al., 1997 used rate of change of TEC index (*ROTI*) based on the standard deviation of $\Delta TEC/\Delta t$ over 5 min interval.

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT^2 \rangle}, \quad ROT = \frac{\Delta TEC}{\Delta t}, \tag{4}$$

Mendillo et al., 2000 found that the use of median instead of mean used in Eqs. (3) and (4) will eliminate the noise spikes that might influence I_{ROT} and *ROTI*. Then they came up with two indices (Eqs. (5) and (6)).

$$f_p(n,hr,i) = Median\left|\frac{\Delta TEC}{\Delta t}\right| \tag{5}$$

where n is the satellite number, hr is hour (0–24 UT), i is 15 min section within an hour ($i = 1,2,3,4$). And

$$F_P(hr) = \frac{1}{nSat(hr)} \sum_{n}^{nSat} \sum_{i}^{k} \frac{f_p(n,hr,i)}{k} \times 1000 \tag{6}$$

where $nSat(hr)$ is the number of satellites observed within an hour and k is the number of f_p values available within an hour for a particular satellite. The multiplicative constant (1000) is used to make F_P an integer index. This value gives average level of irregularities in 1 h over the station. F_P value ≤ 50 represents background levels of irregularities, $50 \leq F_P \leq 200$ shows that irregularities are present, and $F_P > 200$ shows the presence of strong irregularities level. Mendillo et al., 2000 pointed out that the index F_P (Eq. (6)) could be used for occurrence statistical study of fluctuation over a station.

As mentioned earlier, specially modified GPS receivers are being used to study ionospheric scintillation but TEC derived indices from common GPS receiver or geodetic receiver can also be used to study ionospheric irregularities. These kinds of indices (Eqs. (3) and (6)) provide opportunity to study ionospheric irregularities using RINEX files largely available for the stations in the IGS network.

In this current study, we examine each of these four *ROT* derived phase fluctuation indices at two equatorial stations at different longitude. And based on our observation, we later use a slightly modified *ROTI* index to study ionospheric irregularity occurrence at Franceville in Gabon, an equatorial station in the African sector.

2. Data and analyses

We have used RINEX data from two equatorial stations in the IGS network for year 2002 a year of high solar activity. The stations are Franceville in Gabon (Lat. = -1.63°, Long. = 13.55°, Geomag. Lat. = -0.71° station ID = MSKU) and Dededo in the US territory of Guam (Lat. = 13.59°, Long. = 144.87°, Geomag. Lat. = 5.03°, station ID = GUAM). For the period when data used in this study were taken, according to the log file at each station, ASHTECH Z-XII3 dual frequency receiver was at each of these stations.

To obtain relative TEC, we have used the leveled carrier phase measurement of TEC i.e. the so called carrier phase to code leveling. Because phase measurements are affected by or subjected to cycle slip, we used Blewitt, 1990 algorithm for detection and correction of any likely cycle slip in the phase measurements. Butterworth filter of order 4 was used to remove the trends from the data.

Using GNSS data for fluctuation study, the choice of elevation cut-off mask is very important so as not to mistake the multipath effect to fluctuation. To screen out any multipath effects, various authors have used observation data above certain elevation cut-off mask. Chu et al., 2005 used elevation cut-off of 15°, Mushini et al., 2011 used an elevation cut-off mask of 20°, Meggs et al., 2006 used elevation cut-off mask of 35°. Elevation cut-off mask of 25° is used in the current study.

3. Results and discussions

3.1. Phase fluctuation indices

Fig. 1 shows the diurnal panel plots of the four TEC derived indices (i.e. I_{ROT}, *ROTI*, F_P,) and the satellites availability at Franceville. I_{ROT}, *ROTI*, and f_p are for all the satellites in-view while $F_P(hr)$ is computed over the station from all the satellites in-view. The plots are for March 17, 2002, a scintillation day and a geomagnetic quiet day. Satellites outages as observed after local sunset (i.e. top panel in Fig. 1) can be attributed to irregularities activity. It is true that local multipath and shadowing can also cause satellites outages especially for rising and setting satellites. But from this plot, taken into consideration the time of the day, the elevation cut-off mask used and the values of fluctuation indices, we can say that these outages are mainly due to ionospheric irregularities. *ROTI* and F_P values really reflect the satellite outages observed around 20–04 LT at this station. For the other two indices (i.e. I_{ROT} and f_p) it is difficult to relate their values to these outages because their values during this period are equally large like the day time values. Although the plot at Dededo is not shown similar results were obtained.

Since almost all the satellites scintillate (i.e. experience loss of lock), it is reasonable to attribute these loss of lock events (around 20–24 LT) to the irregularities that extend across large regions of the ionosphere. This is captured very well by *ROTI* index and F_P index value around this time unlike the other two indices. As indicated by *ROTI* values, fluctuation activity occurs at these two stations from around 1900 LT to 0400 LT but is more pronounced during pre-midnight hours. Pre-midnight hours pronouncement in fluctuation level is captured by both *ROTI* and F_P indices.

The plot for a scintillation free day, January 9, 2002, is shown in Fig. 2 at Franceville. January 9, 2002 is a geomagnetic quiet day and going by the satellites availability as shown in the top panel of this plot there were no satellite outages on this day. For the whole day, the values of *ROTI* and F_P indices indicate no irregularities activity between 19 and 05 LT that irregularities activity normally occurs. Similar results were obtained at Dededo.

From all these *ROT* derived fluctuation indices, Mendillo et al., 2000 scheme (i.e. Eq. (6)) is believed to give the best result. This has to do with the use of median which remove the effect of spikes or extreme values from the estimate. However, from our observation based on the results presented in Figs. 1 and 2, it appears to us that *ROTI* index slightly looks good than the F_P index when the day time values are compared to the nighttime values. Although the spikes and extreme values are sometimes