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Assessment of scintillation proxy maps for a scintillation study during geomagnetically quiet and disturbed conditions over Uganda

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ABSTRACT

The objective of this paper is demonstrate the validity and usefulness of scintillation proxies derived from IGS data, through its comparison with data from dedicated scintillation monitors and its application to GNSS scintillation patterns. The paper presents scintillation patterns developed by using data from the dedicated scintillation monitors of the scintillation network decision aid (SCINDA) network, and proxy maps derived from IGS GPS data for 2011 and 2012 over low latitude stations in Uganda. The amplitude and phase scintillation indicies (S_4 and σ_Φ) were obtained from the Novatel GSV4004B ionospheric scintillation and total electron content (*TEC*) monitor managed by SCINDA at Makerere (0.34^{0}N, 32.57^{0}E). The corresponding IGS GPS proxy data were obtained from the receivers at Entebbe (0.04^{0}N, 32.44^{0}E) and Mbarara (0.60^{0}S, 30.74^{0}E). The derived amplitude (S_{4p}) and phase (*sDPR*) scintillation proxy maps were compared with maps of S_4 and σ_Φ during geomagnetic storms (moderate and strong) and geomagnetically quiet conditions. The scintillation patterns using S_4 and σ_Φ and their respective proxies revealed similar diurnal and seasonal patterns of strong scintillation occurrence. The peaks of scintillation occurrence with mean values in the range $0.3 < (S_{4p}, sDPR) \leq 0.6$ were observed during nighttime (17:00–22:00 UT) and in the months of March-April and September-October. The results also indicate that high level scintillations occur during geomagnetically disturbed (moderate and strong) and quiet conditions over the Ugandan region. The results show that SCINDA and IGS based scintillation patterns reveal the same nighttime and seasonal occurrence of irregularities over Uganda irrespective of the geomagnetic conditions. Therefore, the amplitude and phase scintillation proxies presented here can be used to fill gaps in low-latitude data where there are no data available from dedicated scintillation receivers, irrespective of the geomagnetic conditions.

1. Introduction

The ionosphere is a partially ionised region of the Earth's atmosphere where incoming UV light ionises particles that form a layer from which radio waves can be reflected (Schunk and Nagy, 2009). The ionosphere crosses several meteorological layers and influences HF radio wave propagation to distant places on the Earth (McNamara, 1991). The ionosphere is a highly dispersive medium at Global Positioning System (GPS) frequencies. The electrical properties of this region allow it to transmit, reflect and refract radio waves as they traverse the ionosphere. Ionospheric plasma density sometimes gets distorted, making it turbulent and conducive for the development of ionospheric irregularities (Amabayo et al., 2014). Ionospheric irregularities manifest as enhancements or depletions of the electron density embedded in the ambient ionosphere (Davies, 1990; Amabayo et al., 2014). Since the ionosphere is dynamic, these irregularities are sometimes moving relative to the radio signals (Davies, 1990). The moving irregularities cause rapid, temporal fluctuations in the signal intensity and phase commonly referred to as amplitude and phase scintillation respectively (Davies, 1989; Amabayo et al., 2014).

Ionospheric scintillation predominantly occurs in the F layer and is known to have significant impact on radio communications, navigation and radar systems (Davies, 1990). Understanding the climatology of ionospheric scintillation both regionally and globally is essential to predict and mitigate the effects of scintillation on radio communication. Ionospheric scintillation pattern has been studied using data from dedicated scintillation receivers, such as the receivers in the scintillation network decision aid (SCINDA). The scintillation receivers have high installation and maintenance costs, making them unaffordable to many countries. However, scintillation in regions with insufficient

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scintillation monitors can now be studied using geodetic dual-frequency GPS receivers. Amplitude scintillation proxies derived from IGS station data by Amabayo et al. (2012) and phase scintillation proxies derived by Ghoddousi-Fard et al. (2013) have provided a good alternative for scintillation pattern studies in developing countries.

Low latitude scintillation has been of a great concern due to its prevalence and impact on the receiver tracking performance during the period of strong scintillation activity. Scintillation levels of $(S_4, \sigma_\Phi) \geq 0.1$ were considered by Amabayo et al. (2014). The study reported here was aimed at providing a scintillation proxy that can be used to fill gaps in SCINDA data that may hinder scintillation modelling over the African region. The scintillation proxy data was then used to develop scintillation patterns for two years (2011 and 2012), comparable with the SCINDA maps in Amabayo et al. (2014). A recent study by Tiwari et al. (2013) reported that ionospheric scintillation at low latitudes can either be inhibited or triggered during geomagnetic storms depending on the phase of the storm, its local time of occurrence and the location of the station. The study by Tiwari et al. (2013) showed that the occurrence of ionospheric scintillation observed during summer months was relatively weak compared to the occurrence recorded during winter and equinox months. According to Tiwari et al. (2013), enhanced magnetic activity suppresses the pre-midnight ionospheric scintillation during equinox and winter, while enhancement of pre-midnight scintillation activity was observed during summer months.

Perturbations induced by geomagnetic storms in the ionosphere have severe impacts on long distance communication and navigation systems. During geomagnetic storms, electron density perturbations may be positive (enhancement) or negative (depletion), which in turn influences the scintillation in different ways. According to Davies (1990), equatorial region scintillation occurs on magnetically quiet days and disappears with the onset of a magnetic storm. The same study stated that there is a strong correlation between scintillation and magnetic storm activity during autumnal and vernal equinoxes. The correlation is moderate during summer (near north solstice) and poor in winter. According to Buresova (2005), the storm effects in the F2 region of the ionosphere are predominantly attributed to ionospheric response to storm effects in the thermosphere. The effects in the lower ionosphere are predominantly caused by the storm-associated precipitation of energetic particles.

A study by Adewale et al. (2008) using GPS-derived *VTEC* observed at Libreville, Gabon (0.35°N, 9.67°E, dip lat 8.05°S), showed that during geomagnetic storms the altered electric fields contribute significantly to the occurrence of negative and positive ionospheric storm effects. The results revealed positive storm effects being more frequent than the negative storm effects. Positive storm effects generally last longer irrespective of the storm onset times. The same study observed that positive storm effects were more pronounced during daytime than the pre-midnight and post-midnight periods. A low latitude scintillation study conducted by Adewale et al. (2012) using scintillation data from Lagos (6.5°N, 3.4°E, mag lat 3.03°S), Nigeria, showed large scale *TEC* depletions, accompanied by increased rate of change of *TEC* (ROT) in the evening hours. This study also observed enhanced amplitude scintillation (S_4) associated with the *TEC* depletions and increased *ROT*. This observation led to a conclusion that plasma bubbles are associated with large scale irregularities (Adewale et al., 2012). The same study reported that the diurnal and seasonal scintillation percentage occurrence peaked during equinox months (March-April) at 23:00 LT. Similar results were obtained by Amabayo et al. (2014) in a scintillation pattern study over the Ugandan region.

In our study, disturbance storm time (Dst) index was used to investigate the relationship between geomagnetic storms and scintillation irregularities. This study adopted storm classification scheme by Tsurutani et al. (2006) and Loewe and Prölss (1997). The current study investigated only moderate ($\mathrm{Dst} \leq -50$ nT) strong ($\mathrm{Dst} \leq -100$ nT) and intense ($\mathrm{Dst} \leq -200$ nT) storms (Loewe and Prölss, 1997; Tsurutani et al., 2006). Negative Dst values indicate the presence of a geomagnetic storm or sub-storm, and the more negative the Dst value, the higher the intensity of the storm. The decrease in the Dst index is the result of the storm time ring current which flows around the Earth from east to west in the equatorial plane. The ring current results from the differential gradient and curvature drifts of electrons and protons in the near Earth region and its strength is related to the solar wind conditions. Large magnetic storms with extreme Dst indices cause prompt penetration of the mid-latitude and equatorial ionosphere electric fields. This results in steep spatial *TEC* gradients and hence scintillation in GPS stations. Scintillation occurrence puts trans-ionospheric satellite communication and navigation at risk. Hence it is necessary to predict and correct errors associated with the phenomenon.

2. Data description and analysis

The raw GPS data were calibrated using the GPS_TEC algorithm developed by Gopi whose detailed description exists in Amabayo et al. (2012). Although GPS_TEC algorithm calculates *TEC* with an elevation mask of 20 °. For further analysis, an elevation cutoff of ≥30 ° was considered to filter multipath effects in the data. Standard geodetic dual frequency GPS data from the stations at Entebbe (EBBE) and Mbarara (MBAR) were used in this study to compute relative *TEC* from carrier-phase measurements. The *TEC* along the signal path between the receiver and the GPS satellite, commonly referred to as slant *TEC* (*STEC*) is defined by Eq. (1):

$$STEC = \int_R^S N_e\, ds, \tag{1}$$

where N_e is the electron density. The *TEC* is measured in *TEC* Units (TECU) with 1 TECU=10^{16} electrons/m^2, *R* and *S* stand for the receiver and satellite positions respectively. GPS satellites are observed along oblique signal paths which pierce the ionosphere at ionospheric pierce points (IPPs). The typical height of the IPP corresponds to the height associated with the peak electron density in the ionosphere, which is taken as 350 km for this study. The *TEC* along a vertical line through the IPP, commonly known as vertical *TEC* (*VTEC*) is modeled using a mapping function and the geographic position of the IPPs (Hoffmann-Wellenhof et al., 1992). Eq. (2) defines the mapping function used in this study.

$$VTEC = STEC \times \sqrt{1 - \left(\frac{R_E \times \sin(z_o)}{R_E + h_m}\right)^2} \tag{2}$$

where R_E and h_m are the mean radius of the Earth and the height of the ionosphere respectively, both measured in km, and z_o is the zenith angle (in degrees) at the observation site. For a known satellite position, z_o can then be calculated and the approximate coordinates of the IPP can be determined.

The *TEC* data was then used to derive the rate of change of *TEC* (*ROT*), rate of change of *TEC* index (*ROTI*) and from the *ROTI*, the S_4-proxy ($S_{4\mathrm{p}}$). The $S_{4\mathrm{p}}$ was computed from *ROTI* by using an elevation-weighted coefficient (γ). The coefficient γ is calculated from a function of GPS satellite motion relative to the ionosphere, which is assumed to be concentrated on an imaginary thin shell 350 km above earth (the phase screen). The S_4 and $S_{4\mathrm{p}}$ were mapped to the zenith by using a mapping developed by Spogli et al. (2009). The *ROTI* and $S_{4\mathrm{p}}$ parameters were derived by means of Eqs. (3) and (4) respectively (Du et al., 2000).

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}, \tag{3}$$

$$S_{4p} = \gamma \times ROTI, \tag{4}$$

where the symbol $\langle\rangle$ in Eq. (3) implies average taken over 10 min and