

Validating the use of scintillation proxies to study ionospheric scintillation over the Ugandan region



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ARTICLE INFO

Article history:

Received 28 October 2014

Received in revised form

11 February 2015

Accepted 16 March 2015

Available online 20 March 2015

Keywords:

Equatorial scintillation

Scintillation proxies

Ionospheric irregularities

ABSTRACT

In this study, we compare the standard scintillation indices (S_4 and σ_ϕ) from a SCINDA receiver with scintillation proxies (S_{4p} and IsDPRI) derived from two IGS GPS receivers. Amplitude (S_4) and phase (σ_ϕ) scintillation data were obtained from the SCINDA installed at Makerere University (0.34°N, 32.57°E). The corresponding amplitude (S_{4p}) and phase (IsDPRI) scintillation proxies were derived from data archived by IGS GPS receivers installed at Entebbe (0.04°N, 32.44°E) and Mbarara (0.60°S, 30.74°E). The results show that for most of the cases analysed in this study, σ_ϕ and IsDPRI are in agreement. Amplitude scintillation occurrence estimated using the S_{4p} are fairly consistent with the standard S_4 , mainly between 17:00 UT and 21:00 UT, despite a few cases of over and under estimation of scintillation levels by S_{4p} . Correlation coefficients between σ_ϕ and the IsDPRI proxy revealed positive correlation. Generally, S_{4p} and S_4 exhibits both moderate and strong positive correlation. TEC depletions associated with equatorial plasma bubbles are proposed as the cause of the observed scintillation over the region. These equatorial plasma bubbles were evident along the ray paths to satellites with PRN 2, 15, 27 and 11 as observed from MBAR and EBBE. In addition to equatorial plasma bubbles, atmospheric gravity waves with periods similar to those of large scale traveling ionospheric disturbances were also observed as one of the mechanisms for scintillation occurrence. The outcome of this study implies that GPS derived scintillation proxies can be used to quantify scintillation levels in the absence of standard scintillation data in the equatorial regions.

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1. Introduction

The ionosphere is known to lie along the signal path between the orbiting GPS satellites and the terrestrial users. The variability of the Earth's ionosphere often poses threats to many navigation systems, radio and commercial applications (such as communications and radio astronomy). The threat is very critical in the high and low latitude regions where ionospheric irregularity sources are common. The interaction of GPS signals with the ionospheric irregularities causes ionospheric scintillation (Davies, 1990). This phenomenon has been studied extensively using scintillation receivers, in a number of sectors across the globe. However, scintillation study in regions with insufficient scintillation receivers is still a problem particularly in developing countries due to high maintenance and installation costs. However, scientists are working hard to solve this problem by making use of data

from the standard geodetic dual frequency receivers (Ghoddousi-Fard et al., 2013; Prikryl et al., 2013; Amabayo et al., 2012). Recent studies by Amabayo et al. (2012), Ghoddousi-Fard et al. (2013) and Prikryl et al. (2013) have provided a good alternative method for scintillation studies using proxies derived from IGS data (Dow et al., 2009).

Ionospheric information from dual frequency GPS receivers is obtained from the code or carrier phase measurements at two frequencies ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz). GPS satellites transmit their ephemeris and other information on the L-band f_1 and f_2 carrier frequencies. The time-based pseudo-range observables associated with f_1 and f_2 frequencies are denoted by P1 (C1) and P2 respectively. The received codes at f_1 and f_2 often show differential bias due to different hardware paths inside the transmitter. The phase observables also experience offsets as a result of unknown carrier phase ambiguities and differential equipment phase delays (Wanninger, 1993). These biases to some extent affect the accuracy of the ionospheric total electron content (TEC) obtained from GPS measurements. The techniques used in the GPS-TEC software developed by Seemala and Valladares

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(2011) to deal with the biases and ambiguities are well described in Amabayo et al. (2012). In this study, IGS data was processed using the GPS_TEC algorithm. An elevation mask of 20° was applied to reduce multipath effects. The diurnal and seasonal pattern of scintillation over the Ugandan region have been reported by Amabayo et al. (2014). Hoffmann-Wellenhof et al. (1992) stated that TEC is a complex parameter since its variability depends on factors such as sunspot activity (~ 11 -year cycle), seasonal and diurnal variations, the line of sight (elevation and azimuth) of the satellite and position of the observer. In this study, TEC data was used to carry out wavelet analysis to identify wave-like structures and to check the spatial location of irregularities.

Studies such as Ngwira et al. (2013), Oron et al. (2013) and D'ujanga et al. (2013) reported amplitude scintillation and TEC measurements over Ugandan region. A recent study by Amabayo et al. (2014) added phase scintillation statistics over this region to the existing literature. The poor ionospheric GPS infrastructure over the region still creates a big challenge due to insufficient data over the region. There are two SCINDA receivers in Uganda installed at Makerere University (32.57°E , 0.34°N) and Mbarara University of Science and Technology (30.66°E , 0.62°S). Data archived at two operational standard geodetic dual frequency receivers installed at Mbarara (30.74°E , 0.60°S) and Entebbe (32.44°E , -0.04°S) was used to derive the proxies. It should be noted that data from the SCINDA receiver in Mbarara was not used in this study due to insufficient data for the period under study. A scintillation climatology study by Amabayo et al. (2014) revealed data gaps from these receivers particularly from the SCINDA receiver at Makerere University. This paucity of scintillation data limits scintillation studies that are aimed at modeling this phenomenon at regional level. The stations are hereafter referred to by the station codes as MAK (Makerere), EBBE (Entebbe) and MBAR (Mbarara). The stations are shown on the map of Uganda in Fig. 1.

The main aim of this study was to derive and validate the amplitude scintillation proxy called S_{4p} and the phase scintillation proxy called ISDPRI derived from IGS GPS data. The proxies for the amplitude and phase scintillation were derived from GPS data sampled at 30 s intervals, to supplement scintillation data from the SCINDA receivers. The derived proxies were compared with standard scintillation data from the nearby scintillation receiver (MAK). The S_{4p} and ISDPRI parameters will be used in the absence

of standard L-band SCINDA data to quantify scintillation levels. These proxies (S_{4p} and ISDPRI) are particularly useful to support scintillation studies with IGS data, where available.

The S_{4p} parameter is derived from ROTI, which is defined as the standard deviation over a 5-min period of ROT calculated from 30-s sampled GPS data (Pi et al., 1997). Studies by Pi et al. (1997), Basu et al. (1999) and Beach and Kintner (1999) earlier on concluded that ROTI measurements could be used as a proxy for assessing the presence of ionospheric amplitude scintillation. Beach and Kintner (1999) concluded that the S_4 scintillation index is roughly proportional to measures of TEC fluctuation for weak scintillation with $\text{ROTI} \approx (2-5) \times S_4$ rendering good proxies for their measurements. Similarly, Basu et al. (1999) found $\text{ROTI} \approx (2-10) \times S_4$ correlations using their data set. The quantitative relationship between ROTI and S_4 depends on the ionospheric projection of the satellite velocity and the irregularity drift velocity. The study by Basu et al. (1999) indicated that ROTI is selective of Fresnel scale structures of 400 m at GPS frequencies.

2. Data processing and analysis

Dual frequency GPS RINEX files sampled at 15 s (EBBE) and 30 s (MBAR) interval were used to compute TEC (STEC) from combined $L1$ and $L2$ code-pseudo-range and carrier phase measurements. The data from EBBE was sub-sampled to 30 s to obtain uniform sampling period for the derivation of the proxies. The TEC along the signal path between the receiver and the GPS satellite, commonly referred to as slant TEC (STEC), is defined as

$$\text{STEC} = \int_R^S N_e ds, \quad (1)$$

where TEC is measured in TEC Units (TECU) with $1 \text{ TECU} = 10^{16} \text{ electrons/m}^2$, R and S stand for the receiver and satellite positions respectively in km. The line integral is assumed to include all the electrons in a column with a cross-section of 1 m^2 and extending from receiver to satellite.

GPS satellites are observed along oblique signal paths which pierce the ionosphere at ionospheric pierce points (IPPs). The height of the IPP corresponds to the height typically associated with the peak electron density in the ionosphere, $\sim 350 \text{ km}$ for this study. The TEC above a receiver, commonly known as vertical TEC (VTEC), is modeled using a mapping function and the geographic position of the IPPs (Hoffmann-Wellenhof et al., 1992). Eqs. (2) and (3) give the mapping function

$$\text{VTEC} = \text{STEC} \times \cos(z'), \quad (2)$$

with

$$\sin(z') = \left(\frac{R_E}{R_E + h} \right) \times \sin(z_o), \quad (3)$$

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

The presence of AGWs was investigated in this study by computing the residual TEC (ΔTEC) using the following equation:

$$\Delta\text{TEC} = \text{VTEC} - \sqrt{\text{VTEC}} \quad (4)$$

The residual TEC is then converted into a time series and used in a wavelet analysis using Morlet as a filter (Torrence and Compo, 1998; Habarulema et al., 2013; Amabayo et al., 2014).

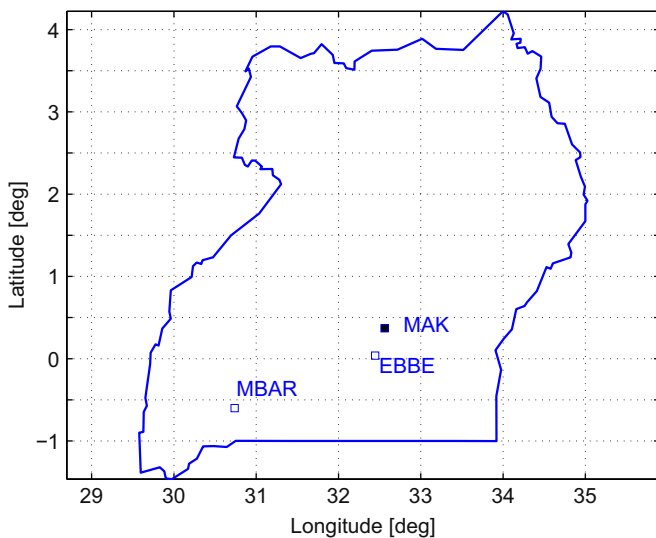


Fig. 1. Map of Uganda showing the location of the SCINDA and GPS receivers used in this study. The distance between the IGS (EBBE) and the SCINDA (MAK) is 36.4 km and between IGS (MBAR) and the SCINDA (MAK) station is 229 km.

2.1. Derivation of amplitude scintillation proxy

The TEC data derived was then used to derive the rate of change of TEC (ROT), rate of change of TEC index (ROTI) and hence the S_4 -proxy (S_{4p}). In this study, the approach used in Amabayo et al. (2012) was followed in computing S_{4p} from ROTI using an elevation-weighted coefficient (γ). The coefficient γ is calculated from a function of a GPS satellite's motion relative to the ionosphere, which is assumed to be concentrated on a thin shell located at 350 km above the Earth. The S_4 and S_{4p} were mapped to the zenith using a mapping function stated in Spogli et al. (2009). The S_{4p} and ROTI parameters were calculated using Eqs. (5) and (6), also available in Amabayo et al. (2012)

$$S_{4p} = \gamma \times \text{ROTI}, \quad (5)$$

$$\text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2}, \quad (6)$$

where

$$\gamma = 6.2135 \times 10^{-3} \left(\frac{v^2}{s} \right),$$

$$v^2 = (v_p^2 + v_d^2 - 2v_p v_d \cos \alpha) \cos^2 \varphi,$$

$$v_p = \frac{v_s (r_s + h)}{R_E + r_s},$$

$$s = \frac{(r_s + h) \cos(\varphi + \theta)}{\cos \varphi},$$

$$\varphi = \sin^{-1} \left[r \cos \frac{\theta}{r + h} \right],$$

with R_E being the Earth radius (6378 km), h the assumed ionospheric height (350 km), θ the satellite elevation angle, α the GPS orbital plane inclination (55°), v_d the ion drift velocity (120 ms^{-1}) from Du et al. (2000), v_p the velocity of the IPP moving at h , v_s the satellite orbital speed (3874 ms^{-1}) and r_s the satellite orbital altitude (20,000 km). The elevation-weighted coefficient (γ) selectively suppresses low elevation scintillation compared to high elevation scintillation.

2.2. Derivation of phase scintillation proxy

In this study, 1 min σ_ϕ and absolute value of $|\text{SDPRI}|$ computed over 60 s were compared. The phase scintillation proxy was derived using a similar approach to that of Ghoddousi-Fard et al. (2013) and Prikryl et al. (2013). Prikryl et al. (2013) stated that this proxy index does not capture the rapid changes of the phase in data sampled at 1 Hz, therefore, is not valid for strong scintillation. According to Ghoddousi-Fard et al. (2013), the rate of change of ionospheric effects can be obtained from the delta phase rate (DPR) using the so-called geometry-free observables ($L1$ and $L2$ GPS signals) on carrier phase (ϕ_g) as

$$\phi_g = L1 - L2 = \left(\frac{f_1^2}{f_2^2} - 1 \right) I_{\phi_{1,r}}^s + (\lambda_1 N_1 - \lambda_2 N_2 + b_{\phi,r} + b_{\phi}^s) + \varepsilon_\phi \quad (7)$$

where f_1 and f_2 are the frequencies of the GPS signals, $I_{\phi_{1,r}}^s$ is the ionospheric effect on carrier phase at $L1$ along the path between satellite s and receiver r , λ_1 and λ_2 are the wavelengths at f_1 and f_2 , N_1 and N_2 are the integer ambiguities of the carrier phase measurements, $b_{\phi,r}$ and b_{ϕ}^s are receiver and satellite inter-frequency hardware delays on the carrier phase measurements, respectively, and ε_ϕ is the combined multi-path and noise effects on the geometry-free phase observable.

For two consecutive epochs (t_i and t_{i+1}) when there is no loss of lock, DPR can be expressed as

$$\psi = \frac{\varphi_{\phi}^{t_{i+1}} - \varphi_{\phi}^{t_i}}{t_{i+1} - t_i} = \frac{\left(\frac{f_1^2}{f_2^2} - 1 \right) \times (I_{\phi_{1,r}}^{s(t_{i+1})} - I_{\phi_{1,r}}^{s(t_i)})}{t_{i+1} - t_i} + \varepsilon_\phi. \quad (8)$$

where ε_ϕ is the combined multi-path and noise effects on delta phase rate and variations in receiver and satellite inter-frequency hardware delays over short intervals are assumed to be insignificant.

By assuming random noise and multipath over short intervals, they also derived a mean value ($\overline{\psi}$) over a statistically meaningful number of epochs to contain mainly the ionospheric disturbances. The mean delta phase rate (mDPR) and the standard deviation (sDPR) from the mean were derived using the expressions

$$\text{mDPR} = \overline{\psi} = \frac{\sum_{i=1}^n \psi_i}{n} \quad (9)$$

$$\text{sDPR} = \sigma_\psi = \sqrt{\frac{1}{n} \sum_{i=1}^n (\overline{\psi} - \psi_i)^2} \quad (10)$$

where n is the number of epochs used (e.g. 30 or 60 for 1 Hz GPS measurements); $n=60$ for this study.

The absolute value of $\overline{\psi}$ ($|\text{mDPR}|$) and σ_ψ ($|\text{sDPR}|$) are mapped to zenith to account for elevation angle of the signal path. The mapping function uses the cosine of the zenith angle of the satellite at the pierce point to map the slant values to zenith (Spogli et al., 2009). Ghoddousi-Fard et al. (2013) stated that $|\text{sDPR}|$ is better correlated with σ_ϕ than mDPR, although both ($|\text{sDPR}|$ and mDPR) are sensitive to scintillation. Therefore, in this current study $|\text{sDPR}|$ was considered for comparison with σ_ϕ . It should be noted that both the 15 s and 30 s data was averaged over one minute for the comparison. It should be noted here that a scaling factor of about 10 and 0.035 was derived between the amplitude and phase scintillation parameters. The scale factors were derived by selecting SCINDA and IGS datasets for the amplitude and phase scintillation of common time. A correlation of the selected datasets was done and the root means square (rms) values obtained for each of the SCINDA and IGS scintillation parameters. The factors were then obtained by taking the ratio of rms value for SCINDA to the IGS data. The scaled proxy values were obtained by multiplying the raw proxies by the corresponding scale factors.

3. Results and discussion

This paper presents results based on the comparison between scintillation observed by SCINDA receiver at MAK and proxies derived from IGS data from EBBE and MBAR. Scintillation events selected were only for the nighttime. The event selection was also subject to simultaneous occurrence of amplitude and phase scintillation and reliable data in all the stations.

3.1. Selected scintillation events

Fig. 2 shows both weak and strong levels of amplitude and phase scintillation as classified in Amabayo et al. (2014). Fig. 2a, b and d reveals that strong amplitude scintillation was accompanied by strong phase scintillation between 17:00 and 22:00 UT. On the other hand, Fig. 2c shows that strong amplitude scintillation was accompanied by weak phase scintillation. Fig. 2e and f illustrates the standard amplitude scintillation index and the corresponding proxy. The top panels of the sub-figures of Fig. 2 show the visible satellite paths with elevation above 20° . For times in the range 17:00 UT–21:00 UT on 2011-04-08 (Fig. 2b), 2011-09-03 (Fig. 2c) and 2011-10-25 (Fig. 2d), scintillation estimated using the S_{4p} and

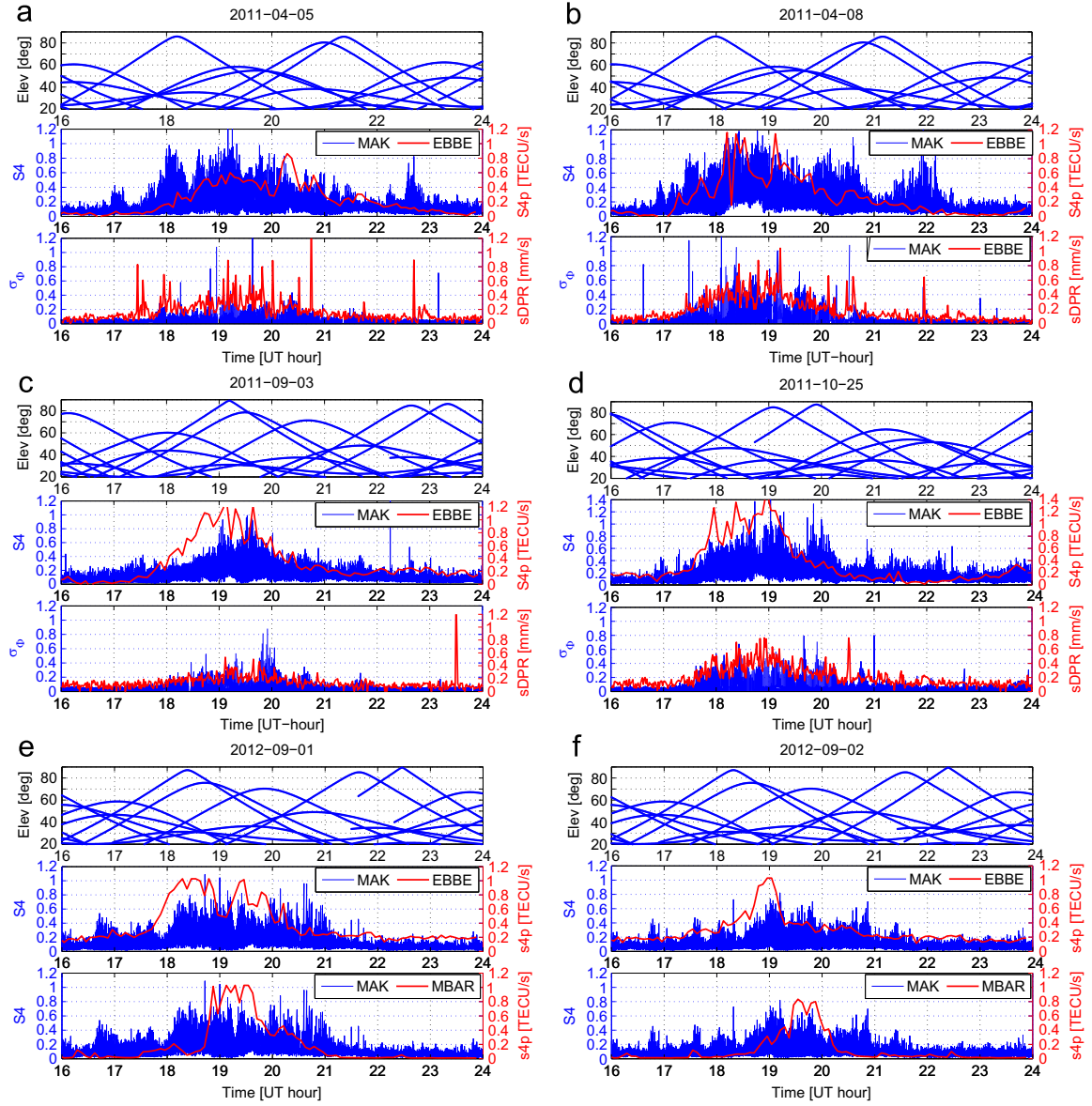


Fig. 2. Nighttime amplitude and phase scintillations as observed using MAK SCINDA and EBBE IGS receives. Local time (LT)=UT+3 h.

IsDPRI shows a good level of consistency with the standard amplitude (S_4) and phase (σ_ϕ) scintillation. However, the S_{4p} parameter did not capture scintillations between 21:00 UT and 23:00 UT on 2011-04-05 and 2011-04-08. Fig. 2b, c, d and e reveals a good agreement between S_4 and S_{4p} between 18:00 UT and 21:00 UT. However, there are cases when S_{4p} slightly over estimated the S_4 (Fig. 2e and f). Similarly, a case of under estimation by S_{4p} was observed on 2012-09-01 between 16:00 UT and 19:00 UT (Fig. 2e) at MBAR. In most of the phase scintillation cases presented (Fig. 2a–d), σ_ϕ and IsDPRI are in good agreement. Generally, IsDPRI is sensitive to phase scintillation levels as observed in Fig. 2a–d. It is clear that amplitude scintillation levels exceed the phase scintillation levels during simultaneous scintillation events over the Ugandan region (Amabayo et al., 2014). This result is in contrast to that obtained by Ghoddousi-Fard et al. (2013) and Prikryl et al. (2013) at high latitudes where strong phase scintillations may occur in the presence of weak amplitude scintillations. A few isolated peaks in the IsDPRI were noted which did not have corresponding peaks in the phase scintillation data along the ray paths from the same satellite. It is not yet clear what is the reason

for these non-correlated events. It may be partly explained by the ionospheric structures that cause the scintillation being smaller in extent than the distances between the IGS and SCINDA stations. This could result in differences between the parts of the ionosphere intersected by the IPPs from the same satellite as observed from the IGS and SCINDA receivers.

To establish any correlation between standard amplitude and phase scintillation indices and corresponding derived proxies, the two data sets were compared. Data corresponding to the common times were captured and processed for comparison. The Pearson linear correlation coefficient (R) was determined and the best straight line fitted through the data points. The correlation between standard (S_4 and σ_ϕ), and proxy (S_{4p} and IsDPRI) values for the scintillation events in Fig. 2 are shown in Fig. 3. A summary of some of the events analysed are shown in Table 1, using MAK as a reference.

Table 1 and Fig. 3a, b, e, f and h clearly show that S_{4p} has strong positive correlation with S_4 as seen from the high values of R . Strong positive correlation coefficients were obtained between EBBE IsDPRI proxy and MAK σ_ϕ on 2011-04-08 (Fig. 3c) and 2011-09-03 (Fig. 3d). On the other hand, Table 1 and Fig. 3g reveal a few

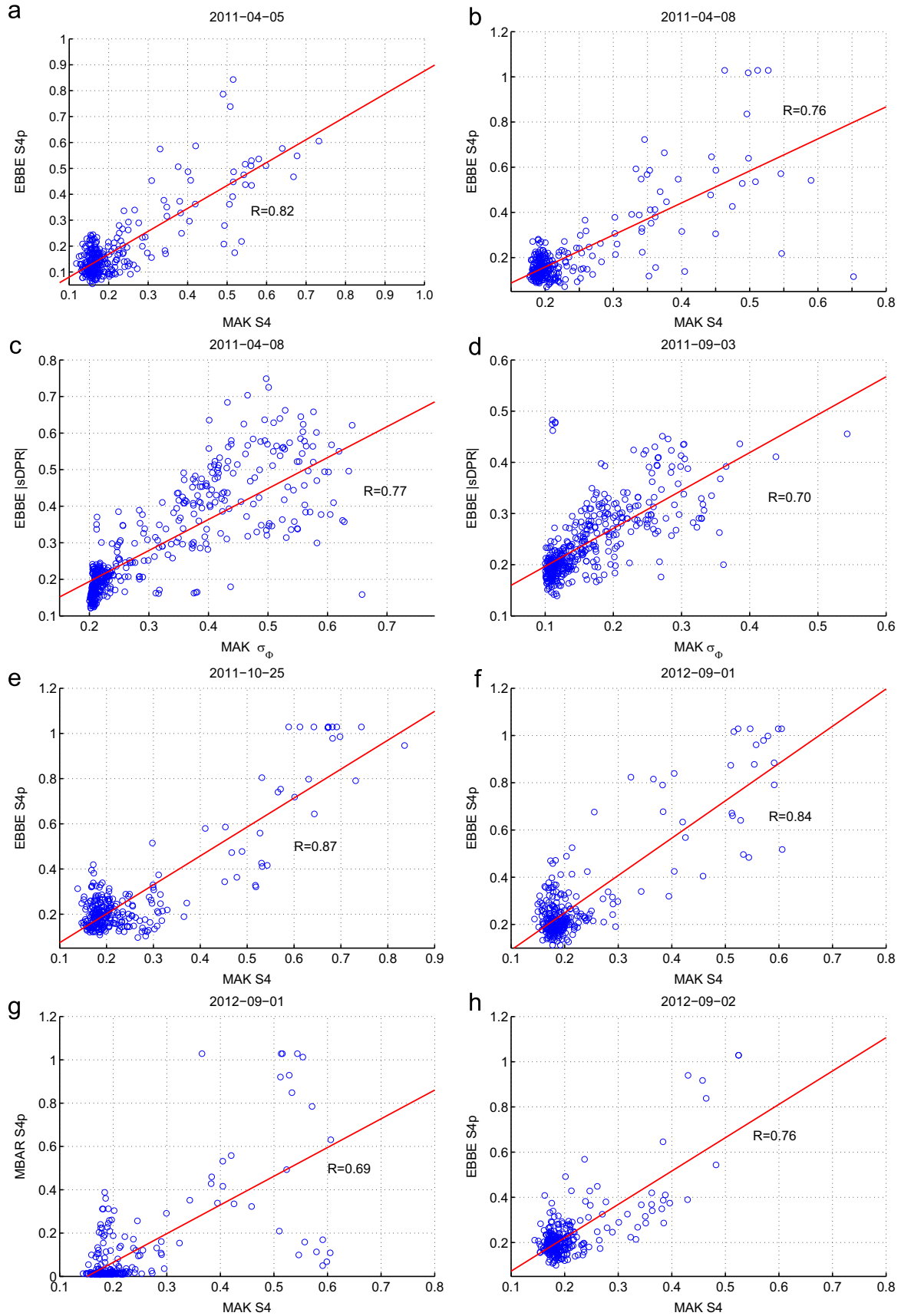


Fig. 3. Correlation analysis for the amplitude and phase scintillation with their proxies for selected days in 2011 and 2012.

Table 1

Summary of other scintillation events analysed in this study.

Date	Station ID	Event type	R
2011-04-04	EBBE	Amplitude scintillation	0.81
2011-04-05	MBAR	Phase scintillation	0.73
2011-09-17	EBBE	Amplitude scintillation	0.54
2011-09-22	EBBE	Amplitude scintillation	0.89
2011-10-26	EBBE	Amplitude scintillation	0.78
2011-10-29	EBBE	Amplitude scintillation	0.71
2012-07-29	MBAR	Amplitude scintillation	0.71
2012-08-27	MBAR	Amplitude scintillation	0.66
2012-09-02	MBAR	Amplitude scintillation	0.55
2012-09-02	MBAR	Phase scintillation	0.60
2012-09-06	MBAR	Amplitude scintillation	0.72
2012-09-19	MBAR	Amplitude scintillation	0.81

cases of moderately positive correlation ($0.50 \leq S_4, \sigma_\phi \leq 0.69$) due to weak scintillations. Weak scintillation ($0.1 \leq S_4, \sigma_\phi \leq 0.3$) probably associated with the remaining multipath sources or small scale TIDs could have been the most dominant causes. This class of TIDs is quite difficult to detect from GPS data since they cause small amplitude variations in the TEC which are comparable to atmospheric noise (Rieger et al., 2006). In general, S_{4p} and $|sDPRI|$ are highly correlated with S_4 and σ_ϕ , despite instances of weak scintillation. These results imply that the IGS derived scintillation proxies can complement standard scintillation values at locations where there are no dedicated scintillation monitors.

After establishing the fact that the scintillation proxies are reliable for studying scintillation phenomena, the next step was to look for spatial locations and sources of the irregularities. The aim was to find possible mechanisms associated with the observed scintillation events in Fig. 2. This was done by investigating the STEC for different satellite ray paths. Some of the results showing irregularities along the line of sight to the receivers are shown in Fig. 4.

The TEC along the ray paths to GPS satellites 2, 15, 27 observed from MBAR and to GPS satellite 11 as observed from EBBE was investigated. The TEC along the ray paths to these satellites showed strong evidence of TEC depletions during the nights of the days presented in Fig. 4. TEC depletions are evident from 18:30 to 21:00 UT (Fig. 4a), 19:00 to 22:00 UT (Fig. 4b), 19:00 to 21:00 UT (Fig. 4c) and 18:00 to 21:00 UT (Fig. 4d). Several intense TEC depletions of magnitude ≥ 40 TECU were observed along the ray paths from PRN 15 and 27 to the receiver at Mbarara. These TEC depletions confirm the presence of small scale irregularities trapped in large scale irregularities, which are responsible for scintillations over the different ray paths. The small scale irregularity signatures are clearly visible for example in Fig. 4c through the frequent depletions at around 20:00 UT and 21:00–21:30 UT. At GPS L-band frequencies, plasma irregularities with scale-sizes of a few hundred meters can be detected. However, under conducive ionospheric environments, small scale irregularities can grow along geomagnetic field lines to form the EPBs with dimension of few hundred kilometers (Ngwira et al., 2013). The irregularities observed on 2011-04-05 (Fig. 4a–c) are attributed to the equatorial plasma bubbles (EPBs) that appear at night over the equator. Plasma bubbles are generally regions of electrically charged particles which develop as flux tubes aligned vertically, and then rising slowly in the upper atmosphere.

One explanation for this phenomenon is that at night, the thermosphere–ionosphere environment becomes conducive for plasma bubbles to form due to a mixture of plasma and electrically neutral gas which becomes unstable after sunset. The daytime solar radiation sustains fairly constant levels of plasma by photo-ionisation in the thermosphere–ionosphere system, thus resulting in a smooth diurnal TEC pattern. The absence of solar radiation at night causes faster recombination rates at lower altitudes, where more heavily charged particles (molecular ions) are found. This

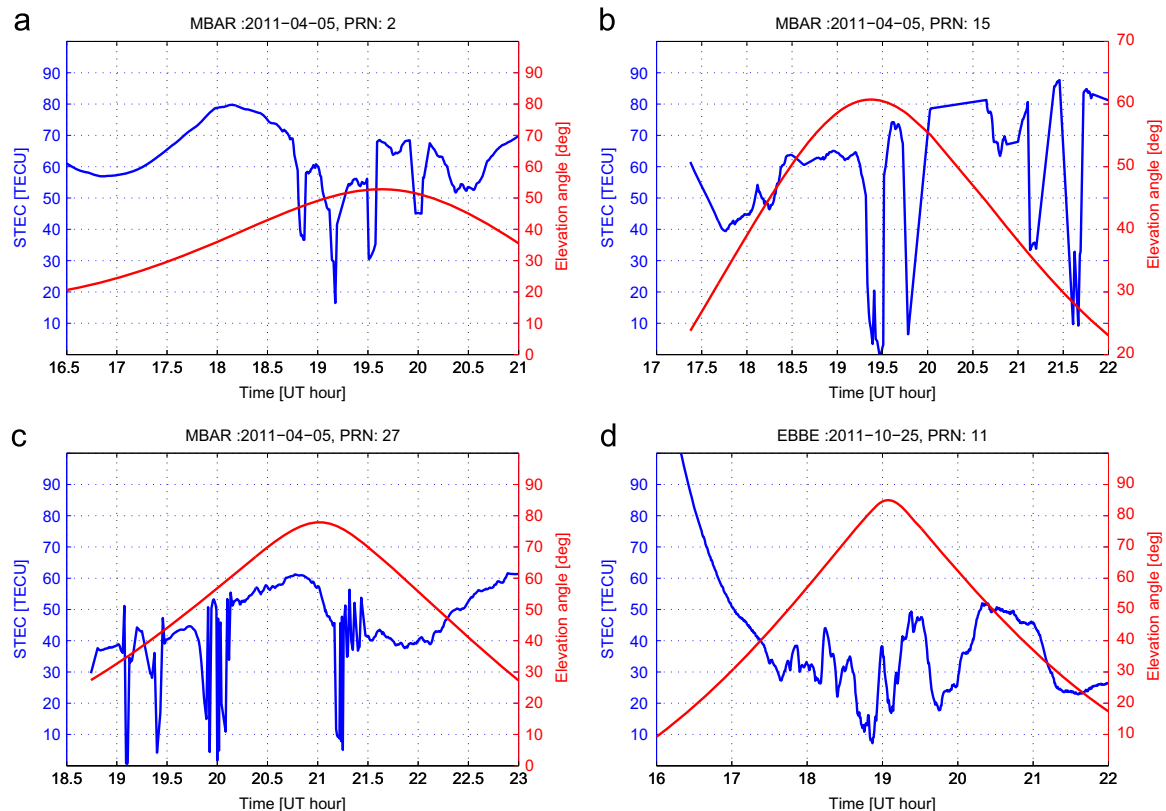


Fig. 4. Variability of STEC as a function of time and elevation angle as observed at MBAR and EBBE GPS IGS stations in Uganda. Note that the TEC depletions along the ray paths to the receivers occur at high elevations.

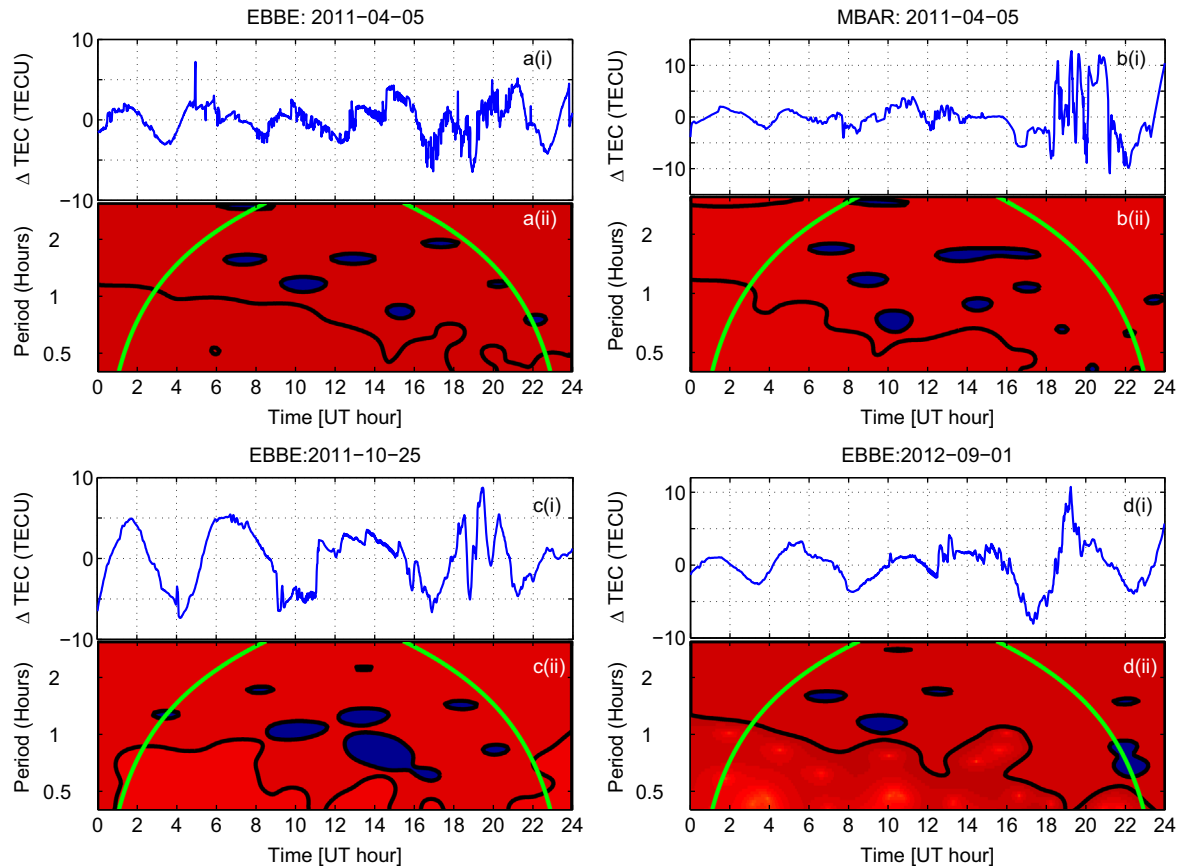


Fig. 5. Time series for ΔTEC (top panels) and scalograms (bottom panels) of the Wavelet transforms evaluated at 95% significance level observed at EBBE and MBAR.

rapid recombination consequently creates less dense plasma at the lower altitudes. This makes the region to become unstable because the less dense plasma below (trapped in the neutral gas) attempts to rise above the higher density plasma that lies above it. The rising plasma depletions of large scale sizes are accompanied by secondary irregularities through cascade processes at the steepening density gradients of the bubbles (Abdu, 2001).

The nighttime plasma in the equatorial regions becomes turbulent since the plasma bubbles are suspended on the Earth's horizontal magnetic field over the equator. The gravitational force on the electrons and ions causes them to drift parallel to the magnetic field. The $E \times B$ drift produced in the opposite direction amplifies the initial perturbation. Such a disturbance tends to generate the so-called atmospheric gravity waves (AGWs). We also investigated the presence of AGWs in this study using wavelet spectral analysis. The results are presented in Fig. 5.

Fig. 5 shows a continuous wavelet transform (CWT) analysis of the time series signal TEC (ΔTEC). Fig. 5a(i), b(i), c(i) and d(i) illustrates the signature of the AGW in the thermosphere. The amplitude of ΔTEC (Fig. 5a(i), b(i), c(i) and d(i)) provides information on the time of occurrence and the degree of different wave events in the signal. The nature of ΔTEC suggests a wave-like activity in the low latitude ionosphere over the Ugandan region. The wave-like nature of ΔTEC has been attributed to signatures of AGW oscillations in the low latitude thermosphere. The size and the number of the blue contour regions in the scalograms (Fig. 5a(ii), b(ii), c(ii) and d(ii)) illustrate the intensity of the wave-like activity. The scalograms therefore reveal the time of the passage of AGWs, with period ranging from 30 min to 2 h. On 2011-10-25 (Fig. 5c(ii)), the wave-like activity increased in intensity between 08:00 and 18:00 UT. We need to point out that the wave activity within the cone of influence (green line) lies within the 95%

significance level. The AGWs are known to provide a seed mechanism for the Rayleigh–Taylor (R–T) instability (Huang et al., 2002; Hoang et al., 2010). The wave-like activities observed in Fig. 5 are more visible from EBBE than from MBAR, suggesting that the wave-like activities were amplified by the localised R–T instability sources in the atmosphere. The period of these wave oscillations resembles those of traveling atmospheric disturbances (TADs) which manifest in the ionosphere as TIDs. The TADs are generated from high latitudes and often cause enhanced thermospheric pressure gradients. The AGWs generated are responsible for large scale TIDs (LSTIDs) propagating from high to low latitudes (Pröls, 1993; Pi et al., 1993; Mikhailov et al., 1995; Ho et al., 1998). These waves propagate equatorward (Kelley, 2009) and cause an uplifting of the F2 layer by pushing the ionospheric plasma along magnetic field lines to higher altitudes where recombination is much lower. When AGWs propagate perpendicular to the magnetic field, they generate polarised electric fields, and these are amplified non-linearly by the R–T instability (Huang et al., 2002). The evening F layer height and the vertical plasma drift are due to the pre-reversal electric field enhancement that is controlled by the thermospheric zonal wind (eastward in the evening) and the longitudinal or local time gradient in the integrated E region conductivity near sunset.

3.2. Conclusion

In this study, SCINDA data from Makerere, Uganda was selected for comparing the standard amplitude and phase scintillation with their corresponding proxies (S_{4p} and ISDPRI) from IGS GPS data archived at Entebbe and Mbarara. The low latitude ionospheric scintillations analysed in this study occur mostly during the

nighttime. Amplitude scintillation occurrence estimated using the S_4 -proxy is fairly consistent with the occurrence of standard S_4 , mainly between 17:00 UT and 21:00 UT. A few cases of over- and underestimation of the scintillation levels by S_4 -proxy were observed. In most of the cases presented in this study, σ_ϕ and phase scintillation proxy (ISDPRI) are in agreement. Generally, ISDPRI is sensitive to all levels of phase scintillation measured using the SCINDA receiver. Strong amplitude scintillation levels dominated the simultaneous occurrence of scintillation over the Ugandan region (Amabayo et al., 2014) during the two years under study. Correlation analysis between the absolute value of the phase scintillation proxy and σ_ϕ revealed strong positive correlation. Generally, S_{4p} and S_4 depict both strong positive correlation and moderately positive correlation. Equatorial plasma bubbles (EPBs) that manifest as plasma depletions at night over the equator were proposed to be responsible for the observed scintillation over the region. The results also show AGWs with periods similar to those of large scale TIDs. These AGWs may be one of the causes of the observed scintillations. The results in this study imply that the GPS derived scintillation proxies can be used to quantify scintillation levels in the equatorial regions where no scintillation receivers are available.

Acknowledgement

The authors acknowledge the International Science Program (ISP) from Uppsala University in Sweden for funding this study. The authors greatly thank and acknowledge the anonymous reviewers for their comments that has improved the quality of this paper. We extend our appreciation to the Boston College and the Air Force Research Laboratory (AFRL), USA, for supplying the SCINDA receivers to Uganda. We also acknowledge the offer of IGS data used in this study, downloaded from <ftp://data-out.unavco.org/pub/rinex/obs>.

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