Statistical characteristics of low-latitude ionospheric scintillation over China

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Abstract

The Global Positioning System (GPS) L-band ionospheric scintillation produced by electron density irregularities in the ionospheric E- and F-regions, is mainly a low- and high-latitude phenomenon. In this study, the statistical behavior of GPS ionospheric scintillation over a Chinese low-latitude station Sanya (18.3°N, 109.6°E; dip lat: 12.8°N) has been investigated. A detailed study on the seasonal and solar activity dependence of scintillation occurrence during July 2004–December 2012 show that the amplitude scintillation pattern, with a maximum occurrence during equinox of solar maximum, agrees with plasma bubble observations by in situ satellites in this longitude. A few daytime periodic scintillation events are found during June solstice months of solar minimum. Interestingly, a significant equinoctial asymmetry of scintillation onset time is found in 2011–2012. The initiation of scintillation during September–October is on average earlier than that of March–April about 25 min. Meanwhile, the zonal drifts of irregularities estimated using two spatially separated GPS receivers over Sanya show a similar behavior during the two equinoxes, slowly decreasing from 150 m/s at post-sunset to 50 m/s near midnight. The possible mechanisms responsible for the occurrence characteristics of GPS scintillation over Sanya, and relevant aspects of the zonal drifts of the irregularities are discussed.

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1. Introduction

Ionospheric scintillation refers to the amplitude and phase fluctuations while the radio waves travel through the ionosphere. Severe amplitude scintillation can cause signal levels drop below a receiver’s lock threshold and thus affect satellite communication and navigation systems. Ionospheric scintillations mainly occur at equatorial and low latitudes, and polar region (e.g., Abdu et al., 1985; Basu et al., 1999; Muella et al., 2010; Alfonsi et al., 2011; Prikryl et al., 2011; Li et al., 2012). The low-latitude ionospheric scintillation is mainly caused by equatorial F-region irregularities with a relatively lower plasma density than the background plasma. These irregularities, firstly discovered in the spread of range and frequency of ionosonde echo, were called equatorial spread F (ESF) (Woodman and LaHoz, 1976). The generally accepted mechanism responsible for the generation of ESF is the Rayleigh–Taylor instability (Kelley, 2009). After sunset, the pre-reversal enhancement of the eastward electric field (PRE) lifts the F layer up to higher altitude through the $\mathbf{E} \times \mathbf{B}$ drifts, leading to a steep upward density gradient formed in the bottom-side of the equatorial F layer, and further destabilizes the density perturbations. And then

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the disturbed plasma structure of the lower heights rises up to the topside ionosphere in the form of equatorial plasma bubbles (EPBs). There is evidence that ESF is not solely controlled by the PRE, some other possible seeding effects, for example the gravity waves or the F layer bottom-side shear flow vortex, are necessary for the ESF occurrence. In this regard, recent observations from radar and ionosonde have shown that the presence of large-scale wave structures in the bottomside F region is also a relevant condition of the ESF development (Abdu et al., 1985, 2013; Li et al., 2013; Patra et al., 2013; Tsunoda, 2013, and the references therein).

The ESF spatial scales range from a few centimeters to hundreds of kilometers (Basu et al., 1978). The severity of signal amplitude fluctuation is a function of the signal frequency, the ambient electron density and the spatial size of the irregularities. The most effective spatial size of irregularities that causes severe amplitude fluctuation is the first Fresnel scale. For Global Positioning System (GPS) L1-band (1575.42 MHz), the Fresnel scale is about 400 m at ionospheric F region (~350 km altitude) (Bhattacharyya et al., 2000). Observations from multi-frequency receivers, radars and in situ satellites have shown that the ESF and its associated scintillation are nighttime phenomena, occurring mainly before midnight. Based on satellite in situ measurements, the longitudinal/seasonal variations of ESF associated bubble occurrence have been investigated by some researchers (e.g., Su et al., 2006; Li et al., 2007a). The longitude sectors Atlantic–African (centered at ~20°E) and Pacific (centered at ~180°E) regions are very prone to the occurrence of ESF during June solstice months. For December solstice, regions of high occurrence rates shift to American–Atlantic longitudes (centered at ~320°E). The longitudinal/seasonal dependence of ESF occurrence has been found to be associated with the geographical latitude of the magnetic equator and the inclination of the sunset terminator with respect to the declination of the magnetic field (Tsunoda, 1985; Su et al., 2006). On the other hand, long term observations from ionosonde and satellite beacon receiver at a given site have shown that the occurrence of scintillation depends on solar activity (Abdu et al., 1998). During solar minimum, the ionospheric scintillation was rarely observed. However, the absence of scintillation during solar minimum does not always indicate the absence of F-region irregularities. Through investigating a large database of spread F obtained from equatorial ionosonde ionograms, together with the simultaneous observations of radar plumes, GPS scintillations and TEC fast fluctuations, Li et al. (2011) have suggested that the discrepancy between the spread F irregularity and GPS scintillation/fast TEC fluctuation could be induced partly by the apparently lower absolute perturbation density during solar minimum. Moreover, earlier works demonstrated that the most intense scintillations appear at the equatorial ionization anomaly (EIA) region, around 15–20° magnetic latitudes where the background plasma density is high. Specifically, using GPS TEC and scintillation observations over Brazil, Muella et al. (2010) reported that the GPS scintillations tend to be highly correlated with the regions of extremely steep electron density gradients at the EIA region.

Though the longitudinal/seasonal variations of ESF occurrence have been extensively studied using satellite in situ measurements, a long-term statistical analysis on the occurrence and characteristics of GPS ionospheric scintillations and its associated TEC fluctuations in the Chinese low-latitude region has not been performed. On the other hand, earlier drift measurements of irregularities producing GPS ionospheric scintillations over Sanya were estimated from the scintillation spectra by using a single receiver (e.g., Li et al., 2007b). To improve the quality of drift measurements, another GPS receiver was installed in July 2007 over Sanya. The two GPS receivers are aligned in the magnetic east–west direction and separated 88 m from each other. In this study, we use measurements of the raw signal intensity obtained by the two spatially separated GPS receivers, to estimate the zonal drifts of the irregularities producing scintillations. The main objective of this paper is to present the statistical dependence of GPS ionospheric scintillations on local time, seasonal and solar activity, and the behavior of solar maximum irregularity drifts over Sanya.

2. Data

The GPS ionospheric scintillation/TEC data were recorded by the GPS Ionospheric Scintillation and TEC Monitor (GISTM) system GSV4004A over Sanya. Besides the amplitude scintillation index $S_4$ (as the standard deviation of the signal power normalized to the average signal power), the GISTM also calculates the $S_3$ index due to ambient noise in such a way that a corrected $S_3$ index can be obtained at the L1 frequency 1575.42 MHz. In the following analysis we use the corrected $S_4$ index (without noise effects) to identify scintillation occurrence over Sanya (e.g., Li et al., 2008). In order to eliminate the multi-path effects, only the $S_4$ data with elevation angles larger than 30° and lock time more than 180 s are used. Based on the TEC values of 30 s interval, the rate of change of TEC Index (ROTI) (Pi et al., 1997) are used as an indicator of appearance of kilometer scale irregularities. Fig. 1 shows an example of $S_4$ and ROTI variations as a function of local time. The values of $S_4$ and ROTI shown in Fig. 1 are the maximum $S_4$ and ROTI at a given time interval (1 min for $S_4$ and 5 min for ROTI). Here we choose the thresholds 0.2 (for $S_4$) and 0.5 (for ROTI) to identify the occurrences of scintillation and fast TEC fluctuation, respectively.

By taking a similar way as that of Muella et al. (2009), the zonal drifts of ionospheric irregularities producing GPS scintillations over Sanya were estimated. Additional details about the calculation of irregularity drifts using spatially separated GPS receivers have been presented in many studies (Ledvina et al., 2004; Otsuka et al., 2006; Muella
et al., 2008, 2009). Briefly, through calculating the scintillation pattern velocity with the cross correlation method (only the data with $S_4 > 0.2$ and elevation angle $> 30^\circ$ are used), the zonal drifts are computed by taking the equation (Ledvina et al., 2004; de Paula et al., 2010),

$$V_{\text{ion}} = \frac{h_{\text{sat}} - h_{\text{ion}}}{h_{\text{sat}}} \cdot V_{\text{scint}}$$

$$+ \frac{h_{\text{ion}}}{h_{\text{sat}}} \left[ V_{\text{satx}} + \left( \frac{q_y}{q_x} \right) V_{\text{saty}} + \left( \frac{q_z}{q_x} \right) V_{\text{satz}} \right].$$

In the above equation, $V_{\text{ion}}$ is the zonal drift velocity; $h_{\text{sat}}$ and $h_{\text{ion}}$ are the heights of the GPS satellite and ionospheric irregularities, respectively; $V_{\text{scint}}$ is the scintillation pattern velocity; $V_{\text{satx}}, V_{\text{saty}}$ and $V_{\text{satz}}$ are the satellite velocity components in the zonal, meridional and vertical directions, respectively; $(q_y/q_x)$ and $(q_z/q_x)$ are mapping factors. Additional details about the equation please refer to for example Kil et al. (2000), Ledvina et al. (2004) and de Paula et al. (2010).

A digital ionosonde (DPS-4D) was operated since May 2011 at Sanya. The peak height of the ionospheric F2 layer ($h_m F_2$) was derived from the manually scaled ionograms at every 15 min. The 10.7 cm solar radio flux (F10.7) index was downloaded from http://www.ngdc.noaa.gov/.

3. Results and discussion

Using the GPS scintillation and TEC data obtained from July 2004 to December 2012 over Sanya, the solar activity and seasonal dependence of GPS scintillations ($S_4$) and fast TEC fluctuations (ROTI), and the statistics of GPS scintillation onset time and the zonal drifts of irregularities producing scintillations during equinox are investigated.

3.1. Solar activity and seasonal dependence of $S_4$ and ROTI

Fig. 2 shows the distribution of diurnal maximum $S_4$ and ROTI from July 2004 to December 2012. The equinoctial months (March–April, September–October) are highlighted in gray. The superposed red line represents the F10.7 index. It is found that the intensity of scintillation, as indicated by $S_4$, gradually decreased from 2004 with decrease in solar flux. The GPS scintillation was rarely observed in 2008–2009, very low solar flux years with mean F10.7 values of 69 and 71, respectively. From 2010, the scintillation increases and its intensity are high with maximum $S_4$ around 0.8 during 2011–2012. Similarly for TEC fluctuation, it can be seen from the figure that with the decrease (increase) in solar flux, ROTI decrease (increase) from 2004 (2010). The maximum value of ROTI is about 8. Besides the solar activity dependence, the figure shows two clear seasonal maxima in scintillation ($S_4$) and significant TEC fluctuation (ROTI), corresponding to the spring (March–April) and autumn (September–October) equinoctial months except in solar minimum years 2008–2009. The seasonal and solar activity dependence of the scintillation occurrence over Sanya agrees with that of EPBs by in situ measurements in this longitude from satellites. For example, the ROCAT-1 and DMSP measurements have shown a high occurrence probability of EPBs during equinoctial months of solar maximum in Southeast Asia (e.g., Burke et al., 2004; Su et al., 2006). The EPB associated irregularities are known to result from nonlinear evolution of the generalized R–T instability.
excited at the upward density gradient region of the equatorial F layer bottom-side. The bubble structures evolved from the bottom-side density perturbations are vertically elongated and can penetrate the F layer peak to the topside ionosphere, reaching altitudes as high as 1500 km or more, and extending to dip latitudes greater than ±15° (Otsuka et al., 2002). For scintillations induced by EPBs, a higher occurrence rate would be expected in the southern sky of Sanya.

We used the $S_4$ data during equinoctial months of 2010–2012 to examine the spatial distribution of GPS scintillation. Fig. 3 shows polar maps of the percentage occurrence of scintillation, which was calculated for each grid (20° in azimuth and 10° in zenith) by considering the number of days with $S_4 > 0.2$ and with a duration of more than 10 min divided by the total number of days. It is clearly seen from the figure that an occurrence peak of scintillation is located at the southern sky of Sanya. The features of scintillation occurrence and ROTI enhancement over Sanya, as presented in Figs. 2 and 3 show consistent results with earlier measurements from other longitudes. For example in the close-by longitude Indian sector, the maximum percentage of occurrence of scintillations and TEC depletions induced by EPBs occur at low latitude during equinoctial months followed by minimum occurrence during winter and summer months (e.g., Rama Rao et al., 2006). The scintillation occurrence with their maximum during equinoctial months has been suggested to be due to the close alignment of the solar terminator with magnetic meridian. The magnetic declination angle over Sanya is about −1°. During equinoctial months, the sunset E-region conductivity on both hemispheres are simultaneously decreased so that the evening pre-reversal enhancement in the eastward electric field (PRE) (developing under the eastward thermospheric zonal wind) is enhanced and a large westward longitudinal gradient of the conductivity is established across the terminator (Abdu, 2001). The enhanced PRE elevate the equatorial F layer to higher altitude through the $E \times B$ drift and thus create favorable conditions for the generation of plasma irregularities responsible for ionospheric scintillations.

Though the seasonal patterns of moderate to strong scintillations and significant ROTI are very similar over Sanya, this does not mean that the scintillation and ROTI enhancement always coexist with each other. A few cases with weak scintillation but without apparent TEC fluctuation have been observed during the June solstice months of 2007–2008. As an example, Fig. 4 illustrates the scintillation and TEC fluctuation parameters ($S_4$ and ROTI) derived from measurements made on 15 August 2007.
corresponds to the first Fresnel scale (meters) as well as large scale (kilometers) irregularities. For GPS L1 frequency and \( \frac{1}{\lambda} \), where \( \lambda \) is the radio wavelength, and \( z \) is the slant range from receiver to ionospheric irregularity (e.g., Basu et al., 1999). For GPS L1 frequency and E region irregularities, the first Fresnel scale is about 200 m. Recently, Patra et al. (2012) reported an interesting case of daytime scintillation associated with strong Es activity and E region irregularities. With regard to this, Ning et al. (2012) showed a high occurrence rate of summer daytime E region 3-m irregularities generated through gradient drift instability (GDI) over Sanya. Since the GDI having sharp plasma density gradient can produce small scale (meters) as well as large scale (kilometers) irregularities (Hysell and Burcham, 2000), the weak daytime GPS scintillations observed over Sanya could be caused by the Es associated hundred-meter scale irregularities.

Simultaneous measurements by radar, ionosonde and GPS receiver would help to demonstrate a link between the daytime periodic scintillation and Es irregularities over Sanya, which will be performed in future.

### 3.2. Equinoctial asymmetry of scintillation occurrence

Observations presented in Fig. 2 suggest that the occurrence of scintillation has been much more frequent during the spring equinox of 2005 than during the autumn equinox. Correspondingly, ROTI tend to occur during March and April in 2005 but not in September and October. Note that the mean solar flux F10.7 values are 88 and 84 respectively during the two equinoxes of 2005. Using Kototabang GPS observations, Otsuka et al. (2006) reported the scintillation occurrence is much higher in March–April than in September–October during 2003–2004. Sripathi et al. (2011) reported that the scintillations observed over India during 2004–2005 reveal an equinoctial asymmetry where scintillations have been noticed frequently during March–April. It has been suggested that a trans-equatorial wind could suppress the R–T instability and cause the equinoctial asymmetry in scintillation occurrence (e.g., Abdu et al., 2006). The trans-equatorial wind tends to push the F layer in the EIA upward along the magnetic field, and subsequently to push the conjugate F layer downward. This can increase the field line integrated conductivity and reduce the nonlinear growth rate of the R–T instability, thereby suppressing the ESF development. Using data obtained from a meridional ionosonde chain along 100°E, Maruyama et al. (2009) showed consistent evidence on the close relationship between the asymmetric meridional wind and asymmetric ESF/scintillation occurrence during the two equinoxes.

On the other hand, Fig. 2 shows that during the solar flux ascending and maximum years 2010–2012, there is not much difference in the occurrence of scintillation (and ROTI) during the two equinoxes. This may suggest that the extent of equinoctial asymmetry in scintillation occurrence reduces with solar activity. Meanwhile, a detailed analysis on the scintillation shows significant difference in the scintillation onset time between the spring and autumn months. Fig. 5 shows the scintillation pattern of 2010–2012. The onset time of scintillation on a given day is marked by black dot. The superposed white curve shows the local sunset time at 300 km altitude. The superposed red and white vertical dashed lines show the mean onset time of scintillations during autumn and spring months of 2011–2012, respectively. It can be seen from the figure that there exists a clear-cut difference in the initiation of scintillation during the two equinoxes of 2011–2012. The scintillation onset time in September–October is apparently earlier than that in March–April. A statistical analysis on the onset time of the scintillation shows that out of 40 (39) days with scintillations in September–October 2011 (2012), there are 18 (16) days when scintillations were initially observed before 1930 LT. However in March–April...
2011 (2012), only 4 (3) events were observed before 1930 LT out of a total number of 37 (31). As indicated by the vertical dashed lines, the mean onset time of scintillations during autumn months is about 25 min earlier than that in spring months.

Before the sunset, the linear growth rate for the R–T instability is small because of the high Pedersen conductivity in the ionospheric E region connected to the bottomside of the F region by magnetic field lines. Using the equatorial atmosphere radar multi-beam steering observations, Yokoyama et al. (2004) have shown that the ESF irregularities exclusively initiated near sunset. By examining the sunset time during the two equinoxes (as indicated by the white curve superposed in Fig. 5), the equinoctial asymmetry of sunset time is seen. The mean sunset time during autumn months is ~24 min earlier than that in spring months. As mentioned in the previous section, the post-sunset scintillations observed over Sanya during equinoctial months were generally produced by ESF irregularities. For the equinoctial asymmetry of scintillation onset time, there could be an apparent effect caused by the sunset time difference during the two equinoxes. Further, Fig. 6 shows the variations of the ionospheric $F_2$ layer peak height ($h_{\text{mF}_2}$) during the equinoctial months of 2011–2012. The bold curve shows the average value of the scatterplots. From the figure we may note that the evening increase of the average height appears perceivably larger (10–20 km) during spring equinox than in autumn months. The more striking feature is that the time when the maximum height appeared during evening hours (caused by the PRE) is obviously earlier in autumn months (red curve) as compared to that in spring months (blue curve). Since the PRE is produced by the interaction of the evening eastward thermospheric wind with the longitudinal E layer Pedersen conductivity that exists across the sunset terminator.
(Abdu, 1997), we believe that the equinoctial asymmetry of scintillation onset time and of PRE time could be caused by the sunset time difference during the two equinoxes.

Another notable feature shown in Fig. 5 is the large dispersion in the scintillation onset times from one day to the other during a given season. Some scintillation events are found to initiate around sunset, and others initiate after sunset about 2 h. Considering the scintillation measurements from GPS satellites cover a wide longitude region of about 10° (with the elevation angle of PRN > 30°), the onset time difference of scintillation during a specified season should be linked with the different location where the scintillation was initially generated. The onset time of scintillation observed at a given site, specifically for the scintillation events observed before ~2000 LT, could represent the time when the irregularities producing the scintillation are initially generated. On the other hand, for the scintillation events observed after sunset about several hours, for example around 2100 LT, the scintillations should be caused by the irregularities initiated on the western longitudes of Sanya and then drifted eastward.

Fig. 7 shows the spatial distribution of scintillation events (initiated before 2000 LT) during 2011–2012 in the azimuth–zenith polar plot. From the figure we can note that the scintillations (before 1900 LT) are more often generated at the eastside of Sanya during September–October. Recent observations by Li et al. (2013) also showed the occurrence difference of ESF associated irregularities at close-by longitude. They suggested that the difference was induced by the bottomside F region small-scale wave structures (several tens of kilometers), which serve as a seeding role for the R–T instability development.

3.3. Zonal drift of irregularity producing scintillation

Fig. 8 shows an example of temporal variation in the signal intensity and $S_4$ from a satellite (PRN 9) on the night of 24 October 2011. As shown in the left panels, strong
Signal intensity fluctuations were observed during 2000–2400 LT when scintillation occurred. The right top panel shows the signal intensity variations observed with the east (blue) and west receiver (green) at 2014–2015 LT. The right bottom panel shows the correlation function between the signal intensity observed by the two receivers. From the time delay of the maximum cross correlation of the signal intensity, the apparent drifts of irregularities in the magnetic east–west direction were calculated. We eliminated the ionospheric puncture point (IPP, assuming at 350 km) velocity due to GPS satellite motion and thus obtained the irregularity zonal velocity.

Fig. 9 shows the mean eastward velocity of irregularity producing scintillation ($S_4 > 0.2$) in spring and autumn months of 2011–2012. The data were sorted into 30-min segments and the standard deviations of the drift velocity at each segment were calculated, as presented as error bars in the figure. In general, a similar pattern of the mean eastward velocities during the two equinoxes, with maximum (∼150 m/s) occurring around 2100 LT and then decreasing with time (down to ∼70 m/s at 0100 LT), is found. The mean decrease rate is approximately 20 m/s. The decrease of the irregularity zonal drift (representative of the ambient plasma drift) is in agreement with earlier observations at equatorial and low latitudes (e.g., Muella et al., 2009). It is relevant to mention that the irregularity does not always drift toward east, especially during geomagnetic storm periods. Li et al. (2009) reported the decreasing of pre-midnight irregularity westward drift from 80 m/s to 30 m/s over Wuhan, China during the geomagnetic storm of 10 November 2004. Abdu (2012) has suggested that one of the possible mechanisms responsible for the westward drift could be the storm-time thermospheric disturbance wind that has westward component in the equatorial region. For the present dataset in 2011–2012, no irregularity with westward drift was found. In addition, it can be seen from the figure that there exists slight difference in the magnitude of zonal drift between the spring and autumn months of 2011–2012. The drifts of irregularities are 13 m/s larger during March–April than during September–October between 20 and 22 LT. This is consistent with previous studies from Otsuka et al. (2006), in which the mean eastward velocity in spring months is 20 m/s larger than in autumn months. The standard deviations of zonal drifts shown in Fig. 8 are 12–61 m/s with an average value of 36 m/s. The equinoctial asymmetry of the irregularity zonal drifts could be caused by the asymmetry of the neutral winds (Otsuka et al., 2006).

4. Summary and conclusions

We have investigated the statistical occurrence and characteristics of GPS ionospheric scintillation and its associated irregularity zonal drift over Sanya. For the statistics of scintillations and TEC fluctuations, and of irregularities zonal drifts, over 8 years of data (during July 2004–December 2012) and 146 days of data (during the equinoctial months of 2011–2012) have been used in the analysis, respectively. The main results are summarized as follows:

1. The statistical analysis on the solar activity and seasonal dependence of GPS scintillation and TEC fluctuation demonstrated a maximum during equinoctial months of solar maximum. The equinoctial asymmetry of scintillation occurrence, with a higher occurrence during March–April than during September–October, was observed in solar activity descending year 2005, but not in solar activity ascending and maximum years 2010–2012.

2. The mean eastward velocities of irregularities, calculated using two spaced receivers over Sanya during the equinoctial months of 2011–2012, range from 150 m/s at post-sunset to 70 m/s near midnight with a mean decrease rate of 20 m/s. The magnitude of the mean eastward velocity during the spring equinox is slightly larger than that of the mean drift measured in autumn months.
(3) Besides the scintillation occurrence with a maximum during equinoctial months of solar maximum, we have observed daytime periodic weak scintillations occasionally during the June solstice of solar minimum 2007–2008. No apparent TEC fluctuations were detected while the periodic scintillation occurred. Considering the high occurrence rate of Es irregularity observed during the June solstice over Sanya, the daytime scintillation could be caused by summer strong Es and its associated irregularities.

(4) The observations of the onset time of scintillation events during 2011–2012 revealed the scintillation in autumn months (September–October) were generally produced earlier than that in spring months (March–April). We suggest that the equinoctial asymmetry of scintillation onset time at a given site is mainly associated with the difference of sunset time between the two equinoxes.

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