Solar Cycle Variations of GPS Amplitude Scintillation for the Polar Region

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Abstract Global Positioning System (GPS) L1 amplitude data, obtained using the Canadian High Arctic Ionospheric Network (CHAIN) during the period 2008–2018, is used to study the seasonal and solar cycle dependence of high-latitude amplitude scintillation. The occurrence of amplitude scintillation is predominantly confined to the 10–18 magnetic local time (MLT) and 72–87° Altitude-Adjusted Corrected Geomagnetic (AACGM) sector and is a winter and equinoctial phenomenon. The occurrence of amplitude scintillation shows a clear seasonal and solar cycle dependence with a maximum value of ~11% during the high solar activity early winter periods, and a secondary maximum in equinoctial months, and almost no occurrence during summer months. This pattern in occurrence suggests that amplitude scintillation is a phenomenon that is closely associated with the presence of patches and particle precipitation events.

1. Introduction

Ionospheric scintillation, the stochastic variation observed in the amplitude and phase of transionospheric radio signals, is directly linked to plasma irregularities as they occur in the ionosphere (Aarons, 1997a; Hewish, 1952). Historically, the scintillation phenomenon was first observed in radio signals emitted by stars (Hey et al., 1946) and was eventually studied in detail using satellite radio beacons (Aarons, 1997a). Studies of scintillation occurrence and forecast have gained a great deal of interest due to the need to understand the impact of this phenomenon on Global Navigation Satellite System (GNSS)-based measurements, including the reduction in accuracy and/or complete loss of positioning ability (Kintner et al., 2007). From a more fundamental point of view, scintillation measurements provide a mean to unveil some of the physical mechanisms, including plasma instabilities responsible for the generation of ionospheric irregularities, which in turn cause the observed radio wave scintillation. By inference, scintillation studies may also lead to the determination of ionospheric irregularity parameters (Carrano et al., 2019).

Furthermore, ionospheric scintillation reveals substantial variability in time as it depends on various factors such as magnetic and solar activity (Basu et al., 2004). Studies have revealed that communication systems can be affected during periods of intense solar activity (Groves et al., 1997). Moreover, studies reported previously have shown that the ionospheric response to geomagnetic storms depends upon the season and the local time (Kashcheyev et al., 2018). Using very high frequency (VHF) amplitude scintillations recorded near the equatorial anomaly crest, a detailed study shows patterns related to magnetic storms (Singh et al., 2004). Under disturbed geomagnetic conditions, the scintillation occurrence is enhanced during summer months, while it is significantly inhibited at premidnight hours during equinoxes and winter. Similar results have been reported with 1.5 GHz scintillation in the equatorial region (Basu et al., 2004).

The wide deployment of Global Positioning System (GPS) receivers over the globe has enabled a thorough study of ionospheric morphology with a strong emphasis on the understanding of radio signal distortions. Global occurrence maps for total electron content (TEC) and phase variation index, over wide latitude and longitude regions, have been constructed using the GPS signal analysis (Akala et al., 2011; Alfonsi et al., 2011; Béniguel et al., 2009; Cervera & Thomas, 2006; David et al., 2016; De Franceschi et al., 2018). Measurements based on GPS receivers located at low to middle latitudes have shown that both $S_\Delta$ and $\sigma_\Phi$ indices are highly correlated (Moraes et al., 2017). However, a recent study has shown that fluctuations seen in the signal phase should be analyzed and interpreted with caution (McCaffrey & Jayachandran, 2019).

While the variations in signal phase are linked to the TEC, magnitude of $S_\Delta$ index relates among other factors, to the electron density variance as well to the geometrical considerations related to the irregularity.
Although a dependence on the ray scan velocity of the rate of change of TEC and $S_4$ has been discussed recently (Carrano et al., 2019), a definite relation between the $S_4$ and $\sigma_\phi$ indices has been established only under some assumptions (Fremouv, 1980).

At northern high latitudes, the most comprehensive occurrence statistics of phase-variation index ($\sigma_\phi$) has been reported by Prikryl et al. (2015) based on measurements by the Canadian High Arctic Ionospheric Network (CHAIN). The occurrence of phase variations clearly revealed seasonal as well as diurnal patterns with maximum occurrence during winter. The region of peak phase variations appeared near the dayside cusp and in the nightside auroral oval. These phase variations gradually amplify with solar activity. These results are in good agreement with studies reported by Jin et al. (2018) using GPS scintillation data from Ny-Alesund, Svalbard, located in the polar region (78.9°N, 11.9°E).

Most of the previous studies on the climatology of scintillation in the polar region have been based on GPS phase measurements (Jin et al., 2018; McGranaghan et al., 2018; Prikryl et al., 2015). This is primarily due to the fact that, in the high-latitude regions, the occurrence of phase fluctuations is believed to dominate that of amplitude scintillations (Moen et al., 2013; Spogli et al., 2009). Recent studies have suggested that this is due to an imprecise use of the detrending frequency (McCaffrey & Jayachandran, 2019; Mushini et al., 2012; Wang et al., 2018). An improper choice of the detrending frequency allows for variations in phase but not necessarily in amplitude. The fluctuations in the amplitude signal result from the presence of Fresnel-scale irregularities and therefore are caused by diffraction. Larger-scale irregularities only produce phase variations consistent with a refraction phenomenon. Consequently, phase variations in the refractive regime (with no amplitude variations) can be mitigated using the ionosphere-free linear combination (IFLC) of the L1 and L2 phase technique. On the contrary, variations in the signal phase in the diffractive regime (accompanied by amplitude scintillation) cannot be mitigated.

In the present work, we investigate the morphology of amplitude scintillations at high-latitude regions in order to understand the physics of ionospheric irregularities and to enhance our technical ability to deal with space weather applications and modeling. In this paper, we present for the first time morphology maps for the occurrence of GPS amplitude scintillation in the polar region for a full solar cycle. In section 2, the data analysis carried out in the present study is briefly described. The amplitude scintillation occurrence morphology is presented in section 3. The essential of results are discussed in section 4.

### 2. CHAIN and Data Reduction

The data used in this study were collected with GPS receivers of the CHAIN (Jayachandran et al., 2009). The network consists of 25 GISTMs/GPS receivers and 9 ionosondes located in Canada at high geographic latitudes covering regions between 56° and 80° (60–87° geomagnetic latitude). The network comprises of 15 Septentrion PolarxS Pro receivers that have been collecting data since 2013 and 10 NovAtel GSV4004B receivers collecting data since 2008. For the purpose of this study, we have chosen to use the data collected by the NovAtel receivers during the entire 24th solar cycle spanning from 2008 to 2018. This choice ensures the availability of data for the whole solar cycle and no potential biases due to instrumental differences.

The amplitude scintillation index $S_4$ was calculated from the detrended raw 50-Hz data. A standard sixth-order Butterworth filter with a cutoff frequency of $f_c=0.1$ Hz was used for the detrending, and the scintillation index was calculated over 1-min periods. Satellite links with elevation angles smaller than 30° were excluded to minimize multipath effects. Scintillation indices were projected to the vertical in order to account for the varying ionospheric contribution to scintillations due to geometrical effects at different elevation angles. The projection uses the method described in Spogli et al. (2009). The satellite Ionospheric Pierce Points (IPPs) were estimated at an altitude of 350 km as it is believed that most of the high-latitude scintillations are caused by irregularities at the $F$ region peak altitude (Basu et al., 1978; Bjøland et al., 2016), although the production of scintillation at a lower altitude cannot be ruled out (Deshpande et al., 2016). The amplitude scintillation index ($S_4$) is computed according to the following expression:

$$S_4 = \sqrt{\langle (SI)^2 \rangle - \langle SI \rangle^2} / \langle SI \rangle,$$  \hspace{1cm} (1)

where $SI$ is the signal intensity. A particular attention has been paid to cleaning the data before the detrending process. First, cycle slips have been identified and excluded from the data selection. Data
collected after power outages were ignored in order to account for the operation recovery inherent to NovAtel receivers. In addition, measurements collected from stations experiencing occasionally Iridium interference have been excluded from the analysis. The locations of GPS stations used in the present study are shown in Figure 1.

3. Results

The magnetic local time (MLT) and the Altitude-Adjusted Corrected Geomagnetic latitude (AACGM) (Shepherd, 2014) representation is used to display the scintillation occurrence map; bins of 1 hr in MLT and 2.5° in AACGM are used to generate the maps. The left panel of Figure 2 shows the number of data points in each bin for the period 2008–2018. This panel shows that there are enough data points in each bin to provide statistically significant information about the frequency of amplitude scintillation events. Given a relatively high elevation mask chosen in the study, maximum IPP coverage occurs at latitudes corresponding to the location of the bulk of GPS receivers. However, the IPP distribution is nearly isotropic in terms of the MLT indicating no particular bias with respect to time. Next, the scintillation occurrence rate is determined as follows: the ratio between the number of $S_4$ values above the threshold level and the total number of $S_4$ values that fall into 1 hr MLT–2.5° magnetic latitude (MLAT) sector.

The occurrence rate of amplitude scintillation index $S_4>0.1$ is shown on the right panel of Figure 2. This threshold might be considered relatively high as the scintillation amplitude at northern latitudes tends to be smaller when compared with lower-latitude regions. The background noise for most of the CHAIN stations, obtained from probability distributions of $S_4$ index, is around $\sim0.07$; using a threshold of 0.1 reduces the likelihood that events can be attributed to the thermal noise fluctuations. Figure 2 clearly shows that most of the scintillation events are confined to the 10–18 hr MLT and 72.5–87.5° AACGM sectors; occurrence peak can be localized at 75–77.5° latitude.

In order to demonstrate the seasonal and solar cycle variations, the monthly average occurrence rate of amplitude scintillation for the period from January 2008 to December 2018 is shown in Figure 3. As can be seen, most of the amplitude scintillation activity was confined to the time interval greater than 10 hr MLT and less than 18 hr MLT during winter and equinoxial months of higher solar activity period (between 2011 and 2015). The highest scintillation activity was 11% during the month of November of 2011 and 2015. Both maxima correspond to periods of higher solar activity. Furthermore, the polar scintillation activity varies during the winter and is noticeably reduced between December and January for specific MLT sectors depending upon the solar cycle phase. Precisely, scintillation level remains below the threshold during the whole month of December 2012 for all MLT. Also, the scintillation level drops below the threshold

Figure 1. Location of CHAIN GPS stations used for the present work.
after 17 hr MLT in December 2013, after 15 hr MLT in January 2014, and after 18 hr MLT in January 2015. We finally emphasize that the scintillation activity in the polar region remained negligible during the summer season. We emphasize that the fluctuations in $S_4$ of thermal origin have been carefully examined, and we have found that they remain insignificant.

A precise illustration of the connection of the solar activity with the scintillation occurrence is shown on Figure 4. The monthly average occurrence rate of amplitude scintillation in the 11–14 MLT and 75.5–82.5° sectors are determined along with 81-day average solar flux index ($F_{10.7}$), as shown in Figure 4. There is a clear dependence of the amplitude scintillation occurrence on the solar activity. According to our knowledge, this is the first reported result indicating the solar activity dependence of $L_1$ amplitude scintillation for the polar region. Scintillation events occur mostly during the solar maximum phase.

The effect of geomagnetic activity on the amplitude scintillation occurrence rate is examined now. For this purpose, the disturbance storm time index ($D_{st}$) is used as an indicator of geomagnetic activity; whenever the $D_{st}$ index drops below $-40$ nT, the full day is considered to be disturbed (Loewe & Prölss, 1997). Minor

Figure 2. Amplitude scintillation occurrence distribution as a function of MLAT-MLT for the period 2008–2018. (left panel) Number of data points. (right panel) Occurrence rate of amplitude scintillation ($S_4 > 0.1$). In each panel, the radial lines from the pole represent the magnetic longitudes while the circles indicate the magnetic latitudes.

Figure 3. Occurrence rate of amplitude scintillation ($S_4 > 0.1$) as a function of magnetic local time and season during the 24th solar cycle. For clarity, occurrence rate less than 1% are shown in white.
changes in the resulting scintillation map are noticed when a threshold value of $D_{st} = -50$ nT is considered. In using this criteria, almost 25% of the data are collected during disturbed periods. As shown on Figure 5, the scintillation occurrence distribution during quiet times (left panel) is very similar to the one determined for the entire analyzed period (right panel of Figure 2). This is expected as the number of quiet time events exceeds that of the disturbed times.

For geomagnetically active days, the development area of scintillation activity spreads to lower latitudes while remaining relatively restricted in the same MLT sectors.

4. Summary and Discussion

GPS $L_1$ amplitude measurements obtained by CHAIN during the 24th solar cycle (2008–2018) are used to determine for the first time a thorough distribution of amplitude scintillation occurrence rate over a wide range of polar regions including the auroral oval, the cusp and the polar cap. The constructed maps clearly

Figure 4. Amplitude scintillation occurrence rate (blue) and 81-day average $F_{10.7}$ solar flux (orange) during the period 2008–2018.

Figure 5. Occurrence rate of amplitude scintillation ($S_4 > 0.1$) as a function of MLAT/MLT for (left) geomagnetically quiet days ($D_{st} \geq -40$ nT) and (right) geomagnetically disturbed days ($D_{st} < -40$ nT).
indicate the scintillation occurrence peaks within a narrow region between 75° and 82.5° MLAT and around noon MLT in AAGCM coordinates with a noticeable prenoon-postnoon asymmetry (Figure 2). In particular, the amplitude scintillation index on the nightside tends to remain below the threshold level. During disturbed geomagnetic conditions, the occurrence rate peaks shift below ~70° MLAT bin while remaining within the same MLT sectors (Figure 2). In addition, amplitude scintillation indices with \( S_4 > 0.1 \) are rare in summer and during the increasing and decreasing phases of the solar cycle (Figure 4).

The location of the higher occurrence rate strongly suggests that the ionospheric effects on \( L_1 \) signal mostly take place near the cusp region and in adjacent polar cap sectors. It is now well established that, at ionospheric altitudes, the MLAT of the cusp is located at 79° latitude under quiet geomagnetic conditions and shifts to 74° during disturbed periods (Stasiewicz, 1991). The cusp's position is consistent with the ionospheric footprint of the outermost magnetic field lines of the magnetosphere for which the magnetic cusp is located at 12 MLT in the AAGCM coordinates system (Stasiewicz, 1991). Moreover, the poleward and equatorward extension might be associated along with auroral oval during substorms. A similar broadening of the signal phase variations during magnetic storms have been reported (Aarons, 1997b).

The spatial region, where the highest scintillation activity is produced, strongly indicates that the cusp region represents a major place where \( L_1 \) Fresnel size structures are formed. Plasma patches produced near the cusp region, and potentially structured by the particle precipitation, might be considered the main cause of GPS \( L_1 \) scintillation. Particularly, changes in electron density resulting from electron precipitation parallel to the magnetic field, leading at the same time to the formation of small plasma structures. Based on the Defense Meteorological Satellite Program (DMSP) particle data, previous studies reported enhanced electron energy fluxes of the order 200 eV caused by precipitation and seen at the cusp, particularly when the interplanetary magnetic field (IMF) components \( B_x < 0 \) and \( B_y < 0 \) (Newell et al., 2004). Within this hypothesis, the lack or low occurrence of amplitude scintillation during summer periods raises questions. One possible explanation stipulates that during northern high-latitude summer, sufficiently large electron density gradients, resulting from precipitation, may be inhibited by the continuous and a constant exposure to sunlight leading to enhanced ionization on both daytime and nighttime sectors. In winter, on the contrary, the electron density changes occur mostly in the cusp region and possibly poleward at the edge of the polar cap. Regardless, the present results seem to be in a good agreement with a recent study from on board receivers on Swarm satellite, which show that the strongest GPS outages are associated with plasma patches based inside the cusp (Xiong et al., 2019).

The significant enhancement in scintillation activity in the 13–18 MLT sectors might result from the difference in electron density between the dawn and dusk convection cells. The structured plasma is expected to follow the convection pattern and move poleward across the polar cap while possibly dissipating and becoming less structured by the time it reaches the nightside. Moreover, the scintillation map obtained during geomagnetically disturbed conditions shows no evidence for a significant change in local time of the occurrence rate except that the area of activity extends to lower latitudes. Although a detailed investigation is needed, these results appear to contrast with findings on scintillation occurrence at low latitudes during disturbed periods (Kashcheyev et al., 2018; Tulasi Ram et al., 2008).

A striking feature in the present report is the reduction in the scintillation occurrence and the confinement of the peak location observed in December and January. The significantly weak scintillation level can occur for a whole month as in December 2013 when the solar flux remains moderately low. This finding can be linked to a GPS TEC survey work previously reported by David et al. (2016) that shows the existence of a "hole" corresponding to tongue to background ratio in the polar cap reaching unity, signifying the lack of patches between 05 and 12 UT during winter days. These observations confirm the results of a numerical simulation of polar patches formation reported earlier by Sojka et al. (1994). Based on their findings, David et al. (2016) ruled out the role of the cusp as a source origin in the formation of ionospheric polar patches as it is expected that plasma precipitation (through the cusp) is season independent.

Remarkably, the present report suggests that \( L_1 \) amplitude scintillation remains weak in the nightside auroral oval region independently of the solar cycle or season. This result appears to contrast to some extent to earlier findings by MacDougall (1990). They found that a significant amplitude scintillation in the nightside auroral oval is seen with signal frequencies that are much smaller than the \( L_1 \) frequency. However, one should mention that the \( S_4 \) index values obtained in the present study are expected to be significantly
smaller (Yeh & Liu, 1982). Furthermore, one cannot exclude the possibility that the noise level of the CHAIN instruments can be higher than the fluctuations caused by the ionospheric diffraction on the nightside. Regardless, it seems that the scintillation cannot be considered as a threat to GNSS systems at high latitudes.

Finally, one should note the striking difference between the $S_A$ and $\sigma_\phi$ distribution occurrence rate for the polar region. Previous studies show significant phase variations in the nightside auroral oval and polar cap (Prikryl et al., 2015). Particularly, the signal phase variations are enhanced during geomagnetically disturbed days. The present report shows that the occurrence rate of amplitude scintillation is ∼20 times lower than the occurrence rate of phase fluctuations. At the same time, the amplitude scintillation remains absent in the nightside. Since radio signals suffer changes in amplitude mainly due to the presence of Fresnel-scale irregularities, it seems that high $\sigma_\phi$ values associated with the nightside auroral oval as well as with sectors of the nightside polar cap result from large-scale irregularities in which the refraction process constitutes the dominant effect on the signal. This explanation could be related to a recent study reported by McCaffrey and Jayachandran (2019) showing that rapid variations observed in GPS phase signals can be removed when the IFLC of the $L_1$ and $L_2$ phase technique is performed. Commonly, the IFLC technique is used to eliminate the refraction effects of the ionosphere.

**Data Availability Statement**

Through https://www.spaceweather.gc.ca/solarflux/sx-5-en.php link, Natural Resources Canada provides the daily solar radio flux values. The Dst index data are provided by the Geomagnetic Data Service link http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html. Infrastructure funding for CHAIN was provided by the Canadian Foundation for Innovation and the New Brunswick Innovation Foundation. CHAIN operations are conducted in collaboration with the Canadian Space Agency. CHAIN data are available through http://chain.physics.unb.caCHAIN data.

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