High Latitude Climatology of the Phase and Amplitude Fluctuations in GPS Signals

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November 23, 2022

Abstract

Electromagnetic waves propagating through the Earth's ionosphere are subjected to changes in group and phase velocities, refraction, dispersion, and diffraction. For systems like GPS, which relies on the usage of L-band signals, rapid and random fluctuations in the phase and amplitude (known as scintillation) of the signals passing through the ionosphere play a major role, as they may cause losses of lock and result in degrading the accuracy and reliability of such systems. Therefore, understanding the physical nature and ability to predict the scintillation has been a challenge since a long time for engineers and scientists. In this work, a climatological model of rapid random fluctuations in phase and amplitude of GPS signals has been presented for high latitudes of the northern hemisphere. The 50Hz GPS raw data from Canadian High Arctic Ionospheric Network (CHAIN) for the 24th solar cycle (2008-2019) have been used to study the climatology of the rapid fluctuations in phase and amplitude of the GPS signals. The statistical analysis has been performed in terms of phase and amplitude scintillation indices (?? and ?4). The results are presented for different geo- and helio-physical conditions, including solar and geomagnetic activity, season, local time and geographical/geomagnetic location of ionospheric pierce points. For the first time, the distribution of the signal phase and amplitude fluctuations are presented for the whole period of the 24th solar cycle. An important quantitative statistical relation of the phase and amplitude fluctuations in GPS signals have been established for the high latitude region. A theoretical explanation is suggested for the observed differences in phase and amplitude fluctuations.

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Canadian High Arctic Ionospheric Network

Abstract

Electromagnetic waves propagating through the Earth's ionosphere are subjected to changes in group and phase velocities, refraction, dispersion, and diffraction. For systems like GPS, which relies on the usage of L-band signals, rapid and random fluctuations in the phase and amplitude (known as scintillation) of the signals passing through the ionosphere play a major role, as they may cause losses of lock and result in degrading the accuracy and reliability of such systems. Therefore, understanding the physical nature and ability to predict the scintillations has been a challenge since a long time for engineers and scientists. In this work, a climatological model of rapid random fluctuations in phase and amplitude of GPS signals has been presented for high latitudes of the northern hemisphere.

The 50Hz GPS raw data from Canadian High Arctic Ionospheric Network (CHAIN) for the 24th solar cycle (2008-2019) have been used to study the climatology of the rapid fluctuations in phase and amplitude of the GPS signals. The statistical analysis has been performed in terms of phase and amplitude scintillation indices (σ_φ and S_4). The results are presented for different geo- and helio-physical conditions, including solar and geomagnetic activity, season, local time and geographical/geomagnetic location of ionospheric pierce points.

For the first time, the distribution of the signal phase and amplitude fluctuations are presented for the whole period of the 24th solar cycle. An important quantitative statistical relation of the phase and amplitude fluctuations in GPS signals have been established for the high latitude region. A theoretical explanation is suggested for the observed differences in phase and amplitude fluctuations.

Motivation

- To understand the climatology of the high latitude GPS amplitude scintillation and phase fluctuations and their dependence on different geo- and helio-physical conditions
- To identify the most probable sources of high latitude scintillation, their geographical, local time and seasonal distribution
- To estimate and quantify the occurrence rate of amplitude scintillation with respect to phase fluctuations
- To construct an empirical model of high latitude L1-band amplitude scintillation and phase fluctuations

CHAIN

The Canadian High Arctic Ionospheric Network (CHAIN) is an array of ground-based radio instruments deployed in the Canadian Arctic and operated by the University of New Brunswick. The network consists of 25 GNSS Ionospheric Scintillation and TEC Monitor (GISTM) receivers and 9 CADI ionosondes located at high latitudes spanning between 56˚ and 80˚. The CHAIN instrument components consist of 10 NovAtel GSV4004B and 15 Septentrio PolaRxS dual frequency GNSS receivers collecting phase and amplitude data of the tracked GNSS signals at a rate of 50 or 100 Hz. GNSS data have been routinely collected and stored at the University of New Brunswick starting from 2008 (2015) for NovAtel (Septentrio) receivers. The existing full dataset represents the full 24th solar cycle period.

Data processing

GPS L1 phase and signal intensity raw data with 50 Hz sampling rate have been used to calculate phase fluctuations and amplitude scintillation indices σ_φ and S_4. A standard sixth order Butterworth filter with cutoff frequency of 0.1 Hz was used to remove low frequency fluctuations. Scintillation indices were computed over one-minute time intervals and corrected for geometrical effects using the following formula (Spogli et al., 2009):

$$S_{4\,COR} = S_4/F(\theta)^{0.9} \qquad \sigma_{\varphi\,COR} = \sigma_\varphi/F(\theta)^{0.5} \qquad F(\theta) = 1\Big/\sqrt{1-\left(\frac{R_e\cos\theta}{R_e+H_{IPP}}\right)^2}$$

Data from nine NovAtel receivers for the period from 2008 to 2018 have been selected for the current study. To minimize effects of multi-path on the obtained results, elevation mask of 30˚ has been applied to data, leaving out a significant amount of satellite-to-receiver links. Particular care has been taken to cleaning the data before detrending process, i. e. identifying and excluding from the analysis cycle slips and ignoring data after instrument power outages in order to account for the reference clocks warm-up periods, identifying and correcting sudden jumps in amplitude data inherent to NovAtel receivers.

Scintillation occurrence

To study latitudinal and local time distribution of scintillation activity, phase fluctuations and amplitude scintillation occurrence rates (σ_φ > 0.1 and S_4> 0.1) have been calculated using data set ranging from year 2008 to 2018 and consisting of ~30M satellite-to-ground links. The choice of 0.1 as a threshold is based on the background noise levels of σ_φ and S_4 that was estimated for the selected GPS receivers using probability distribution functions of the corresponding quantities. For visualization purposes, coordinates of ionospheric pierce points were computed in the Altitude-Adjusted Corrected Geo-Magnetic (AACGM; Shepherd, 2014) coordinate system considering the thin shell height of 350 km. All data points were binned into bins of 1 hour in magnetic local time (MLT) and 2.5˚ in magnetic latitude (MLAT) size and plotted in form of maps.

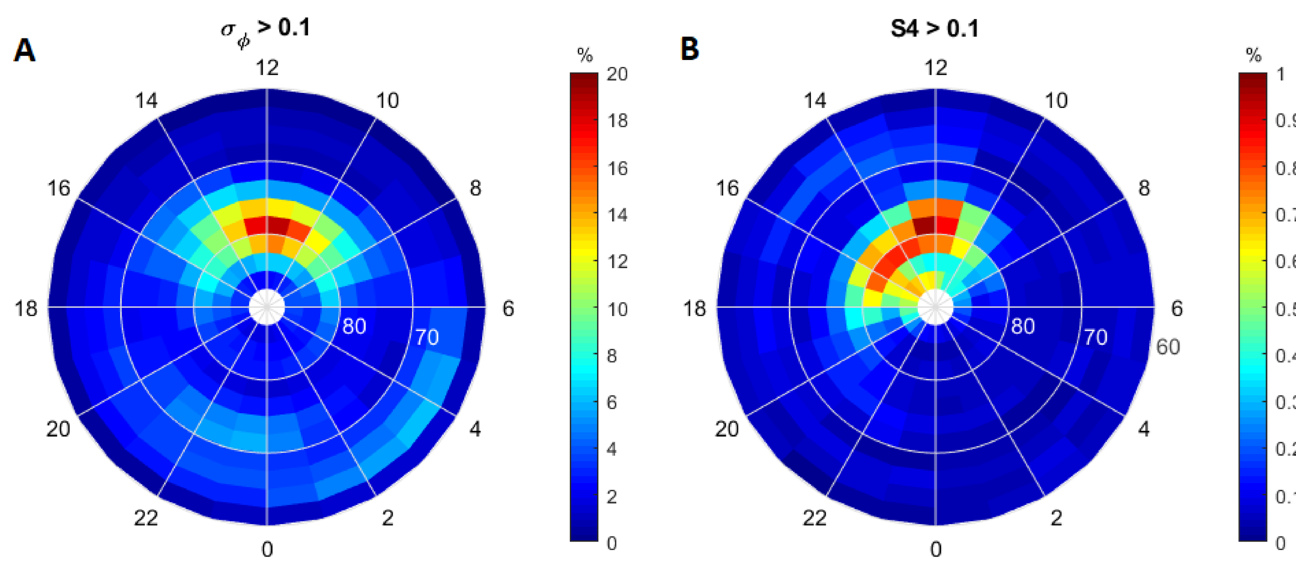


Figure 1. Phase fluctuation (A) and amplitude scintillation (B) occurrence rate distribution as a function of MLAT/MLT for the period 2008-2018. Note the different dynamic ranges for σ_φ and S_4.

Solar cycle fluctuations

To demonstrate the solar activity level dependence, phase fluctuations and amplitude scintillation occurrence rates are calculated for the sector confined to 11-14 MLT and 75˚ to 82.5˚ MLAT, where maximum amplitude scintillation activity occurs (see Figure 1). Blues curves in Figure 2 show phase fluctuation occurrence rate (σ_φ > 0.1) on left panel and amplitude scintillation occurrence rate (S_4> 0.1) on right panel. Orange curves on both panels show the variation in solar activity level, 81-day running average F10.7 index. As can be seen on the plots, both phase and amplitudes scintillation occurrence rates increase with the solar activity level. At the same time, both have significant seasonal fluctuations not present in F10.7 variations.

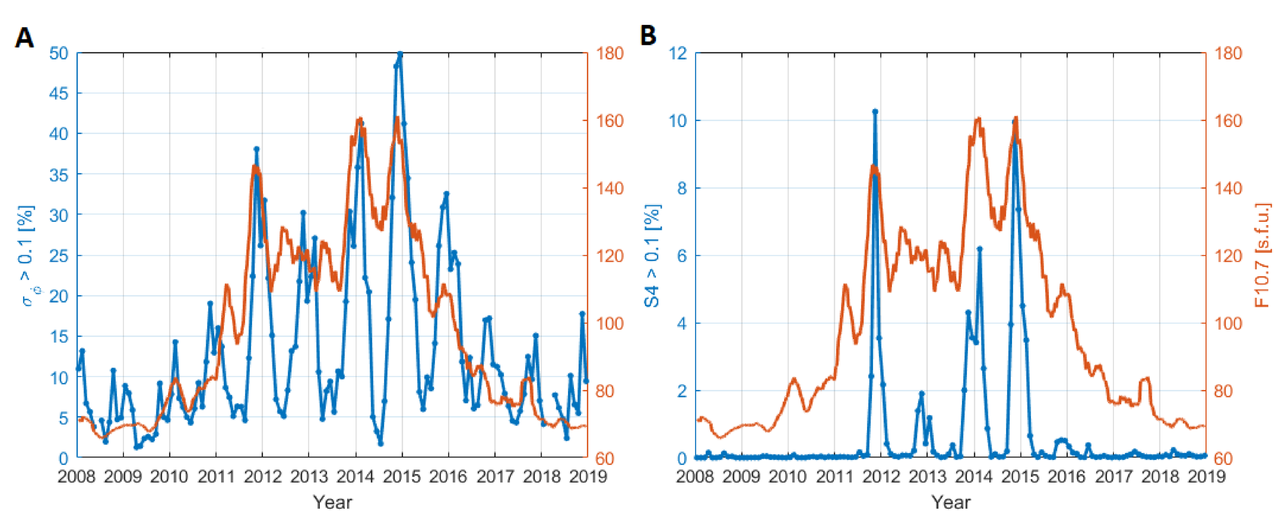


Figure 2. Phase fluctuation (A) and amplitude scintillation (B) occurrence rate in 11-14 MLT and 75˚ to 82.5˚ MLAT sector as a function of time for the period 2008-2018. On both panels, orange curves show fluctuation of 81-day running average F10.7 index.

Local time/seasonal variations

In order to understand the local time and seasonal dependence, monthly occurrence rates of phase fluctuations and amplitude scintillations (σ_φ > 0.1 and S_4> 0.1) are presented as a function of MLT and month in Figure 3.

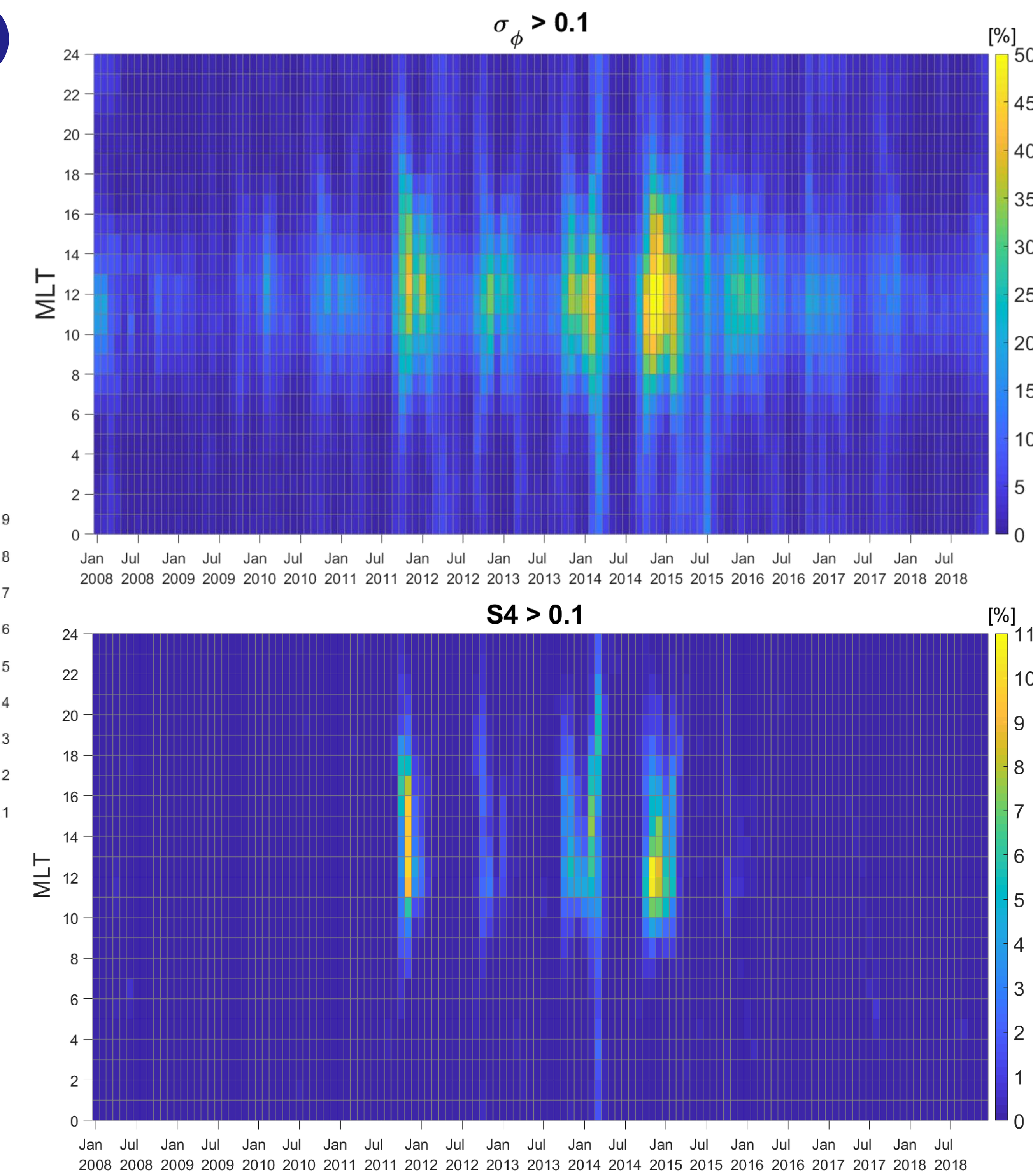
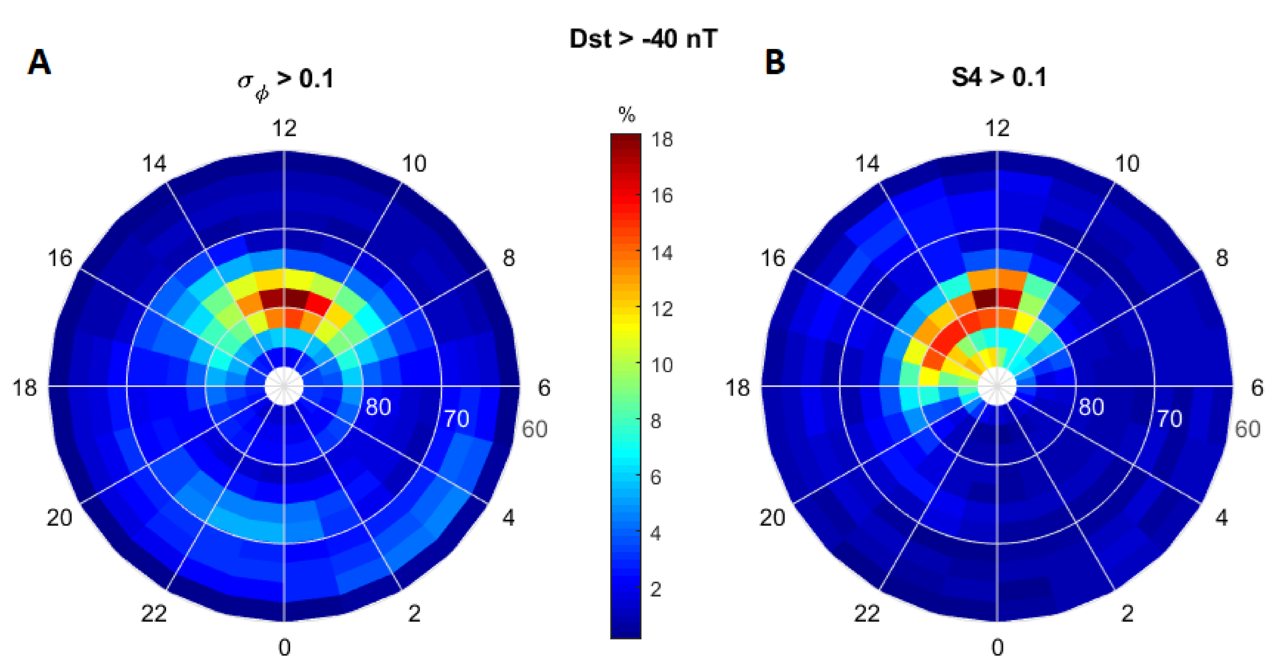


Figure 3. Phase fluctuation (top panel) and amplitude scintillation (bottom panel) occurrence rate (σ_φ > 0.1 and S_4 > 0.1) as a function of MLT and month for the period from 2008 to 2018. Note the different dynamic ranges for σ_φ and S_4.

Geomagnetic activity dependence

To study the behavior of phase fluctuations and amplitude scintillation in GPS signals with respect to the geomagnetical activity level, all data set has been split into two subsets. Days with the Dst index lower than -40 nT have been considered to be geomagnetically disturbed, all the other days were marked as geomagnetically quite time. The distribution of the occurrence rates (σ_φ > 0.1 and S_4> 0.1) are presented as a function of MLAT/MLT for two subsets in Figure 4.



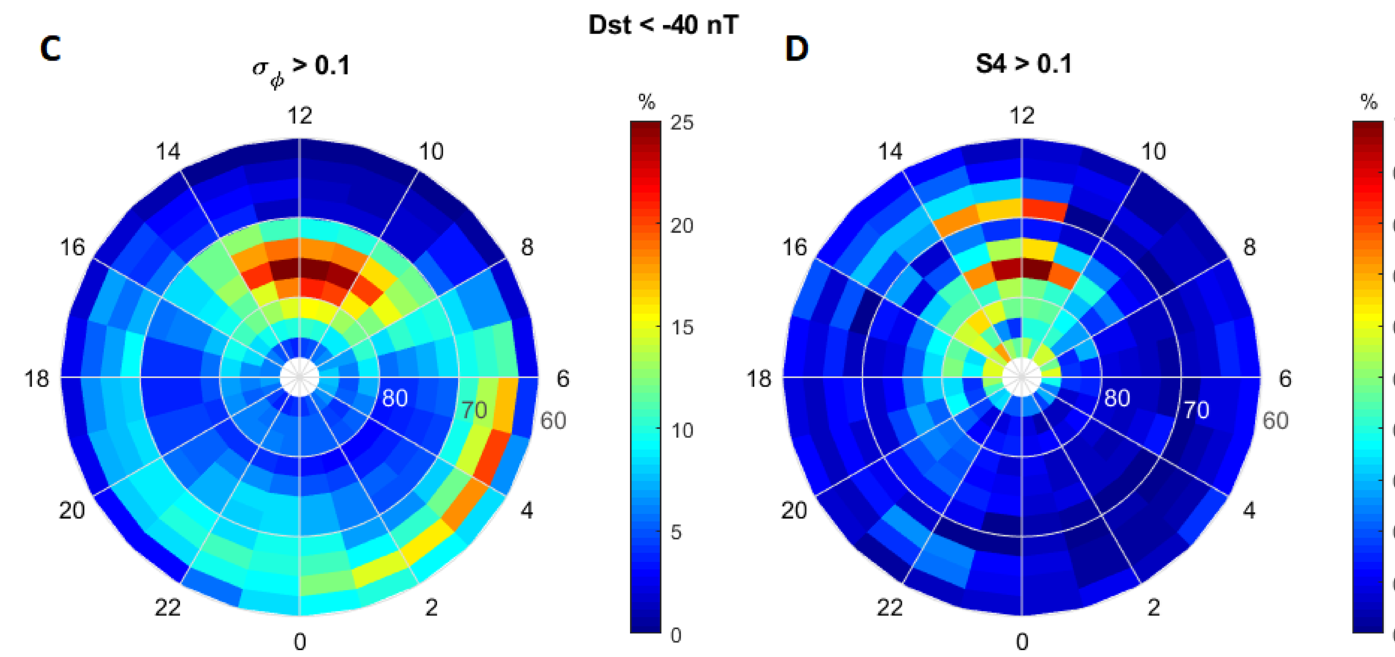


Figure 4. Phase fluctuation and amplitude scintillation occurrence rate distribution as a function of MLAT/MLT for the geomagnetically quite periods (Dst > -40 nT) during 2008-2018 on A and B; and during geomagnetically disturb periods (Dst < -40 nT) on C and D.

Discussion

The presented maps demonstrate clearly that the peak of phase fluctuation (σ_φ) and amplitude scintillation (S_4) activities is confined in 75˚ to 82.5˚ MLAT area around noon MLT with an asymmetrical displacement towards post-noon hours in S_4. At the same time, the phase fluctuation level has an evident increase in the night-side auroral oval, that can not be seen in amplitude scintillation. It might be explained by the selected threshold (S_4 > 0.1) considered in this study. From another hand, the noise level in the amplitude data caused by multi-path and thermal noise of the instruments does not allow to significantly change this threshold.

Both $\sigma_\varphi$and S_4 occurrence rates follow the solar activity level. The clear seasonal variation in σ_φ and S_4 shows that scintillation are predominant in winter and equinoctial month and are not seeing (or seeing at a significantly lower levels) in summer-time. This fact suggests strongly that amplitude scintillation are attributed mainly to ionospheric structures with big gradients (e.g. patches or poleward moving auroral forms) and not to cusp region precipitation. However, further studies have to be performed in order to verify the suggested mechanism.

Conclusions

- Climatology of the GPS amplitude scintillation and phase fluctuations in high latitudes during the 24th solar cycle has been presented for the first time;
- Occurrence rate of amplitude scintillation in high latitudes is of an order of magnitude less than that of phase fluctuations and overall does not exceed 1% of the total time during 24th solar cycle;
- Most of the amplitude scintillation occur during winter-time around noon time, that are related to ionospheric structures with high gradients (e.g. patches or poleward moving oval forms);
- Further analysis must be performed in order to study latitudinal and local time behavior of the scintillation occurrence rate as a function of interplanetary magnetic field and solar wind characteristics.

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