GPS Phase Scintillation and HF Radar Backscatter Occurrence in the High-Latitude Ionosphere

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Abstract

The Canadian High Arctic Ionospheric Network (CHAIN) of ten dual-frequency GPS receivers has been operating since 2008. One-minute amplitude and phase scintillation indices and total electron content (TEC) are computed from data sampled at 50 Hz. The climatology of GPS phase scintillation for 2008-2009 [1] is updated to include year 2010 as the solar activity gradually increases and more coronal mass ejections impact the geospace. As a function of magnetic local time and geomagnetic latitude, the phase scintillation predominantly occurs in the cusp and the nightside auroral oval. The auroral phase scintillation shows an expected semiannual oscillation with equinoctial maxima known to be associated with aurorae, while the cusp scintillation is dominated by an annual cycle maximizing in autumn-winter. Depletions of the mean TEC are identified with the statistical high-latitude and mid-latitude troughs. Scintillation-causing irregularities may coexist with small-scale field-aligned irregularities detected as HF radar backscatter. The occurrence climatology of phase scintillation and of the HF backscatter at high latitudes are compared.

1. Introduction

The Canadian High-Arctic Ionospheric Network (CHAIN) is an array of Global Positioning System (GPS) receivers and ionosondes [2] for studying ionospheric structure at high temporal resolution and horizontal spatial scales from 1000 km down to a few hundred meters at high latitudes. Such structuring gives rise to irregularity causing scintillation, rapid fluctuations of radio signal amplitude and phase that may affect performance of radio communication and navigation systems. In this paper the data from the first three years of CHAIN operation contribute to the climatology of phase scintillation at high latitudes under solar minimum conditions. The results are supported by a statistical analysis of occurrence of F-region decameter irregularities monitored with HF radars of the SuperDual Auroral Radar Network (SuperDARN) and by magnetometers recording the perturbation of the ground magnetic field due to ionospheric currents.

2. Instruments and Data

The current CHAIN instruments [2] are ten specialized GPS receivers and six Canadian Advanced Digital Ionosondes (CADIs) distributed in the auroral oval and the polar cap (Fig. 1a). The CHAIN GPS receivers are the GPS Ionospheric Scintillation and TEC monitors (GISTM) GSV 4004B. GISTM consists of a NovAtel OEM4 dual frequency receiver with special firmware specifically configured to measure and record power and phase of the GPS L1 signal at high sampling rate (50Hz). The receiver computes ionospheric TEC (total electron content) from the GPS L1 and L2 signals. The GSV 4004B can also automatically compute and log the amplitude scintillation index, *S4*, which is the standard deviation of the received power normalized by its mean value, and the phase scintillation index σ_φ, the standard deviation of the detrended phase using a filter in the receiver with 0.1 Hz cutoff. This receiver is capable of tracking and reporting scintillation and TEC measurements simultaneously from up to 10 GPS satellites in view [2]. The collected GPS and CADI data are transferred to the University of New Brunswick CHAIN data center in near real time using satellite links (TELESAT – Ka Band). Data can be accessed and displayed through an interactive interface available at http://chain.physics.unb.ca/chain.

The Super Dual Auroral Radar Network (SuperDARN) is a network of coherent-backscatter HF radars with field of view covering a large fraction of the high-latitude ionosphere [3]. The main objective of SuperDARN is to study ionospheric convection (electric fields) by observing the backscatter from FAIs, which drift in the **E**×**B** direction, where **E** and **B** are electric and magnetic fields, respectively. The Saskatoon radar field of view covers the entire high-latitude portion of CHAIN. The data from the Saskatoon (MLAT 61.34° N) radar beam no. 8 pointing over Hall Beach and Pond Inlet are used in this study.

3. TEC and Phase Scintillation Climatology

As a result of the coupling between the solar wind and the magnetosphere/ionosphere system, TEC and phase scintillation are functions of magnetic local time and geomagnetic latitude. To construct TEC and phase scintillation maps data have been ordered and binned by magnetic local time (MLT) and the Altitude Adjusted Corrected Geomagnetic (AACGM) latitude [4]. Assuming IPPs at 350 km altitude, the data are merged and the indices averaged into bins of 1 hour MLT × 2.5˚ CGM latitude. Before averaging, the observed 60-s slantTEC values and phase scintillation indices are projected to the vertical, to account for varying elevation angles as discussed in [5]. An elevation cutoff of 30˚ and a threshold of 0.1 radians are used to obtain the percentage occurrence of phase scintillation. The scintillation occurrence is defined $100\times N(\sigma_\varphi > 0.1) / N_{tot}$, where N is the number of cases when phase scintillation index exceeded a given threshold and N_{tot} is the total number of data points in the bin. Following the approach in [5], we adopt the same criterion to remove the contribution of bins for which $R = 100\times\sigma(N_{tot}) / N_{tot}$ is greater than 2.5%, where $\sigma(N_{tot}) = \sqrt{N_{tot}}$ is the standard deviation of the number of data points in each bin.

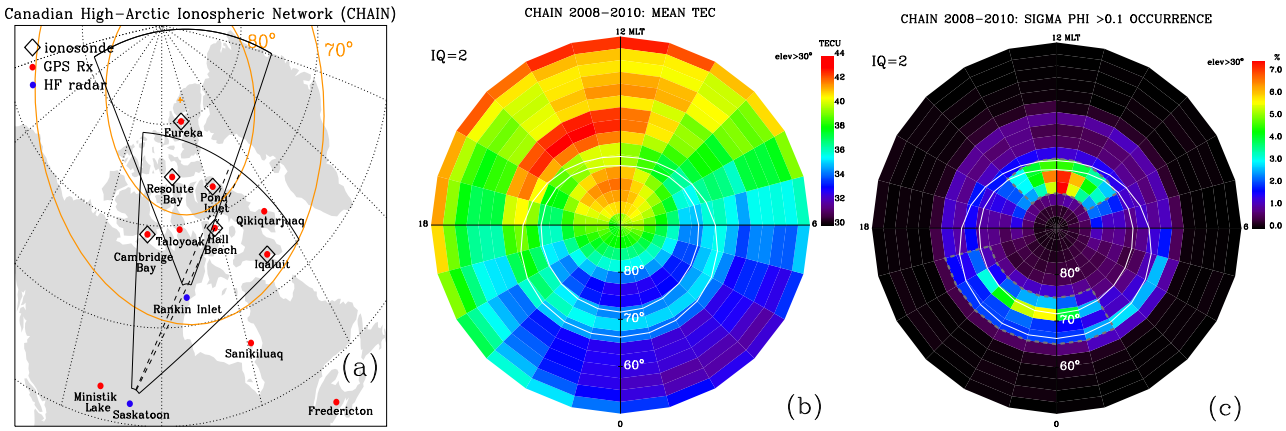

Figure 1. (a) Canadian High Arctic Ionospheric Network (CHAIN). The CGM latitudes 70° and 80° and fields of view of two SuperDARN radars are superposed over the geographic grid. Beam no. 8 for the Saskatoon radar that is used in the statistical study is shown with dashed line. Maps of **(b)** mean TEC and **(c)** phase scintillation occurrence, as a function of MLT and CGM latitude. Superposed in white line is the Feldstein oval for IQ=2.

Figures 1b and 1c show the maps of mean TEC and the percentage occurrence of phase scintillation with σ_φ exceeding 0.1 radians as a function of MLT and CGM latitude. Superposed on the maps are the boundaries of the Feldstein statistical auroral oval for quiet conditions (IQ=2) [6]. As expected, the dayside TEC is enhanced but varies with latitude and MLT. The mean TEC (Fig. 1b) is highest at latitudes less than 55˚, peaks also at dayside subauroral (~70˚) latitudes, and is enhanced from the cusp/cleft region to the polar cap (poleward of ~75˚). These regions are separated by mean statistical troughs, namely the main (mid-latitude) trough [7] centered at ~60˚ and the mean high-latitude trough at ~75˚ CGM latitude, that are deepest just after midnight and that weaken towards noon. The occurrence of phase scintillation is enhanced in the cusp/cleft (hereafter referred to as "cusp") and in the nighttime auroral oval indicated by dashed sectors (Fig. 1c). Asymmetry about magnetic local noon and midnight is observed: there is higher occurrence of phase scintillation in pre-noon and pre-midnight hours.

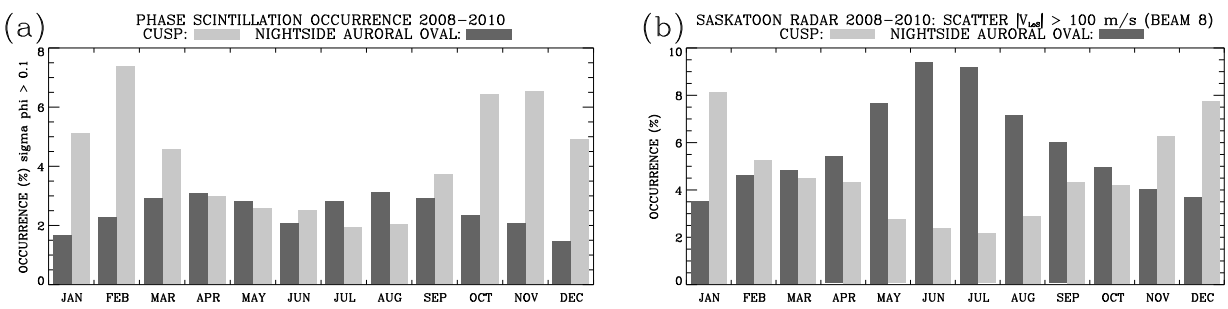

Figure 2. Seasonal variation in the cusp and nightside auroral oval of the occurrence of **(a)** phase scintillation $\sigma_\varphi > 0.1$ radians, and **(b)** the F-region ionospheric radar backscatter with LoS velocity exceeding 100 m/s .

To examine the seasonal variation of the scintillation occurrence in the cusp and auroral oval, the data were grouped by months and averaged over two sectors defined by CGM latitude and MLT as indicated by grey dashed sectors in Fig. 1c. Figure 2a shows the seasonal variations of phase scintillation occurrence in the cusp and nightside auroral oval. The auroral scintillation shows a typical semiannual oscillation with equinoctial maxima known to be associated with aurorae. In the cusp, phase scintillation is dominated by the annual cycle.

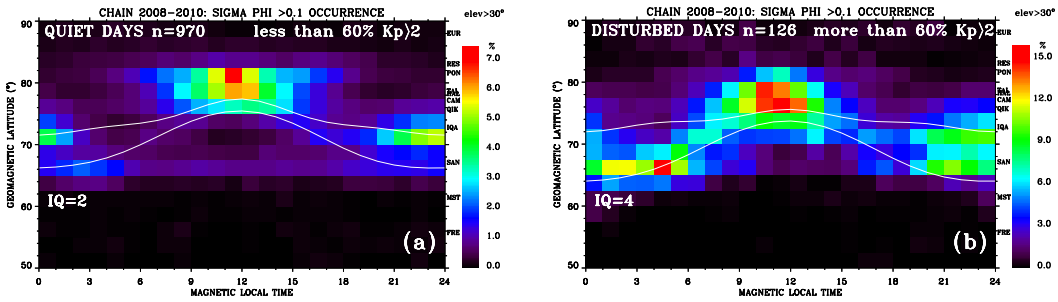

Figure 3. Phase scintillation maps for **(a)** quiet and **(b)** disturbed days. Note different color scales.

So far, CHAIN has operated during very quiet solar and geomagnetic conditions, except for some moderately disturbed periods when phase scintillation was significantly enhanced. To discriminate between very quiet and moderately active periods the scintillation statistics are divided into two parts by 3-hourly Kp index level over 24 hours (Figs. 3a and 3b). A disturbed day is defined as having a 3-hourly Kp index greater than 2 for more than half of the day. Even such low threshold value gives relatively sparse statistics of moderately disturbed days. Nevertheless, there is a significant equatorward shift of about 2.5° in latitude (one latitude cell) of the scintillation regions in the cusp and auroral oval when Kp index is elevated. In general, the occurrence of phase scintillation significantly increases in these regions.

4. HF Radar Backscatter Occurrence

Scintillation is caused by ionospheric irregularities of scale sizes from hundreds of meters to a few kilometers. These larger irregularities may coexist with small-scale field-aligned irregularities produced by plasma instabilities such as the gradient-drift instability [8]. Decameter ionospheric irregularities are observed by SuperDARN radar. Fig. 4a shows the mean occurrence of ionospheric backscatter with line-of-sight velocities exceeding 100 m/s observed by the Saskatoon radar beam no. 8 averaged and mapped into bins of 1 hour MLT × 1.5° CGM latitude for geomagnetically quiet days in 2008-2010. For comparison of the HF backscatter with phase scintillation occurrence, the irregularity drift is important since the phase scintillation is expected to be closely linked to the magnitude of relative motion of the irregularity and its variability. The F-region backscatter tracks well the statistical auroral oval that is shown for relatively quiet conditions (IQ=2). The highest occurrence of HF radar backscatter is in the post noon and pre-midnight auroral oval including the E-region backscatter (range < 800 km or CGM latitude less than 67°). Around 12 MLT the occurrence of HF radar backscatter is enhanced poleward of the oval in the cusp/cleft (above ~75° CGM latitude). For moderately disturbed days (Fig. 4b) the backscatter regions shift equatorward showing a clear predominance of occurrence rate in the pre-midnight sector. These relative enhancements in occurrence of drifting irregularities in the cusp and pre-midnight oval agree well with the phase scintillation occurrence (Figs. 3a and 3b).

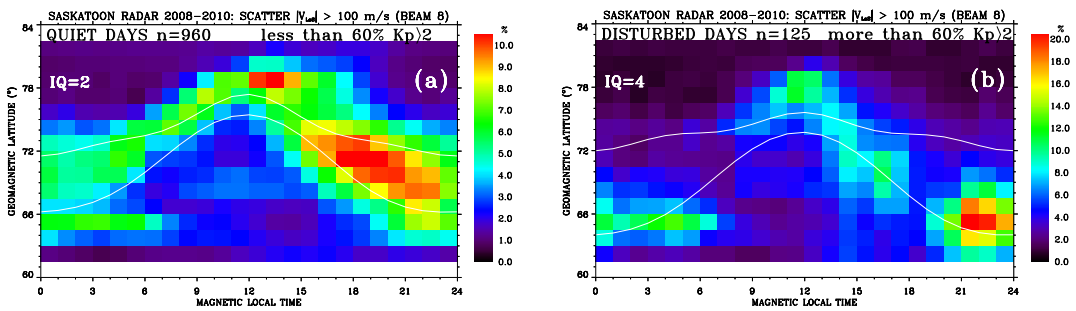

Figure 4. The occurrence of E- and F-region ionospheric backscatter with absolute value of LoS velocity exceeding 100 m/s observed by the Saskatoon radar beam 8 in 2008-2010 during **(a)** quiet and **(b)** moderately disturbed days.

Figure 2b shows the seasonal variations of ionospheric backscatter occurrence in the cusp and nightside auroral oval. Similarly to phase scintillation (Fig. 2a), the cusp backscatter shows an annual cycle with a minimum in summer and maximum in winter. The nightside auroral backscatter occurrence has a minimum in winter but unlike the phase scintillation it shows a large maximum in summer months, which is due to more favorable HF propagation condition in a dense ionosphere that refracts the radio waves to perpendicularity with the magnetic field at near ranges from the radar. This annual variation due to propagation conditions almost completely masks the semiannual oscillation due to aurora occurrence, although a plateau in the monthly occurrence distribution near the spring equinox is suggestive of superposed equinoctial enhancement.

5. Summary and Conclusions

The data from the first three years of operation of CHAIN have been analyzed to develop the climatology of GPS phase scintillation at high latitudes. During the period of 2008-2010 that included a deep solar minimum, the amplitude scintillation (*S4* index) remained insignificant but strong phase scintillation events frequently occurred. In the nightside auroral oval the phase scintillation was associated with auroral arc brightening and auroral substorms. Around local noon, the phase scintillation occurred in the cusp ionosphere that is perturbed by intense and dynamic convection. Some characteristics of phase scintillation occurrence were different in the nightside auroral oval comparing to those found in the cusp. The nightside auroral phase scintillation tended to be more intermittent, localized and of short duration than in the cusp. The dayside scintillation individual events sometimes lasted for several minutes per satellite and scintillation persisted over a large area of the cusp/cleft region sampled by different satellites for several hours.

The GPS phase scintillation occurrence observed by CHAIN at high latitudes has been compared with the occurrence of HF radar backscatter from E×B drifting field-aligned irregularities observed by SuperDARN. The phase scintillation and F-region HF backscatter as a function of magnetic local time and geomagnetic latitude primarily occur in the nighttime auroral oval and in the ionospheric cusp. Subset maps for geomagnetically quiet and moderately disturbed periods show expected shifts in latitude of the ionospheric regions both in the occurrence of phase scintillation and the HF radar backscatter. F-region backscatter occurrence is strongly dependent on HF propagation and thus primarily controlled by annual cycle of solar illumination of the ionosphere. Auroral scintillation occurrence shows semiannual variation with maxima around equinoxes. In the cusp, scintillation occurrence is dominated by an annual cycle maximizing in autumn-winter. The differences between the auroral and cusp scintillation occurrence point to different scintillation-causing irregularity production mechanisms: energetic electron precipitation into dynamic auroral arcs versus cusp ionospheric convection dynamics.

6. Acknowledgments

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7. References

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