On the collocation of the cusp aurora and the GPS phase scintillation: A statistical study

Yaqi Jin¹, Jøran I. Moen¹², and Wojciech J. Miloch¹

¹Department of Physics, University of Oslo, Oslo, Norway, ²Arctic Geophysics, University Centre in Svalbard, Longyearbyen, Norway

Abstract The climatology map of the GPS phase scintillation identifies two regions of high scintillation occurrences: around magnetic noon and around magnetic midnight. The scintillation occurrence rate is higher around noon, while the scintillation level is stronger around magnetic midnight. This paper focuses on the dayside scintillation region. In order to resolve the role of the cusp auroral processes in the production of irregularities, we put the GPS phase scintillation in the context of the observed auroral morphology. Results show that the occurrence rate of the GPS phase scintillation is highest inside the auroral cusp, regardless of the scintillation strength and the interplanetary magnetic field (IMF). On average, the scintillation occurrence rate in the cusp region is about 5 times as high as in the region immediately poleward of it. The scintillation occurrence rate is higher when the IMF \( B_z \) is negative. When partitioning the scintillation data by the IMF \( B_x \), the distribution of the scintillation occurrence rate around magnetic noon is similar to that of the poleward moving auroral form (PMAF): there is a higher occurrence rate at earlier (later) magnetic local time when the IMF \( B_x \) is positive (negative). This indicates that the irregularities which give rise to scintillations follow the IMF \( B_x \)-controlled east-west motion of the aurora and plasma. Furthermore, the scintillation occurrence rate is higher when IMF \( B_y \) is positive when the cusp is shifted toward the post noon sector where it may get easier access to the higher density plasma. This suggests that the combined auroral activities (e.g., PMAF) and the density of the intake solar EUV ionized plasma are crucial for the production of scintillations.

1. Introduction

The Global Navigation Satellite Systems (GNSS) become more and more important for both the civilian and military usages. However, the positioning accuracy is largely dependent on the ionosphere. The ionospheric electron density irregularities modify the transionospheric radio waves. The interference of radio waves that passed through regions with ionospheric irregularities can lead to rapid fluctuations in the received wave amplitude and phase on the ground, which is often referred to as ionospheric scintillations [see, e.g., Yeh and Liu, 1982; Kintner et al., 2007; Beach, 1998, and references therein]. It is said that the ionospheric scintillation is one of the first known space weather effects [Hey et al., 1946; Kintner et al., 2007; Yeh and Liu, 1982]. Intense scintillations degrade the signal quality and may even cause failure of signal reception. Therefore, in the presence of scintillations, the positioning systems (e.g., GNSS) and communication systems can be severely degraded.

Ionospheric scintillations are most severe in the equatorial region and at high latitudes [Aarons, 1982; Aarons et al., 1983; Basu et al., 1999, 2002; Kintner et al., 2004, 2007, and references therein]. As space weather is of growing concern for increased human activities in the Arctic, it motivates more research on the connection between scintillations and phenomena of the polar cap ionosphere. The ionospheric scintillations at high latitudes are strongly controlled by the solar wind-magnetosphere-ionosphere coupling [Prikryl et al., 2012]. However, currently there are no functional scintillation models to precisely predict solar wind effects in navigation and communication systems.

Early investigations of scintillations were primarily using VHF and UHF radio bands [Fremouw et al., 1978; Rino, 1979; Rino and Owen, 1980; Rino et al., 1983; Aarons et al., 1981; Kersley et al., 1988; Basu et al., 1988, 1990, 1998; Weber et al., 1986; Buchau et al., 1985]. Basu et al. [1998] studied the plasma structuring in the cusp/cleft region by using the all-sky imager and the amplitude scintillation at 250 MHz from a polar satellite. They observed the electron density irregularities (leading to amplitude scintillations) at daytime from 09:00 magnetic local time (MLT) to 15:00 MLT at ~78° magnetic latitude (MLAT) (2° poleward of the receiver station.
at Ny-Ålesund), and suggested that the field-aligned currents (FACs) may be the actual source of these irregularities. Carlson et al. [2007] observed strong amplitude scintillations from a radio beacon satellite when a series of five newly formed polar cap patches passed over the line of sight of the raypaths. They observed a sequence of scintillation events, where each event in the sequence was associated with a poleward moving auroral form (PMAF) and a polar cap patch [Carlson et al., 2008].

In recent years, several statistical and case studies of high-latitude scintillations at GPS L1 frequency (1.575 GHz) have been conducted [Mitchell et al., 2005; De Franceschi et al., 2008; Smith et al., 2008; Spogli et al., 2009; Li et al., 2010; Alfonsi et al., 2011; Prikryl et al., 2010, 2011, 2013; Moen et al., 2013; Jin et al., 2014; van der Meeren et al., 2014]. Since strong amplitude scintillations at GPS frequency are more rare at high latitudes [Spogli et al., 2009; Li et al., 2010; Prikryl et al., 2010; Moen et al., 2013], most of these studies have focused on phase scintillations. The climatology study of GPS phase scintillations at high latitudes identified two major scintillation regions: one is in the 75°–78° MLAT range around MLT noon, while another is in the nightside auroral oval around MLT midnight [see, e.g., Spogli et al., 2009; Prikryl et al., 2011]. These scintillation regions were tentatively attributed to the statistical auroral oval and the transport of polar cap patches. Auroral particle precipitation and polar cap patches are both candidates for scintillations at high latitudes. Jin et al. [2014], in a case study on the relative phase scintillation levels on the nightside, found that scintillations were strongest when patches interacted with substorm auroral arcs.

Considering the scintillation climatology maps presented by Spogli et al. [2009] (their Figure 5) and Prikryl et al. [2011] (their Figure 6), the dayside scintillation region is offset a little poleward of the statistical auroral oval. There are still some uncertainties in the conclusion about the potential role of auroral processes versus polar cap patch instability processes in producing irregularities. The motivation for this study was to identify where the most intense scintillation region at dayside is located relative to the cusp auroral region.

We take advantage of the collocation of the all-sky imager and GPS receiver at Ny-Ålesund, Svalbard, to explore scintillations in the cusp inflow region. Due to the geographic location and accessibility, Svalbard is an ideal place for studying plasma transport from lower latitude into the polar cap. We subdivide the dayside ionosphere into three regions:

(i) The subauroral region is located equatorward of the cusp auroral boundary.

(ii) The cusp auroral region is associated with strong 630.0 nm optical emission due to the direct entry of the soft electron precipitation from the magnetosphere. This region includes the transient auroral forms which are related to the magnetopause reconnection [Sandholt et al., 1998; Lorentzen and Moen, 2000; Moen et al., 2004].

(iii) The third region is the region poleward of the cusp aura with deenergized particles and lower flux of particle precipitation from the plasma mantle [Lorentzen and Moen, 2000].

There are different plasma conditions in these three different regions in the dayside high-latitude ionosphere. It is well established that the intake of the solar extreme ultraviolet (EUV)-ionized plasma through the cusp inflow region plays an important role in the polar ionosphere dynamics [Foster, 1984; Foster et al., 2005; Carlson, 2012, and references therein]. For the subauroral region (region (i)), it is usually postulated that the plasma condition is stable and very few irregularities are embedded. However, the general idea that the high-density plasma reservoir is a smooth region without plasma gradients may not always be appropriate. Moen et al. [2006] observed a group of isolated high-density plasma patches with a horizontal scale size of 300–700 km well equatorward of the cusp precipitation region, which are referred to as subauroral patches. Moreover, as shown by Zhang et al. [2013], the discrete blobs, which are created from the polar cap patches after these exit the nightside polar cap, can be transported to the dayside by the sunward return flow. Therefore, the subauroral patches and returned blobs may serve as the subject for the growth of irregularities in the subauroral region. The subauroral patches could be further cut into smaller pieces later when they are pulled across the cusp auroral precipitation region [Moen et al., 2006].

The plasma condition inside the cusp aurora (region (iii)) is most complex of the three regions. This is due to the reconnection dynamics, with the discrete precipitation (FAC sheets) and flow channels [Pinnock et al., 1995; Provan et al., 1998; Oksavik et al., 2004; Moen et al., 2008b; Rinnie et al., 2011]. This is the region where the solar EUV-ionized tongue of ionization (TOI) enters the polar cap [Foster et al., 2005; Thomas et al., 2013] and the TOI may be cut into patches [Sojka et al., 1993, 1994; Rodger et al., 1994; Lockwood et al., 2000, 2005; Carlson et al., 2006; Lorentzen et al., 2010; Zhang et al., 2011, 2013]. As the result of particle precipitation, the enhanced plasma will be produced locally in the cusp ionosphere [Walker et al., 1999;
Density gradients may arise due to the patch formation as well as due to the particle impact ionization, and they can support the development of small-scale irregularities in terms of the gradient drift instability (GDI) [Kelley et al., 1982; Moen et al., 2012b]. Note that more instability modes were proposed to explain the production of the plasma irregularities. For example, the observed strong plasma flow shears in the cusp region suggest that the shear-driven instability may play an important role in the rapid onset of irregularities across the cusp [Carlson et al., 2007, 2008].

In region (iii) (poleward of the cusp aurora), where there is a lack of effective particle precipitation, the polar cap patches are the most important structures to host irregularities. The polar cap patches are mostly found during southward interplanetary magnetic field (IMF). After the polar cap patches are produced in the cusp inflow region, they are frozen into the convection streamlines. Deep in the polar cap, they are mainly transported antisunward [Carlson et al., 2007]. Another large-scale structure inside the polar cap which could support plasma irregularities growth is the polar cap arcs during northward IMF [Tsunoda, 1988; Kullen et al., 2002]. However, polar cap arcs have minor effects on radio wave scintillations due to their low electron density [Tsunoda, 1988; Basu et al., 1998]. Since we did not observe any polar cap arcs in our data set, we will not discuss polar cap arcs in this paper.

The major findings in this paper are that the dayside scintillation occurrence rate peaks inside the cusp auroral region, there is higher scintillation activity during IMF $B_z$ negative than that during IMF $B_z$ positive, and there is an IMF $B_z$ effect on the MLT distribution of scintillations around noon.

The paper is organized as follows: Section 2 presents the instruments and the method used to subdivide the three ionospheric regions. The scintillation climatology map with data from our GPS receiver is shown in section 3, followed by detailed data analysis in the context of the auroral morphology. In section 4, the main results are discussed with the emphasis on the importance of the auroral activity in producing the ionospheric irregularities. Section 5 provides a short summary and concluding remarks.

2. Instrumentation and Methodology

In this study, we use the University of Oslo’s GPS scintillation receiver and all-sky imager which are collocated at Ny-Ålesund, Svalbard [78.9°N, 11.9°E; 76.6° MLAT]. The GPS scintillation receiver is the standard GPS Ionospheric Scintillation/total electron content (TEC) Monitor (GISTM), model GSV4004 [Van Dierendonck et al., 1993]. The phase ($\sigma_\phi$) and amplitude scintillation indices ($S_q$) are calculated and recorded automatically by the GISTM. The phase scintillation index is defined as the standard deviation of the carrier phase that has been detrended by the high-pass sixth-order Butterworth filter with a cutoff frequency of 0.1 Hz:

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2},$$

where $\langle . \rangle$ denotes the expected value and $\phi$ is the detrended carrier phase. We use $\sigma_\phi$ that were computed over 1 min intervals. An elevation cutoff of 15° is used for the GPS data to minimize the multipath effects. This cutoff angle for GPS data from Ny-Ålesund has been used earlier by, e.g., Jin et al. [2014] and Spogli et al. [2009]. As will be shown in section 3, the scintillation was well collocated with region (ii) which usually corresponds to regions of high-elevation angle. Therefore, it is unlikely that the multipath effect appreciably affects the scintillation data. Following Spogli et al. [2009], the phase scintillation indices are projected to the vertical to account for different elevation angles [Rino, 1979]:

$$\sigma_\phi = \sigma_\phi(e_l) \sqrt{\sin(e_l)}$$

Here $\sigma_\phi(e_l)$ is the phase scintillation index at a certain elevation angle (el), and $\sigma_\phi$ is the corresponding vertical phase scintillation index. It should be noted that this will underestimate the real scintillation condition as the slant scintillation index is the direct result of the ionospheric disturbance.

Note that, while $\sigma_\phi$ is the most established phase scintillation index that is used at high latitudes [e.g., Spogli et al., 2009; Prikryl et al., 2011], there have also been some studies on using a different detrending methods for the GPS scintillation data analysis [Forte and Radicella, 2002; Mushini et al., 2012]. We have verified that different detrending techniques will not affect our results qualitatively, and we therefore use the well-established $\sigma_\phi$ phase scintillation index in the following.
The amplitude scintillation is very rare at high latitudes: Spogli et al. [2009] showed that the amplitude scintillation occurrence rate is about 0.025% around the cusp region, whereas the occurrence rate of the phase scintillation is about 2%, which is 80 times larger than the occurrence rate of the amplitude scintillation. Therefore, we consider the phase scintillation only.

The all-sky imager uses the electron multiplying charge-coupled device [Sangalli et al., 2011]. The all-sky imager records 630.0 nm and 557.7 nm images every 30 and 15 s, respectively. For the 630.0 nm images, the exposure time is 2 s, while for 557.7 nm ones, it is 1 s. Because the minutely \( \sigma_\phi \) is used in this study, only the corresponding minutely 630.0 nm images are used to mark the cusp auroral location. However, the 557.7 nm images are used to identify the clear sky together with the 630.0 nm ones. For our study of interest (the cusp aurora), all necessary information is contained in the 630.0 nm channel, and thus we only consider this channel in this study. The all-sky data are cropped at an elevation of 15°. This cutoff elevation corresponds to a latitude range from 72.3°N to 85.6°N geographic latitude (−70°–83° MLAT), when the all-sky images are projected onto an altitude of 250 km.

The GPS receiver runs continuously; however, the all-sky imager is only operated when the Sun is more than 10° below the horizon, which corresponds to the time between late November to early February, and when the Moon is below the horizon. As this paper concentrates on the scintillation condition around the cusp region, we consider the time intervals about 2 h before and after the MLT noon, i.e., from 10:00 MLT to 14:00 MLT at the station (~07:00 UT to 11:00 UT). This roughly corresponds to the statistical cusp location [Newell and Meng, 1992; Fasel, 1995; Sandholt et al., 1998]. We use data from November 2010 to the end of 2013. Out of 134 days of operation, a total of 37 days are found with clear-sky conditions within the considered time intervals. Figure 1 shows the universal time (UT) distribution of all-sky data by counting the number of days with clear-sky observations. On average there are 32 days with clear-sky observations. The MLT distribution of the GPS data points is shown in Table 1.

To partition the optical data and GPS data by the \( z \) and \( y \) components of IMF, we use the IMF data in geocentric solar magnetospheric coordinates from the OMNI data set [King and Papitashvili, 2005]. The 1 min resolution spacecraft-interspersed IMF data are from the OMNI web, which is called the high-resolution OMNI data set (http://omniweb.gsfc.nasa.gov/html/sc_merge_data1.html). The OMNI IMF data are already shifted from the observation points to the Earth’s bow shock nose by using several shift techniques.

In order to estimate the transit time from the bow shock through the magnetosheath to the magnetopause, the following formula is used [Khan and Cowley, 1999]:

\[
t_{\text{sheath}} = \frac{1.66 R_{\text{MP}}}{(V_{\text{SW}} - 72)} \ln \left( \frac{V_{\text{SW}}}{72} \right),
\]

where \( R_{\text{MP}} \) is the subsolar magnetopause position in kilometers, which can be calculated by the following equation:

\[
R_{\text{MP}} = \frac{111}{[\pi V_{\text{SW}}]^{1/6}} R_E,
\]

where \( R_E \) is the Earth radius in km, and \( V_{\text{SW}} \) is the solar wind velocity in km/s, and \( n \) is the solar wind density in cm\(^{-3}\). The simplified form of transit time depends on the solar wind velocity and density. We
First calculate the transit time $t_{\text{sheath}}$ for every minute and then average them for every day. This is equivalent to assume that the propagation time of the solar wind in the magnetosheath is constant during the 4 h interval each day. Additional 2 min are added to account for the transit time from magnetopause to the ionosphere [Lockwood et al., 1989; Liou et al., 1998; Khan and Cowley, 1999; Moen et al., 1999]. Another 1 min is added to account for the irregularity response assuming that the GDI is the dominant mode [Moen et al., 2012b; Spicher et al., 2015]. The total estimated time delay from the bow shock for each day varies from 11 to 18 min with an average time of 15 min.

In order to assign the GPS locations to the three regions (subaurora, cusp aurora including PMAFs, and poleward of the cusp aurora), the following procedure is performed (an example of the assignment is shown in Figure 2):

1. First, a $5 \times 5$ pixel median filter is applied on the all-sky image to smooth the image and reduce the noise.
2. Then we derive the auroral boundary by calculating the isointensity contour line at the average of maximum and minimum optical intensities. This value is tested to well represent the auroral boundary (see blue line in Figure 2). Sometimes there are spatially separated auroral forms for which several contour lines are derived.
3. Since the GPS receiver is colocated with the all-sky imager, the position of each GPS satellite is then projected onto the all-sky image by using the azimuthal and elevation angles of the satellite viewed from the camera position [Jin et al., 2014]. (This is the same way how the photons hit the CCD chip of the all-sky imager.) This method connects GPS scintillation measurements to the auroral observations without any assumptions of the auroral emission altitude and the ionospheric altitude (which are normally the largest uncertainty factors in such studies).
4. If the GPS satellites are located inside the contour lines, they are classified as within the cusp auroral region (region (iii)).

Then if the GPS satellite is located outside the auroral contour lines, it must either locate in region (i) (subaurora) or in region (iii) (poleward of the cusp). The steps (5)–(9) are performed in order to determine where the data point is located relative to the auroral boundary. If located equatorward of it, it is obviously in region (i). If located poleward of the equatorward auroral boundary, it must in region (iii), since all the data point inside the cusp auroral band have already been selected for region (ii) in previous steps. The following procedure is used for the data points outside the cusp auroral band:

5. The keogram data are produced by scanning the all-sky data along the magnetic meridian over the station (see solid black line in Figure 2).
6. Then we calculate the open/closed magnetic field line boundary (OCB) from the keogram data by using the maximum gradient method (i.e., where the gradient of emission intensity maximizes, see, e.g., Moen et al. [2001a]; Johnsen et al. [2012]). The OCB marks the equatorward boundary of the cusp aurora activity (see black square annotated as “B” in Figure 2).

7. The OCB locations are then transformed into the Altitude Adjusted Corrected Geomagnetic coordinate system at the altitude of 250 km [Baker and Wing, 1989].

8. The GPS satellite piercing points are calculated by assuming that the single-layered ionosphere is at an altitude of 350 km.

9. The MLAT of the GPS satellite piercing point (step 8) is directly compared with the MLAT of the OCB (step 7). If the GPS location is outside of the auroral contour line and the piercing point of the GPS satellite is equatorward of the OCB, then the GPS satellite is classified as within the subauroral region (region (i), equatorward of the cusp aurora; in Figure 2, they are pseudo-random noise (PRN) 21, PRN29, and PRN30). If the GPS location is outside the auroral contour line and the MLAT of the piercing point of the GPS satellite is poleward of the OCB, then the GPS satellite is classified as in the polar cap region (region (iii), poleward of the cusp aurora; in Figure 2, they are PRN7 and PRN13).

A supporting information which exemplifies these steps can be found together with the online version of this article.

In some works, the polar cap is referred as a region with open magnetic field lines and thus the cusp is considered as a part of the polar cap region [Blanchard et al., 1995; Pinnock and Rodger, 2001]. While in other works, the dayside polar cap is referred to a region that is poleward of the cusp aurora in contrast to the noticeable cusp auroral precipitation [e.g., Carlson et al., 2008]. In this paper, for simplicity, we refer polar cap to the region poleward of the cusp aurora where there is little or no effective precipitation that affects the ionosphere. Note that since the scintillation receiver and the all-sky imager are collocated, we have not made any height assumption to determine the scintillation measurements within the auroral cusp (region ii). There is an uncertainty for assigning scintillation measurements to the other two regions which are located outside the auroral region. This is because we then have to assume the 630.0 nm emission altitude (250 km) and the GPS satellite piercing point (at the height of 350 km). However, the latitudinal assignment error, which these assumptions may lead to, is considered small compared to the latitudinal width of the cusp auroral region, which is typically 1°. Thus, there is a marginal risk to assign the scintillation data wrongly between region (i) and region (iii).

3. Results

In order to relate the present study to the previous scintillation statistics, the scintillation climatology map is shown in Figure 3. Figures 3a–3c show the GPS phase scintillation occurrence rate as a function of MLAT and MLT by using data obtained by our GPS receiver at Ny-Ålesund. The data are presented in the similar format as by Spogli et al. [2009] and Prikryl et al. [2011]. The data are binned into 1 h MLT × 2° MLAT. The scintillation occurrence rate is defined as $100 \times N(\sigma_\phi)/N_{tot}$, where $N(\sigma_\phi)$ is the number of data points, for which the phase scintillation index is within a certain range of values and $N_{tot}$ is the total number of data points in the bin. The data for producing Figure 3 were recorded from year 2010 to 2013 during the winter time (January, February, November, and December). The red curves ring out the statistical auroral oval which is reproduced from the Feldstein model [Holzworth and Meng, 1975; Feldstein, 1963]. The Feldstein model was derived by fitting a simple formula of the Fourier series using the DMSP auroral photographs. The input parameter for the Feldstein model is the index Q (IQ), which ranges from 0 (most quiet) to 6 (most active) and is related to different levels of magnetic activity. This oval model is widely used, for example, in high-latitude scintillation studies [Spogli et al., 2009; Li et al., 2010; Alfonsi et al., 2011; Prikryl et al., 2011; Moen et al., 2013] and in HF radar backscatter studies (see, e.g., Milan et al. [1997]). The MLAT of Ny-Ålesund station is marked by the blue circle in each panel.

In Figure 3a, the dayside scintillation occurrence rate for the weak scintillations ($\sigma_\phi \leq 0.1, 0.25$) rad) peaks around magnetic noon and poleward of the statistical auroral oval at around 78° MLAT (even poleward of the most quiet oval when IQ = 0). There is also a slight prenoon shift around magnetic noon. Another clear feature is the high-scintillation occurrence rate in the afternoon sector in the deep polar cap (around 80° MLAT), in contrast to the low-scintillation occurrence in the corresponding morning sector. This feature is also shown.
on the scintillation map by Spogli et al. [2009] and Moen et al. [2013], and also agrees with the rate of total electron content index (ROTI) map by Jacobsen and Dahnn [2014], which has been attributed to the transport pattern of polar cap patches in the polar cap region. The scintillations which occur at the subauroral region during prenoon and postnoon intervals may be related to subauroral patches and returned blobs (see the introduction section).

Figure 3b, when comparing it with Figure 3a, shows that the main scintillation region for intermediate scintillations ($\sigma_\phi \in (0.25, 0.5) \text{ rad}$) are better collocated with the statistical oval. The slightly prenoon enhancement is further pronounced. The afternoon polar cap scintillations are still visible in this $\sigma_\phi$ range, although the occurrence rates are lower. Figure 3c shows the scintillation map for the strong phase scintillations ($\sigma_\phi \geq 0.5 \text{ rad}$). Apparently the occurrence rate of strong scintillations on the dayside is even further constrained to the statistical oval. Only isolated scintillation bins are found in the dayside polar cap and they are located in the prenoon sector not far from the cusp inflow region and in the afternoon sector in the deep polar cap (14–18 MLT, >80° MLAT). Note that the scintillation occurrence rates have different orders of magnitude for different scintillation ranges: the magnitude of the weak scintillation occurrence rate is 1 order higher than the intermediate scintillation occurrence rate, which is again 1 order of magnitude higher than the strong scintillation occurrence rate.

When comparing the dayside and nightside scintillation occurrence rates, we find that the weak and intermediate scintillations are mainly distributed at the dayside (Figure 3a), while the strong scintillations are mostly situated at the nightside (Figure 3c). Jacobsen and Dahnn [2014] found that more elevated ROTI values occur around the dayside cusp region, and the ROTI values are stronger when they are found at the nighttime. The nightside scintillations are mostly distributed south of the station and extend into the auroral oval. Since the latitude of the station is high, the data set only covers a small part of the nightside auroral oval.
However, similar to previous studies [e.g., Spogli et al., 2009; Prikryl et al., 2011], the scintillation occurrence shows a slightly premidnight enhancement. At night, the high-scintillation occurrence poleward of the oval may be caused by pure polar cap patches or by the poleward expansion of the oval due to substorm activity and the blobs [Jin et al., 2014; Lorentzen et al., 2004; Moen et al., 2007].

Figures 3d and 3e show the standard deviation and mean of the phase scintillation indices. The standard deviation shows the variability of the scintillation condition, whereas the mean value indicates the average scintillation condition. For both of them, there are two regions of interest: beneath and poleward of the statistical auroral oval at daytimes as well as poleward and right beneath the auroral oval around midnight. Since most of the scintillations are weak, and the weak scintillations are mainly distributed at daytimes, the mean value of $\sigma_\phi$ is higher at daytimes and poleward of the cusp. However, Figure 3d shows that there are similar standard deviation values (up to 0.05 rad) in the daytimes and nightside scintillation regions. This means that while on average the nightside scintillation is lower than that in the daytimes, the strong scintillation (see Figure 3c) contributes to the high variability in this region. The daytimes scintillation shows high-scintillation occurrence rates at both weak and strong scintillations; as a result there are both large mean value and high variability.

This paper mainly focuses on the daytimes scintillation condition and on the distribution of phase scintillations with respect to the three regions introduced in section 1. From Figure 3, it is clear that scintillations do not coincide in general with the statistical oval. The question is whether they are related to the dynamics of the oval or can be attributed to the specific region in the high-latitude ionosphere. Thus, we will present below the scintillation statistics using the method introduced in section 2.

An example of the connection between the daytimes auroral morphology and the GPS phase scintillation observations is presented in Figure 2. The figure shows the auroral emission at 630.0 nm at 09:00 UT (~12:00 MLT at the station), so the left side of the black line (magnetic meridian line) indicates prenoon MLT, while the postnoon MLT is on the right side as shown on the bottom right of the all-sky image. The three regions of interest are annotated by "subaurora," "cusp," and "polar cap," whose definitions were given in section 2. Nine GPS satellites are tracked with elevation greater than 15° at this time: three satellites are in the subauroral region, four satellites are in the cusp region, and the other two are immediately poleward of cusp aurora (that is in a region referred to as polar cap in this paper).

During the time of interest in Figure 2, the solar wind speed was steady around 350 km/s. Before 09:00 UT, the IMF $B_z$ fluctuated around 0, then it turned northward gradually and became strongly northward for around 10 min after 09:00 UT (data not presented). The IMF $B_z$ was predominately positive and then turned into to a little negative to finally fluctuate rapidly around 0. The clock angle rotated quickly from 90° to 0° and then back again from 0° to 90°. According to the IMF delay technique introduced in section 2, the IMF $B_z$ was mainly positive around this time; however, the IMF just changed from $B_z$ dominant ($|B_z| > 1$) to $B_x$ dominant. This IMF $B_x$-dominant condition favors the occurrence of PMAF activity [Sandholt et al., 2004]. One example of such PMAF can be seen to the west of PRN5 in Figure 2. The brightening aurora moved northward, passed through PRN5, and continued to move northward as shown by the white arrow. An island of high-density plasma was associated with the aurora as confirmed by the GPS total electron content (TEC) data (not shown in this paper). However, we are unable to resolve whether the plasma was directly produced by the auroral precipitation or if it was convected from the subauroral region during reconnection (which is the dominant mechanism for the production of polar cap patches). Strong scintillations up to 0.8 rad were found on the trailing edge of this plasma structure and the auroral form.

The very active case presented in Figure 2 shows that scintillations occurred in all the three regions: in subaurora (PRN30), cusp (PRN3, PRN5, PRN6, and PRN16), and the polar cap (PRN13). But the cusp region shows the most violent scintillation condition: the signals from all four satellites were scintillated, and two of the four satellite signals showed intermediate to strong phase scintillations ($\sigma_\phi \geq 0.25$ rad).

Using the method introduced in section 2, we carried out the statistical study on the scintillation occurrence rate. The main results are summarized in Figure 4 together with the number of data points considered. As an example of how to derive the scintillation occurrence rate, in Figure 4b, the red bar is defined as $100 \times N_{\sigma_\phi \geq 0.1 \text{ rad}} / N_{\text{tot}}$, where $N_{\text{tot}}$ is the total number of data points in the cusp region as indicated in the title above Figure 4b and $N_{\sigma_\phi \geq 0.1 \text{ rad}}$ is the number of data points when $\sigma_\phi \geq 0.1$ rad. The occurrence rates are binned in black bars by $\sigma_\phi$ from (0.1, 0.25) rad, (0.25, 0.5) rad, and $\geq 0.5$ rad. Similar to Figure 3, the
scintillation occurrence rate for higher phase scintillation values is generally lower. This implies that most of the scintillations that occurred were weak scintillations. However, the occurrence rate for stronger scintillations follows the same trend as the occurrence rate for weaker scintillations: the weak scintillation occurrence rate is highest in the cusp region, and the same is the case for intermediate and strong scintillations. The total scintillation occurrence rate is highest in the cusp region (15.6%), followed by the polar cap (3.4%) and subauroral (0.9%) regions. Intermediate to strong scintillations can be found in the cusp and polar cap regions, but in the subauroral region, only weak scintillations are found.

Although a few scintillations are found poleward of the auroral region (polar cap), it can be inferred from Figure 4 that the high-latitude dayside irregularities are mostly found inside the cusp auroral region. Therefore, care must be executed when discussing scintillation climatology results with the reference to the statistical auroral oval. In fact, the location of the cusp aurora is quite dynamic as the oval expands and contracts considerably during unbalanced dayside and nightside reconnection processes [Cowley and Lockwood, 1992]. Moen et al. [2004] observed that the dayside OCB (the equatorward boundary of the cusp aurora) varied from 76° to 71° MLAT during the substorm cycles and were explained in the conceptual expanding-contracting polar cap model [Lockwood et al., 2005]. Furthermore, the Feldstein oval was derived from the DMSP photography, which was not sensitive to the dayside cusp aurora [Dandekar and Pike, 1978]; therefore, the data for deriving the oval model were mainly from the nightside aurora. Thus, one should expect the model to represent better the night aurora location than the dayside cusp location. From Figures 3a and 3e, it seems that the highest scintillation occurrence rate is offset poleward of the aurora, but this was actually not the case when comparing with actual auroral observations. The highest scintillation occurrence rate is always inside the cusp auroral region. Moreover, we can safely conclude from Figures 3 and 4 that the intermediate and strong scintillations are mainly produced in the auroral cusp region. Note that Figures 3 and 4 give the same order of the peak scintillation occurrence rate, being ~10% for weak scintillations, ~1% for intermediate scintillations, and ~0.05% for strong scintillations.

The auroral morphology and the high-latitude ionospheric convection are controlled by the IMF conditions, in particular, by the IMF $B_z$ and $B_y$ components. Therefore, we further subdivide our scintillation occurrence rate according to the IMF $B_z$ and $B_y$ in Figures 5 and 6. Figure 5 shows the scintillation occurrence rate for different IMF $B_z$ conditions in the three regions. The white bars correspond to IMF $B_z > 0$, whereas the gray bars are for IMF $B_z < 0$. As for Figure 5, the scintillation occurrence rate is still highest in the cusp region. Moreover, in all three regions, scintillation occurrence rates are higher during IMF $B_z < 0$, which agrees with the general view of a more disturbed ionospheric condition and intake of high-density solar EUV-ionized plasma when IMF $B_z < 0$. The scintillation occurrence rate in the auroral cusp region when IMF $B_z < 0$ is ~11% higher than the occurrence rate when IMF $B_z > 0$.

Figure 6 shows the scintillation occurrence rate for IMF (a) $B_y > 0$ and (b) $B_y < 0$, respectively. These three regions are subdivided into four MLT intervals, namely, prenoon (<11:00 MLT), noon 1 (11:00 MLT–12:00 MLT), noon 2 (12:00 MLT–13:00 MLT), and postnoon (>13:00 MLT). For the subauroral scintillations, there is no apparent IMF $B_y$ dependence. However, for the cusp region, we find from Figure 6a (IMF $B_y > 0$) that the scintillation occurrence rate is higher at earlier MLT. Despite the scintillation occurrence distribution being almost symmetric around noon for IMF $B_y < 0$ (Figure 6b), there is still a clear increase in the scintillation occurrence rate at postnoon versus prenoon, as well as noon 2 versus noon 1. Furthermore, the average
scintillation occurrence rate is higher for IMF \( B_y > 0 \) in contrast to IMF \( B_y < 0 \) (18.1% versus 12.5%). This may explain the more symmetric character for IMF \( B_y < 0 \); because of a more quiet condition for IMF \( B_y < 0 \), the threshold used for defining the scintillation in this study (0.1 rad) may be too high to reflect the prenoon and postnoon asymmetry. For the polar cap region, there is a clear prenoon shift in the scintillation occurrence rate for IMF \( B_y > 0 \), but pattern of the scintillation occurrence rate is more irregular for IMF \( B_y < 0 \). We have tested the time delay from the cusp region by adding from 1 to 15 min, and the distribution of the GPS phase scintillation in the polar cap remains remarkably similar.

4. Discussion

As was shown in Figure 3, the dayside scintillations are mainly distributed above or poleward of the Ny-Ålesund station (marked with the blue circles in Figure 3), whereas the nightside scintillations are mainly distributed equatorward of the station. This can be easily explained by the average location of the auroral oval. During daytime, the cusp aurora is usually located above Svalbard, while at night the aurora is centered over northern Scandinavia and reaching Svalbard during the poleward expansions of the auroral substorm dynamics. Thus, Ny-Ålesund is well inside the polar cap at night and the nightside auroral activity is under the southern horizon most of the time.
The transpolar plasma transport plays an important role in the ionospheric condition at high latitudes. The scintillation climatology maps show that the dayside scintillations agree well with formation of plasma irregularities in the cusp inflow region, and the nightside scintillations agree with the polar cap patches exiting the polar cap into the nightside auroral oval [Spogli et al., 2009; Moen et al., 2007, 2008a, 2013].

Another prominent feature in Figure 3 is that the scintillation levels are typically low at daytime and the probability for strong scintillations is highest at nighttime. The polar cap patches that are observed at nighttime in the Scandinavian Arctic sector entered the polar cap 1–3 h earlier in the North American Arctic sector at daytime. Moen et al. [2008a] demonstrated that above Svalbard, the $F_2$ region peak electron density around midnight, which has already decayed during the 1–3 h transit across the polar cap, is similar to the daytime $F_2$ peak electron density. Due to the $\sim$11° tilt of geomagnetic pole toward North America, the polar cap patches that are scooped into polar cap from the North American sector have much higher density than those scooped from the Scandinavian Arctic sector [Basu et al., 1995, 1998; Moen et al., 2006]. At the nightside polar cap, after 1–3 h of transport, most of the polar cap patches become fully or partially structured due to nonlinear processes related to GDI [Hosokawa et al., 2009]. During the expansion phase of substorms, the polar cap patches exit the polar cap and then they are termed blobs when interacting with the substorm auroral dynamics. The scintillation levels associated with blobs exceed the scintillation levels associated with polar cap patches and the scintillation levels associated with substorm auroral arcs without patches [Jin et al., 2014].

The major new finding in this paper is that the dayside scintillation region is closely collocated with the cusp auroral region for all kinds of IMF conditions. From Figure 3, the occurrence rates of weak and intermediate scintillations and the mean $\sigma_\phi$ are highest poleward of the dayside statistical auroral oval, and this is consistent with the study by Spogli et al. [2009]. However, by taking the advantage of the collocated all-sky imager and GPS scintillation receiver, we have placed the scintillations in the context of actual auroral observations. With this method, we have accurately pinned the daytime scintillations relative to the daytime cusp aurora.

From Figure 4, we see a clear predominance for scintillation occurrence collocated with the cusp aurora. Figures 5 and 6 show that this is valid for all different IMF conditions. The scintillation occurrence rate is about 5 times higher within the cusp than in the region poleward of it. This indicates that polar cap patches which were produced in the Scandinavian Arctic sector do not effectively contribute to scintillations immediately poleward of the dayside cusp. Thus, the classic view that the GDI efficiently creates scintillation targets on the trailing edges of the polar cap patches [e.g., Tsunoda, 1988] seems to be invalid for patches that just entered the polar cap after being formed in the cusp region. That the scintillations are mostly found in the cusp auroral region manifests the importance of the cusp auroral dynamics in producing irregularities. The soft electron precipitation in the cusp region could modulate (or produce) the $F$ region plasma structure and build up the large-scale plasma gradients (>10 km), then the GDI can work on these gradients to produce smaller scale irregularities [Kelley et al., 1982; Moen et al., 2012b]. Immediately poleward of the cusp aurora, there is no effective precipitation which makes a considerable impact on the ionosphere. Therefore, when the electron density irregularities are found on the dayside polar cap, they should be transported from the cusp region. The possible reason for lower scintillation occurrence rate poleward of the cusp region is due to the fact that the 0.5–1 keV electron precipitation ionizes density gradients below 250 km [Moen et al., 2001b; Millward et al., 1999], and these density gradients disappear within a few minutes and the GDI that is associated with these gradients stops as well. This can explain why the polar cap patches produce much less scintillations immediately poleward of the cusp auroral region [Basu et al., 1998; Kelley et al., 1982; Vickrey and Kelley, 1982].

Our observation setup is sketched in Figure 7, where the blue circles indicate the example of all-sky fields of view for prenoon and postnoon observations, and the purple shaded region show the cusp aurora. There are both prenoon and postnoon measurements during both IMF $B_y$ positive and negative. When IMF $B_y > 0$ ($B_y < 0$), the cusp shifts toward the postnoon (prenoon) sector, but the magnetic tension force drives the newly opened flux and the accompanying plasma to move northwestward (northeastward) as shown in Figure 7a (Figure 7b).

When partitioning the scintillation data according to the IMF $B_y$, the scintillation occurrence rate in the cusp region around magnetic noon concurs with the PMAF statistics presented by Karlson et al. [1996]: characterized by higher occurrence rate at prenoon (postnoon) for IMF $B_y > 0$ ($B_y < 0$). This suggests that the PMAF phenomenon relates to the scintillation production (as exemplified in Figure 2). However, this IMF $B_y$ effect on the scintillation occurrence rate is less pronounced for IMF $B_y < 0$ than the IMF $B_y > 0$ condition.
Furthermore, the scintillation occurrence rate is generally higher during IMF $B_y > 0$ (see Figure 6). Therefore, some other effects besides the PMAF need to be considered. One possible reason for the higher scintillation occurrence rate during positive IMF $B_y$ is the regulation of the intaking high-density plasma from the subauroral region. For IMF $B_y > 0$, the postnoon-shifted cusp inflow region can get easier access to the higher density solar EUV-produced plasma (as indicated by the red color in Figure 7a) than for IMF $B_y < 0$ when the plasma intake is shifted toward the prenoon sector (Figure 7b). Since the scintillation effects are dependent on the absolute fluctuation of the electron density ($\Delta N$) rather than the relative fluctuation of the electron density ($\Delta N/N$) [Kivanc and Heelis, 1997; Basu et al., 1998; Carlson, 2012], we suggest that the intake of higher density plasma from the postnoon sector is more prone to produce scintillations (the case for IMF $B_y > 0$).

The PMAFs are the moving discrete auroral forms that have been attributed to transient magnetopause reconnection in the form of flux transfer events [Sandholt et al., 1986, 1990, 1998; Fasel, 1995]. The dayside reconnection pours the energy into the ionosphere by means of the particle precipitation and electromagnetic energy [e.g., Kelley et al., 1991]. The precipitating particles can ionize neutrals and build up density gradients onto the existing plasma. Furthermore, the PMAFs are accompanied with strong flow channels and reversed flow events [Oksavik et al., 2004; Rinne et al., 2011; Moen et al., 2012a], and the high flow velocity can increase the instability growth rate. Thus, the irregularities can develop rapidly and the scintillation patterns are observed by the GPS receiver. Furthermore, the PMAFs are often accompanied by the generation of polar cap patches [Carlson et al., 2006; Lorentzen et al., 2010]. The polar cap patches that are islands of high-density plasma can support the irregularity growth.

The southward IMF condition favors, in general, the transport of high-density plasma from subauroral region through the cusp into the polar cap, which forms the polar cap patches or TOI. The scintillations in all three regions (subaurora, cusp, and polar cap poleward of cusp) are stronger during southward IMF $B_y$, but the largest effect of the IMF $B_z$ polarity change happens in the cusp auroral region (cf. Figure 5). It should be noted that the highest scintillation occurrence rate is located in the cusp region also for IMF $B_y$ positive. This indicates that the precipitation plays a central role in the irregularity formation even during northward IMF.

One reason that we do not see clear IMF trends in the scintillation regions outside the cusp region is that the estimated time delay from the bow shock to magnetopause reconnection is not applicable outside the magnetopause reconnection region (e.g., region (iii)). Exact timing elsewhere needs exact tracing of the plasma flow which we found practically impossible to incorporate in this statistically study. For region (iii), the additional time delay (by adding from 1 to 15 min) did not show noticeable differences in the distribution of the GPS phase scintillation. This means that the IMF dependence of polar cap scintillation (region (iii)) cannot be easily obtained by assuming some uniform delay time, i.e., the actual time delay is determined by the distance from the scintillation measurement to the cusp aurora and the plasma velocity. Another issue may be the stability of the IMF: In the case of rapid IMF polarity change, it may be difficult to make a one-to-one correspondence of the IMF data and the GPS scintillation measurements. For example, the polar cap patches that were produced prior to an IMF $B_y$ northward turning will stay in the polar cap (region (iii)) and contribute to the scintillations when the IMF is northward. Therefore, the GPS phase scintillation can still be seen in region (iii) when the IMF $B_y$ is northward (cf. Figure 5).
Returning back to Figure 3, while the strong scintillations are constrained to the auroral oval (Figure 3c), the region of enhanced occurrence rate of weak scintillations extends into the dusk MLT sector (Figure 3a). Weak scintillations also extend into the dawn sector but at lower occurrence rate than dusk sector. These regions of weak scintillations are likely due to irregularities generated on patches which convect from the European Arctic sector toward the American sector. This implies that the plasma patch produced in the European sector is an active GNSS space weather phenomenon, but the scintillation region within the cusp aurora is by far the most intense. And this is the case for all IMF conditions.

5. Summary and Concluding Remarks

We have made the first statistical analysis on the collocation of the cusp aurora and GPS phase scintillations by using the collocated GPS receiver and all-sky imager. There are three clear results:

1. There is one peak in the occurrence rate of GPS phase scintillation around magnetic noon and another peak around magnetic midnight. In the European Arctic sector, the phase scintillation occurrence rate is higher in the dayside, while the strong phase scintillation occurs more frequently during night. Nonetheless, strong phase scintillation events (0.8 rad in Figure 2) can also be triggered at daytime in association with the PMAF.

2. The scintillation occurrence rate in the cusp auroral region is higher by a factor 5 than immediately poleward of it. Thus, the polar cap patches which are found immediately poleward of the cusp auroral region seem to be less effective for the GPS phase scintillation production than the cusp aurora.

3. There is a clear IMF polarity impact on the scintillation occurrence rate: the occurrence rate is higher when the IMF $B_y$ is southward and the occurrence rate in the cusp region concurs the PMAF statistics. The scintillation occurrence rate is found to be higher during positive IMF $B_y$ which indicates that the scintillations are sensitive to the combination of auroral precipitation and inflow of higher density solar EUV-ionized plasma.

In conclusion, in the European Arctic sector, the highest scintillation occurrence rates appear inside the auroral region around magnetic noon and midnight. In order to predict the locations of worst scintillation impacts for the GNSS users, the key is to keep track of the positions of the cusp aurora around magnetic noon (polar cap inflow region) as well as the substorm aurora around magnetic midnight (polar cap outflow region). Care should be taken when studying the GPS scintillations by using the statistical auroral oval instead of the actual dayside auroral activities.

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