

A survey of plasma irregularities as seen by the midlatitude Blackstone SuperDARN radar

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[1] The Super Dual Auroral Radar Network (SuperDARN) is a chain of HF radars that monitor plasma dynamics in the ionosphere. In recent years, SuperDARN has expanded to midlatitudes in order to provide enhanced coverage during geomagnetically active periods. A new type of backscatter from *F* region plasma irregularities with low Doppler velocity has been frequently observed on the nightside during quiescent conditions. Using three years of data from the Blackstone, VA radar, we have implemented a method for extracting this new type of backscatter from routine observations. We have statistically characterized the occurrence properties of the Sub Auroral Ionospheric Scatter (SAIS) events, including the latitudinal relationships to the equatorward edge of the auroral oval and the ionospheric projection of the plasmapause. We find that the backscatter is confined to local night, occurs on $\approx 70\%$ of nights, is fixed in geomagnetic latitude, and is equatorward of both the auroral region and the plasmapause boundary. We conclude that SAIS irregularities are observed within a range of latitudes that is conjugate to the inner magnetosphere (plasmasphere).

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1. Introduction

[2] Ionospheric plasma irregularities are density variations that have been augmented over thermal levels by plasma instability processes [Fejer and Kelley, 1980; Keskinen and Ossakow, 1983; Tsunoda, 1988]. The spatial scale of such structures can range from a few centimeters to thousands of kilometers. Ionospheric electric fields play an important role in amplifying or damping the growth of irregularities. At high-latitudes the dominant *F* region instability processes at decameter scales are thought to be the Gradient Drift Instability (GDI) and the Current-Convective Instability [Baker et al., 1986; Hosokawa et al., 2001]. Both instabilities are associated with $\mathbf{E} \times \mathbf{B}$ drifts of the ambient plasma that arise from ionospheric electric fields of auroral origin. In the subauroral, midlatitude region, however, the situation is less understood. The electric fields and irregularity drifts in this region are typically much smaller in magnitude, lessening the effectiveness of the GDI and Current-Convective Instability mechanisms. A case study performed by Greenwald et al. [2006] suggested that the Temperature Gradient Instability

(TGI) [Hudson and Kelley, 1976] could be responsible for generating decameter-scale plasma irregularities in the quiet time midlatitude ionosphere on the nightside.

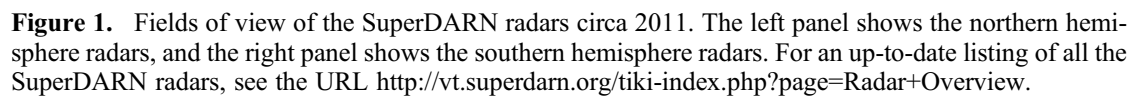
[3] The Super Dual Auroral Radar Network (SuperDARN) consists of chains of HF radars in the northern and southern hemispheres that monitor ionospheric dynamics [Chisham et al., 2007] through the detection of decameter-scale field-aligned plasma irregularities in the *E* and *F* regions of the ionosphere. SuperDARN data has been used to study high-latitude plasma irregularity processes in both the *E* and *F* regions [e.g., Ruohoniemi and Greenwald, 1997; Koustov et al., 2004]. Maps showing the locations and fields of view of the radars currently operating in the northern and southern hemisphere are shown in Figure 1. The polar cap radars are shown in green, the high-latitude radars are shown in blue, and the midlatitude radars are shown in orange. The radars are labeled with 3-letter identifiers, e.g., the radar at Blackstone, Virginia is labeled BKS. Note that the radar at Halley Station, Antarctica (HAL) is currently out of service due to an ongoing rebuild of that site.

[4] Traditionally, SuperDARN radars have been built at magnetic latitudes near 60° to maximize coverage of the auroral regions. With the construction of the Wallops Island radar (located at $L = 2.4$) in 2005, SuperDARN expanded to magnetic latitudes below 50° in the northern hemisphere. The expansion was motivated by the need to provide improved coverage of the auroral oval as it expands equatorward during storm periods [Baker et al., 2007]. However, once the Wallops Island radar became operational, it was found that

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[5] Many studies have compared SuperDARN HF Doppler measurements with satellite and incoherent scatter radar (ISR) measurements for the purpose of studying ionospheric plasma dynamics [e.g., *Ruohoniemi et al.*, 1987; *Xu et al.*, 2001; *Drayton et al.*, 2005; *Gillies et al.*, 2010]. *Greenwald et al.* [2006] compared velocity data from the new type of irregularity backscatter with data from the Millstone Hill ISR and found good agreement. They noted that the low Doppler velocity, low spectral width irregularities occurred with great frequency (they observed events on 19 out of 27 days examined in February 2006). They also noted that the scatter was observed exclusively at night, and attributed that fact to a shorting effect of the conducting E region on F region electric fields during the day [*Davies et al.*, 1999]. Using the

[6] In 2008, a second midlatitude radar in North America became operational, this time at Blackstone, Virginia ($L = 2.3$). As with the Wallops Island radar, low velocity, low spectral width ionospheric backscatter has been observed with this radar on a very regular basis. We have developed a method for distinguishing between backscatter from (1) the low-velocity nightside irregularities, (2) irregularities at midlatitudes that are caused by equatorward expansion of the auroral oval during geomagnetically active periods, and, (3) the ground, i.e., “ground scatter”. The purpose of this paper is to examine the statistical properties of the quiet time nightside midlatitude ionospheric plasma irregularities and to determine their relationship with the auroral boundary with an eye to establishing their connection to the inner magnetosphere.

[7] SuperDARN radars consist of an electronically-phased antenna array which is operated at HF between 8 and 20 MHz. HF is chosen in order to exploit refraction in the

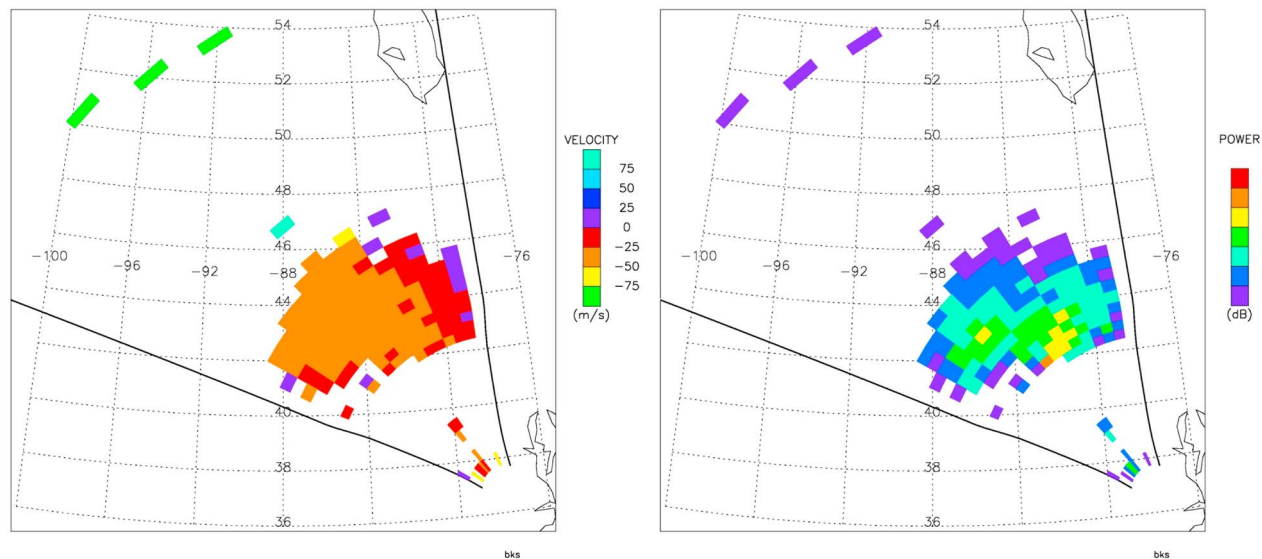


Figure 2. Field-of view plots for the Blackstone, Virginia SuperDARN radar. The data shown are from a single azimuthal scan at 06:00–06:02 UT on 3 February 2011, during a typical nightside backscatter event. The left panel shows Doppler velocity and the right panel shows backscatter power (signal-to-noise ratio).

ionosphere and maximize the range of observations. A requirement for backscatter to be observed is that the rays from the radar be orthogonal to the terrestrial magnetic field, and refraction of the HF signal allows for more rays to meet this criterion. Typically, a SuperDARN radar has 16 look directions (beams), 75–100 range gates along each beam, and a 45 km range resolution. The azimuth step between beams is $\approx 3.3^\circ$, and an azimuthal scan across all 16 beams generally lasts 1–2 minutes with a dwell time between 3 and 7 seconds on each beam. In the F region, plasma irregularities drift at the $\mathbf{E} \times \mathbf{B}$ velocity, which allows determination of electric fields from SuperDARN velocity measurements.

[8] A single 2-minute scan from the Blackstone radar on 3 February 2011 is shown in Figure 2. Figure 2 (left) shows Doppler velocity in m/s while the right panel shows backscatter power (signal-to-noise ratio) in dB. These plots show properties typical of backscatter from midlatitude nightside ionospheric irregularities as described in the introduction. The Doppler velocity magnitude is confined to values less than about 50 m/s and the backscatter power peaks near 30 dB. Note that the velocity color scale follows the astronomical standard, such that red/blue indicates motion away/toward the radar. SuperDARN radars measure only the line-of-sight component of the two-dimensional $\mathbf{E} \times \mathbf{B}$ drift velocity, so the smaller velocities on the more eastward-facing beams and the higher velocities on the westward-facing beams indicate a predominantly westward motion across the band, consistent with a poleward ionospheric electric field. This is the usual situation for the ionospheric plasma drifts and electric field associated with the low-velocity nighttime backscatter. On this particular night the backscatter persisted for about 10 hours (02:00–12:00 UT). The Kp for the time shown in the scan was 0+, indicating quiet conditions.

2.2. Classification Method

[9] Ionospheric backscatter seen at midlatitudes during quiet time is difficult to distinguish from commonly

occurring ground scatter because it also exhibits low Doppler velocity and narrow Doppler spectrum [Greenwald *et al.*, 2006; Baker *et al.*, 2007]. The traditional method of classification is to apply a threshold to the Doppler velocity and spectral width to produce a point-to-point classification [Blanchard *et al.*, 2009]. Using this method, much of the scatter shown in Figure 2 would be classified as ground scatter and therefore not suitable for analysis of ionospheric plasma drifts, instabilities, and electric fields.

[10] Figure 3a shows a time series of velocity over a 12 hour period with ground scatter classified in the traditional point-to-point manner. This period is centered on the nightside and corresponds to the period of peak occurrence of the quiet time ionospheric backscatter. Low-velocity ionospheric scatter predominates between $52^\circ \leq \Lambda \leq 59^\circ$, patches of true ground scatter are seen near $\Lambda = 60^\circ$ during the early and later hours, and a patch of higher velocity ionospheric scatter is seen near $\Lambda = 64^\circ$. The band of scatter at the lowest latitudes ($\Lambda \approx 50^\circ$) is due to meteor trails in the lower ionosphere [Hall *et al.*, 1997]. Data that are identified as ionospheric scatter are plotted in color, and data that are identified as ground scatter using the traditional method are plotted in gray. Note that the classification of the low-velocity ionospheric scatter is patchy, because its backscatter characteristics place it near the threshold for classification as ionospheric scatter.

[11] Ribeiro *et al.* [2011] developed a method that is able to identify periods of low velocity, low spectral width ionospheric scatter by finding clusters of connected backscatter points and analyzing their velocity characteristics as a whole to classify them as “events” (long-lived periods of ionospheric scatter) or “non-events” (other types of backscatter). To demonstrate its application, we present an example of midlatitude Doppler velocity data obtained on a single beam of the Blackstone radar on a typical day. Figure 3b shows the same data as in Figure 3a, but processed with the method of Ribeiro *et al.* [2011]. Data that are identified as part of an ionospheric scatter event are plotted in color, and data

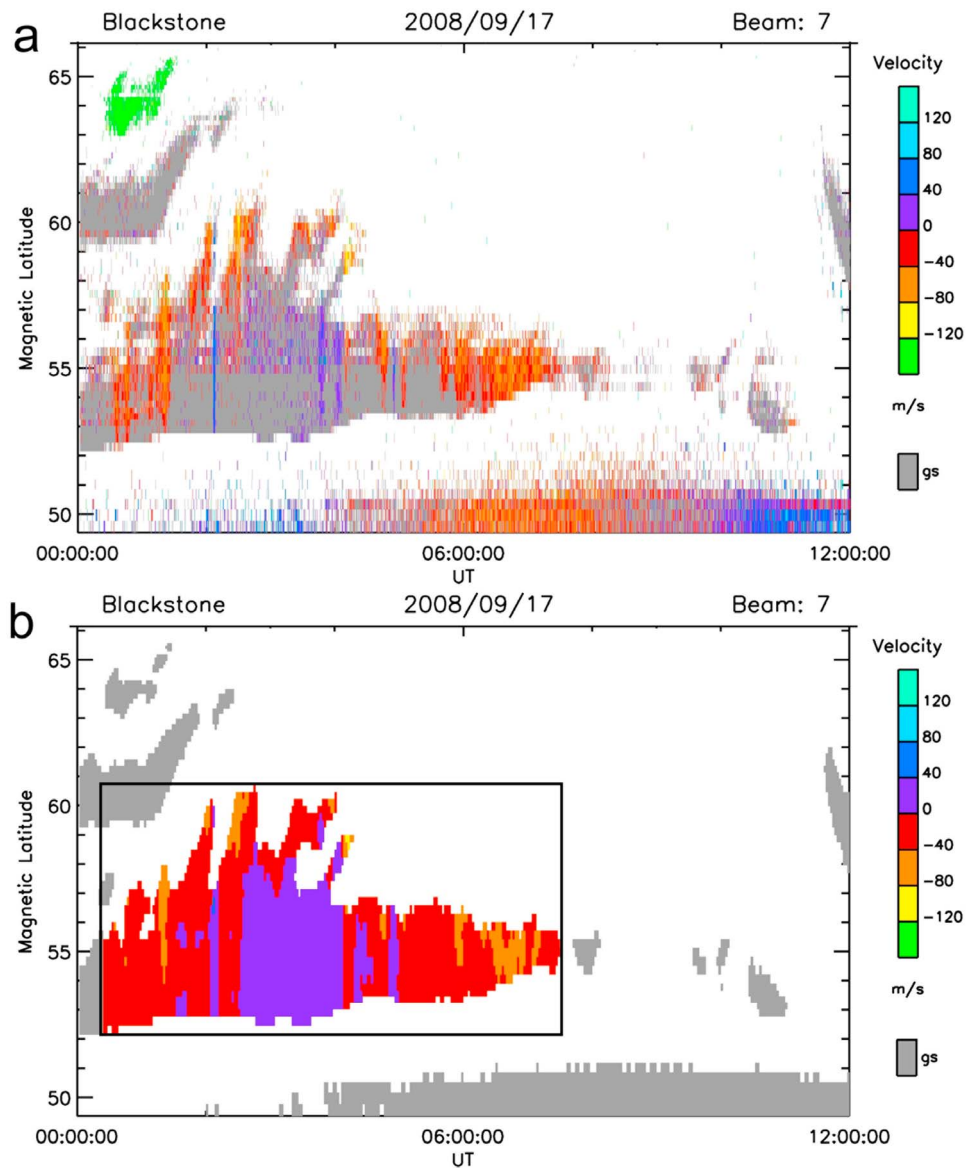


Figure 3. A comparison of the traditional and new backscatter classification methods. (a) A 12-hour range-time plot for beam 7 of the Blackstone radar on 17 September 2008. The data that are plotted in gray have been classified as ground scatter, and the data plotted in color have been identified as ionospheric scatter, as identified by the traditional method of distinguishing between ionospheric and ground scatter. (b) The same 12-hour range-time plot for beam 7 of the Blackstone radar on 17 September 2008 using the new classification method. These data show a typical midlatitude low-velocity ionospheric scatter event. The data that are plotted in gray have been classified as non-events, and the data plotted in color have been identified as belonging to events of ionospheric scatter, according to the search method of *Ribeiro et al.* [2011]. Additionally, the region of scatter that has been identified as an ionospheric event has been boxed off.

identified as non-events (i.e. ground scatter/meteor scatter) are plotted in gray. Additionally, the data that have been identified as constituting an “event” are boxed for easy identification. Note that as part of the processing, the data shown in Figure 3b have been median-filtered to remove salt and pepper noise. The reason that the data classification goes from gray to colored within the interval of quiet time ionospheric scatter occurrence is a result of post-processing, whereby the leading and trailing edges of a data cluster are

examined in order to avoid a ground scatter event leading into an ionospheric event, or vice versa (see *Ribeiro et al.* [2011] for details). The slight loss of event data is deemed an acceptable trade-off to avoid contamination by ground scatter. This type of ionospheric activity is seen quite frequently, and will be discussed further in Section 3.1.

[12] The scatter classification method of *Ribeiro et al.* [2011] does a good job of identifying periods of ionospheric scatter observed by the midlatitude SuperDARN

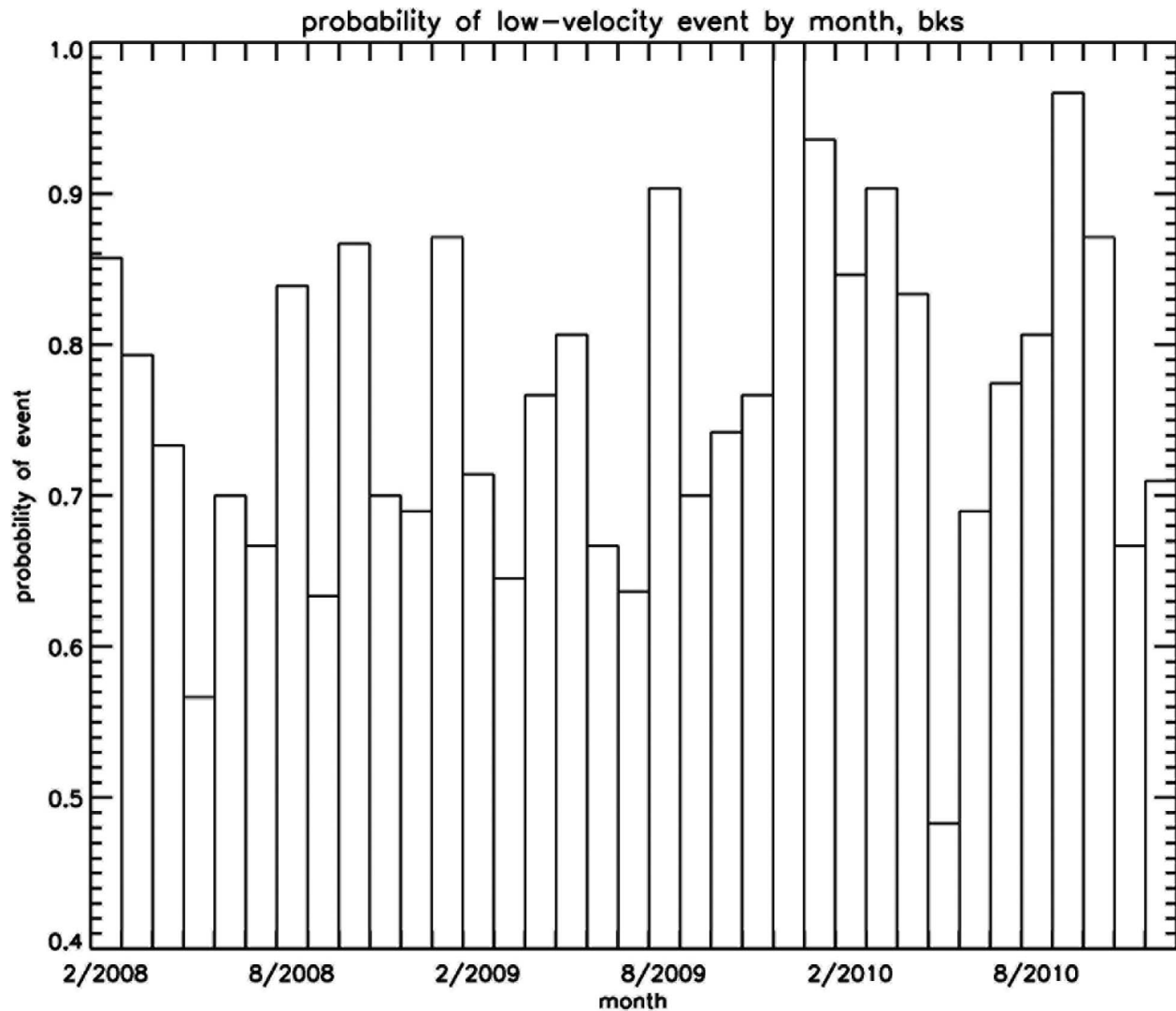


Figure 4. Probability of observing a low-velocity event on at least three beams for the Blackstone radar on a given UT day, organized by month. The probability is determined as the number of days with at least three beams observing at least one low-velocity event divided by the number of days the radar was operational.

radars, but it identifies both low Doppler velocity ionospheric backscatter seen very frequently at midlatitudes, and high Doppler velocity backscatter associated with disturbance conditions as one and the same. That is, it flags both high and low velocity events as generic ionospheric events although they clearly have different drivers. (Note that the patch of high-velocity ionospheric scatter seen in Figure 3a at higher latitudes did not last long enough to be identified as an “event” by the method of *Ribeiro et al.* [2011].) Because our aim is to examine the characteristics of the quiet time mid-latitude irregularities in isolation, an additional separation must be performed. We add the condition that within an ionospheric event, if the 3rd percentile of the velocity distribution is above -120 m/s and the 97th percentile of the velocity distribution is below 120 m/s, the data in the cluster are flagged as low-velocity ionospheric backscatter. Otherwise, they are flagged as high-velocity ionospheric backscatter. These velocity values have been chosen through

trial-and-error because during typical quiet time conditions, the midlatitude radars rarely observe backscatter with Doppler velocity magnitudes in excess of 120 m/s. The practical impact of imposing this condition is that backscatter from disturbed days and high latitudes is largely excluded from the analysis. In this paper, we aim to statistically describe the occurrence frequency, local time dependence, geomagnetic activity level dependence, and latitudinal variation of the low-velocity midlatitude events. Hereinafter, we refer to these types of events as Sub Auroral Ionospheric Scatter (SAIS) for reasons that will be demonstrated in Section 3.

3. Observations

[13] The ability to automatically identify SAIS makes possible analysis of its characteristics in order to provide insight into the natures of the irregularities. Specifically, we will examine the seasonal variations, diurnal variations,

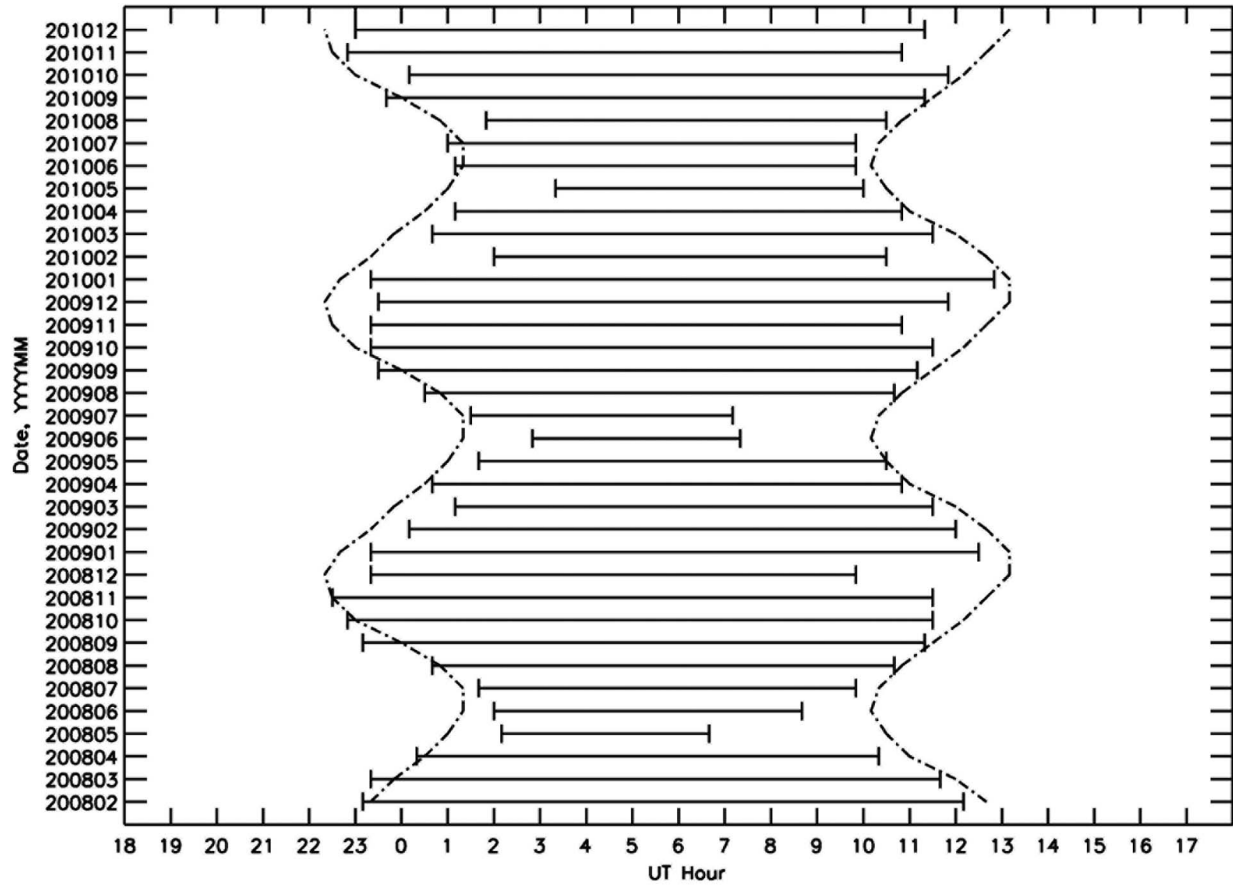


Figure 5. Typical monthly start/stop times for low-velocity events seen by beam 7 of the Blackstone radar and a comparison to sunset and sunrise. The dash-dot vertical curve on the left is sunset for Chicago, IL (approximately under the center of beam 7) and the vertical curve on the right is sunrise for Chicago. The bars in the center span from the typical start of low-velocity events in a given month to the typical end of low-velocity events.

dependence on geomagnetic activity level, latitude of observation, and latitudinal relation to geophysical features.

3.1. Seasonal Dependence

[14] Low-velocity plasma irregularities are frequently observed by the midlatitude SuperDARN radars. In Figure 4, the probability of the Blackstone radar detecting a low-velocity event on a given UT day is shown for February 2008 to December 2010. The probability is calculated as the number of days a low-velocity event of at least one hour duration was observed on at least three beams divided by the number of days the radar was running that month. For most months, the probability of seeing at least one event on a given night is around 70%, which is consistent with the preliminary characterization from early observations with the Wallops Island radar [Greenwald *et al.*, 2006]. This suggests that the instability processes causing these irregularities are very common. We see no clear correlation of probability of occurrence with season or with solar cycle. Perhaps with more years of data a solar cycle pattern could emerge, however, it seems unlikely that there is a strong seasonal factor in the probability of occurrence of SAIS.

3.2. Local Time Dependence

[15] Another important feature of the low-velocity midlatitude irregularities is that they are seen almost exclusively during local night, as was first noted by Greenwald *et al.* [2006]. In fact, the typical start/stop times coincide almost exactly with sunset/sunrise. This time envelope is illustrated in Figure 5, which shows the typical monthly start/stop times for low-velocity backscatter events observed on beam 7 of the Blackstone radar. The typical start time is defined as the time when at least 3 days in the month have had a low-velocity event begin, and the stop time was determined as the time when only 3 days still have a low-velocity event occurring. Sunset and sunrise times from the 15th (approximately the middle) of every month at Chicago, Illinois are also shown. Chicago was chosen because it is under the center of the Blackstone radar's field of view for this beam. There is a clear correlation between time of occurrence and sunset/sunrise, and the total absence of irregularities after sunrise indicate a strong likelihood that the irregularities are not present during the day. This could be caused by a conducting *E* region shorting out the electric fields during the daytime, as suggested by Greenwald *et al.* [2006]. Another possibility is that

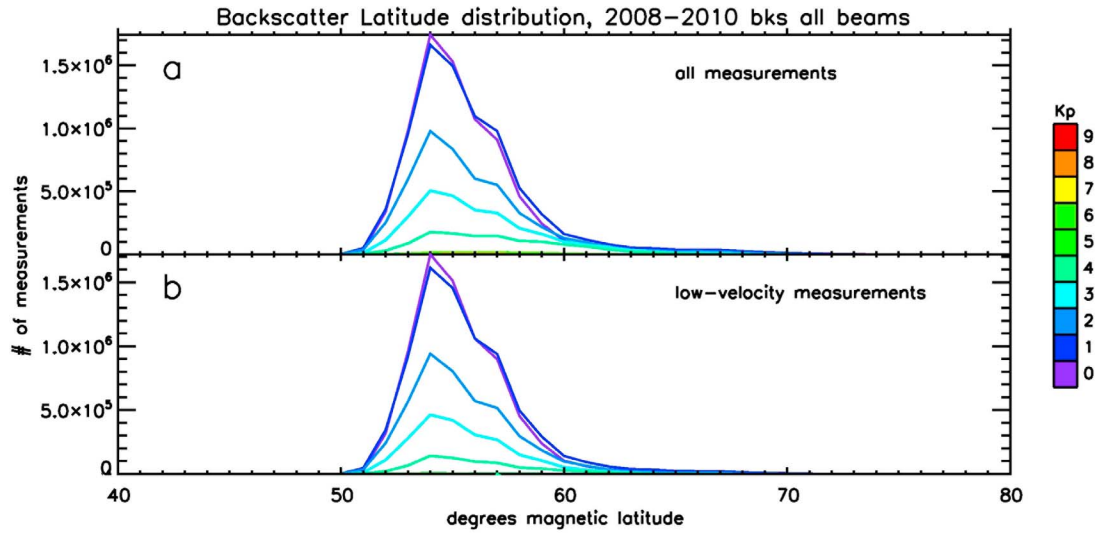


Figure 6. (a) The latitude distribution of ionospheric backscatter seen by all beams of the Blackstone radar across all local time sectors. (b) The latitude distribution of backscatter that has been classified as low-velocity.

they are not visible to the radar until after sunset because of requirements on propagation that are not satisfied during the daylight hours.

3.3. Relation to Geomagnetic Activity Level

[16] A cursory review of the data indicates that SAIS is common at all geomagnetic activity levels; we now consider whether the irregularities causing the backscatter are more frequent at certain activity levels and whether there is a connection to geomagnetic features, such as the plasmopause, which has an ionospheric footprint that moves equatorward

with enhanced activity. The SAIS caused by ionospheric plasma irregularities seen by the Blackstone radar is observed almost exclusively between $50^\circ < \Lambda < 60^\circ$. This is illustrated in Figure 6. The upper panel shows the distribution in magnetic latitude of all backscatter identified as ionospheric by the method described by *Ribeiro et al.* [2011]. $\Lambda = 50^\circ$ is the lower boundary for observation of SAIS because this is the near-range horizon for F region backscatter for the Blackstone radar, but the irregularities most likely extend beyond this latitude. The lower panel shows the distribution in

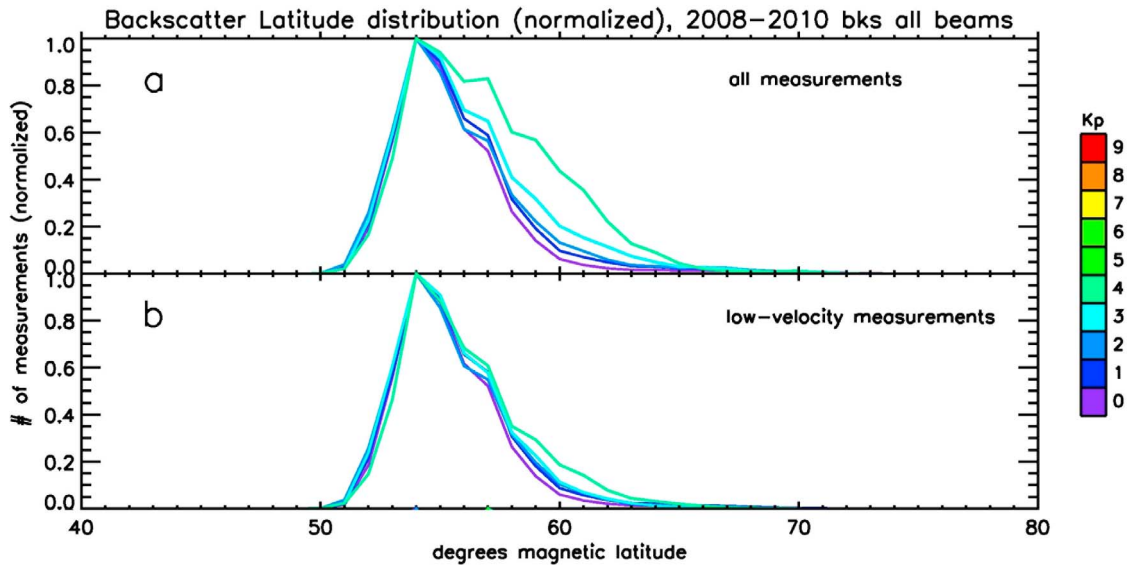


Figure 7. (a) The normalized latitude distribution of ionospheric backscatter seen by all beams of the Blackstone radar. The data has been modified from Figure 6 by multiplying all points along the distribution for a given Kp index by a factor that results in all activity levels having the same maximum. (b) The normalized latitude distribution of low-velocity backscatter events. Data for $0 \leq Kp \leq 4$ have been plotted, as there is an insignificant number of points for $Kp > 4$ in Figure 6a.

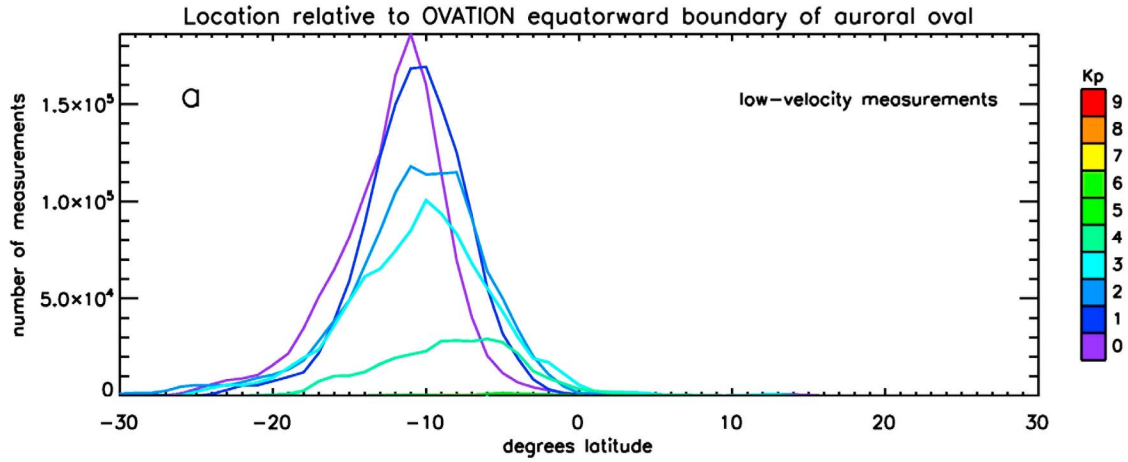


Figure 8. Latitude of low-velocity data points relative to the OVATION equatorward boundary of the auroral oval. A negative value means that the backscatter is equatorward of the boundary, and a positive value means that the backscatter is poleward of the boundary.

magnetic latitude for the data clusters of low-velocity irregularities (SAIS). Panels (a) and (b) look very similar because of the fact that nearly all of the data obtained during solar minimum had low Doppler velocity. It is quite evident, though, that the SAIS events occur basically in the same range of magnetic latitude for all values of Kp . Moreover, the shape of the distribution does not seem markedly dependent on Kp .

[17] The properties discussed in the previous paragraph become even more visible when the distributions are normalized for the number of measurements at each Kp value, which is shown in Figure 7. For each value of Kp with a significant number of measurements (maximum greater than 100000 Doppler measurements) within the distribution ($0 \leq Kp \leq 4$), the number of measurements is normalized. For context, $Kp = 5$ had only 18000 measurements and is therefore excluded. Each distribution is normalized to its maximum and registered on a scale from 0 to 1. It is immediately apparent that Figures 7a and 7b do in fact have different

properties, which were not clearly visible in Figure 6. In Figure 7a, it can be seen the number of data points at higher magnetic latitudes increases with increasing Kp . In Figure 7b, where only SAIS is considered, it can be seen that the distributions for all Kp values are almost identical. In fact, the only level of geomagnetic activity that shows a difference is $Kp = 4$, which could be due to a lack of data at this activity level. The slight difference could also be the result of the classification method erroneously flagging some backscatter from irregularities associated with geomagnetic disturbance as SAIS. These results indicate that the observed location of SAIS does not depend significantly on geomagnetic activity. Furthermore, we have considered the possibility that SAIS is observed more frequently at certain geomagnetic activity levels. A comparison of the number of measurements at each geomagnetic activity level $0 \leq Kp \leq 4$ with the number of time periods at each geomagnetic activity level has shown that the frequency of observation of SAIS is independent of Kp .

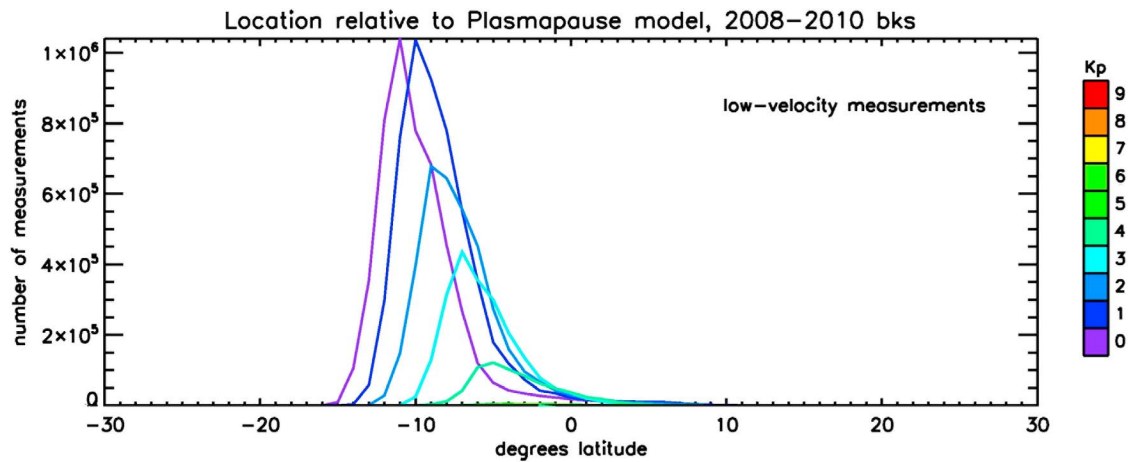


Figure 9. Latitude of low-velocity data points relative to the plasmapause model described by *Moldwin et al.* [2002]. A negative value means that the backscatter is equatorward of the model, and a positive value means that the backscatter is poleward of the model.

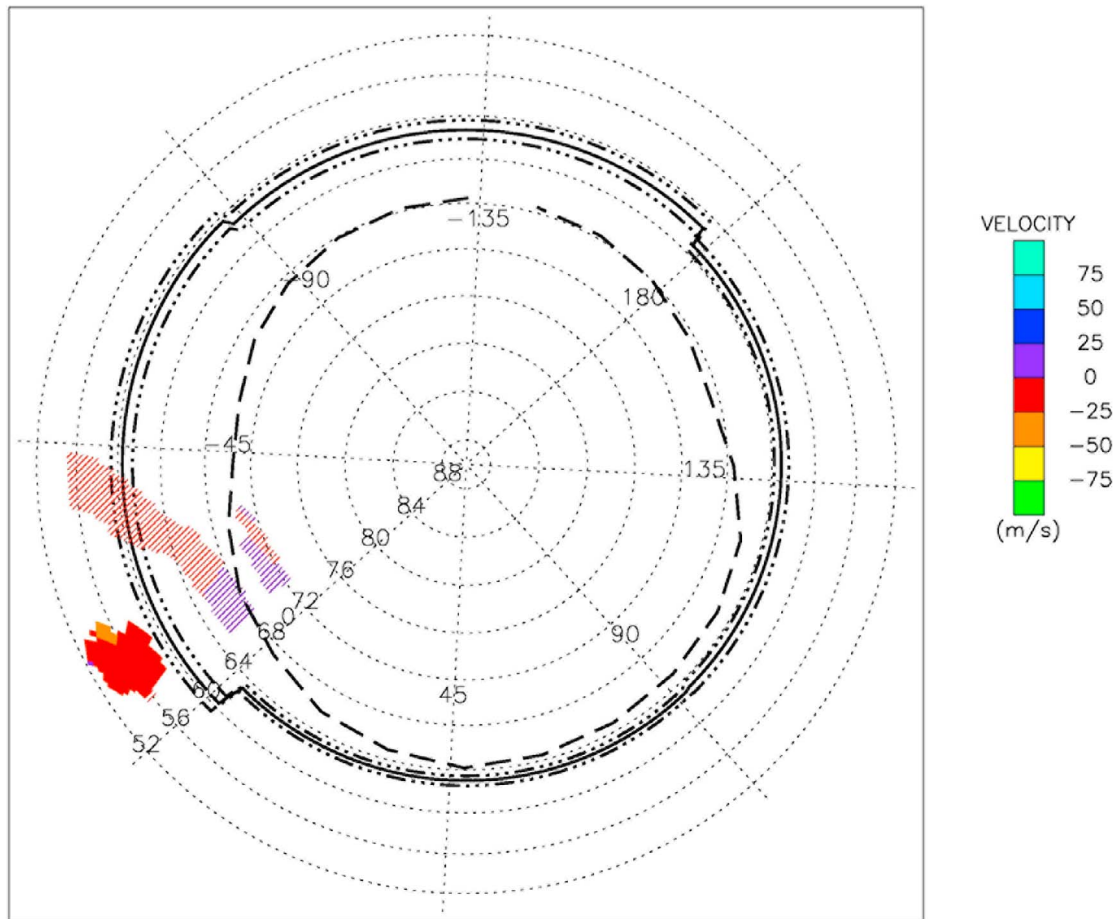


Figure 10. A field of view plot of a 2-minute scan for the Blackstone radar on 17 September, 2008. The filled cells are data that have been identified as SAIS, and the shaded cells have been identified as ground scatter. The dashed line represents the OVATION equatorward boundary of the auroral oval. The solid line represents the plasmopause location according to the model proposed by *Moldwin et al.* [2002], while the dash-dot lines represent the error on the model.

3.4. Relation to Auroral Oval

[18] The results presented in Figures 6 and 7 suggest that the observations of SAIS are not sensitive to the magnetic activity level in terms of the latitudinal distribution, but perhaps they are instead organized by some geophysical feature. An obvious choice for comparison is the location of the auroral oval. Oval variation, assessment, tracking, intensity, and online nowcasting (OVATION) is a technique that approximates the location of the auroral oval using several data sets, including DMSP, auroral imaging, and high-latitude SuperDARN [Newell et al., 2002]. Using the equatorward boundary locations as determined by OVATION for 2008, we can compare the location of the low-velocity irregularities to the auroral oval. The comparison is between the latitude of radar measurements and the latitude of the auroral boundary at the magnetic local time closest to the data point. In Figure 8, the latitude distribution of low-velocity Doppler measurements as a function of relative distance to the equatorward edge of the auroral oval for 2008 is shown. For the low-velocity data, the great majority of the points for

all activity levels clearly lie equatorward of the auroral region, shifting somewhat closer to the equatorward edge as the level of geomagnetic activity increases. This is because the auroral oval is expanding with increased geomagnetic activity, while the latitude where SAIS is being observed remains constant. Since the irregularities seem to be entirely subauroral, the term SAIS is justified.

3.5. Relation to Plasmopause

[19] *Moldwin et al.* [2002] described a new plasmopause model developed using CRRES spacecraft measurements. Their model expresses the boundary in L-shell as a linear function of Kp and local time sector. Because the Kp index and magnetic local time of radar backscatter measurements are readily available, this model is ideal for comparison to the latitude of radar measurements, at least in a statistical sense. The results of this comparison are illustrated in Figure 9 in the same fashion as Figure 8. The magnetic latitude of the SAIS approaches the plasmopause boundary as geomagnetic activity increases. In reality, the plasmopause is moving to lower latitudes with Kp and this is closing up the

difference. In any case, the SAIS distribution clearly extends well equatorward of the location of the plasmapause. It is possible that the latitudinal profile of SAIS is influenced by HF propagation factors, nonetheless, it is apparent that the location of the irregularities responsible for SAIS is not tied to the location of the plasmapause; rather, the irregularities populate a wide region of an area of ionosphere that spans the projection of the plasmasphere extending to the plasmapause.

[20] Statistical distributions alone cannot give a holistic portrait of where SAIS occurs in relation to geophysical features. We therefore select one event for closer examination. Figure 10 shows a field-of-view plot of one 2-minute scan from the Blackstone radar. The data are from the interval 01:30–01:32 on 17 September 2008, which is the same date as the plot shown in Figure 3. In this field of view plot, data that have been flagged as SAIS and ground scatter are both visible. Additionally, the OVATION equatorward boundary of the auroral oval, as well as the plasmapause model position according to *Moldwin et al.* [2002], are shown. The ionospheric backscatter (filled cells) lies in the $50^\circ < \Lambda < 60^\circ$ range, as was observed in the distributions. The data are from a moderately active period, with $Kp = 2+$. It can be seen that the scatter is well equatorward of the auroral region and equatorward even of the lower-latitude error limit of the plasmapause. This is typical SAIS as shown in the distributions, that is, a long-lived band of ionospheric irregularities with Doppler velocities in the tens of m/s, occurring equatorward of both the auroral oval and the plasmapause.

4. Discussion

[21] *Greenwald et al.* [2006] observed a new type of backscatter from ionospheric irregularities at midlatitudes with HF radar. Based on a case study involving coordination between the Wallops Island radar and the Millstone Hill ISR, they were able to draw some conclusions about the nature of the irregularities. *Oksavik et al.* [2006] and *Baker et al.* [2007] also used measurements from the new Wallops Island radar to examine midlatitude plasma dynamics during geomagnetically active periods. We have collected 3 years of midlatitude SuperDARN data from the Blackstone, Virginia radar for an examination of the low-velocity, narrow Doppler spectrum ionospheric irregularities. Based on the examination of where the low-velocity scatter occurs for different Kp levels, as well as the relation to the equatorward edge of the auroral oval, the conclusion is that these irregularities are subauroral, as was first mentioned in the Introduction.

[22] SAIS observed by the Blackstone radar is very frequent, being observed on $\approx 70\%$ of nights. Additionally, SAIS is seen almost entirely on the nightside. It is probable that the irregularities do not exist during the day because of a conducting E layer shorting out electric fields. However, even if they do exist during the daytime, the sunlit ionosphere could affect signal propagation in such a way that the radar signals do not encounter the irregularities at all, or do not encounter them under suitable magnetic aspect conditions, rendering the irregularities effectively invisible to the radar. The modeling of propagation modes and resolution of the propagation factor in observations of SAIS will be the subjects of future studies.

[23] The comparisons with the OVATION boundaries and plasmapause model also provide insight into the source

mechanism of the irregularities. In Figure 8, the latitudinal distribution of SAIS approaches the auroral oval as geomagnetic activity increases. In fact, the expanding auroral oval is actually approaching the SAIS, which is nearly stationary in geomagnetic latitude, regardless of Kp . The SAIS shows a similar relationship to the plasmapause model as it does to the auroral boundary. That is, it remains in the same window of latitudes as the model plasmapause moves equatorward during periods of enhanced geomagnetic activity. This observation suggests that the source region for SAIS is not only subauroral, but also that it extends far equatorward of the ionospheric projection of the plasmapause, which indicates the outer boundary of the plasmasphere [*Carpenter*, 1966]. This implies that SAIS is observed on magnetic field lines that map to the inner magnetosphere, specifically, to the plasmasphere.

[24] The fact that SAIS is observed with such high frequency, and always in the same window of magnetic latitudes suggests that the nightside midlatitude ionosphere is littered with plasma irregularities. It then follows that the observed latitudinal distribution of SAIS may be strongly influenced by propagation factors. Which instability processes cause the generation of irregularities is not yet known, nor whether the variable occurrence of SAIS on a given night is due to plasma instability or propagation factors. *Greenwald et al.* [2006] suggested that the TGI was generating the instabilities after a coordinated campaign with the Millstone Hill ISR revealed opposed temperature and density gradients. These are the conditions necessary for the TGI as described by *Hudson and Kelley* [1976]. Opposed temperature and density gradients are a common feature in the vicinity of the ionospheric projection of the plasmapause. However, SAIS seems to be found all over the nighttime midlatitude ionosphere and is routinely observed from regions more than 10° equatorward of the plasmapause projection, i.e. quite far from the most prominent source of the TGI. The fact that irregularities produced by the TGI would decay with increasing distance from the source region (plasmapause), and that the latitudinal distribution of SAIS is insensitive to the level of geomagnetic activity suggests that the TGI is unlikely to account for the bulk of the observations of these irregularities. More campaigns between midlatitude SuperDARN radars and the Millstone Hill ISR should help reveal what mechanisms predominate.

[25] An instability process that is known to cause irregularities at high latitudes is the GDI. The GDI has been credited with causing “dusk scatter”, which arises following sunset from the auroral boundary region and persists for typically a 1–2 hour period with velocities somewhat lower than those associated with scatter from the auroral oval [*Ruohoniemi et al.*, 1988; *Hosokawa et al.*, 2002; *Hosokawa and Nishitani*, 2010]. This seems unlikely to be the source of SAIS irregularities however, because the characteristic velocities of SAIS are much lower than those seen in dusk scatter events, and are easily distinguished from groundscatter events. In addition, the predominant westward drift of the ionospheric plasma associated with SAIS noted here is inconsistent with a mechanism that would populate the nightside ionosphere with irregularities generated near the dusk terminator.

[26] The Perkins instability is another nighttime midlatitude instability which is capable of generating irregularities

[Perkins, 1973]. The requirements for this process are an eastward electric field which supports F region plasma against gravity and a northward electric field, which drives instability. Westward velocities (corresponding to northward electric fields) are commonly observed in SAIS. This instability, however, generally has a low growth rate. The problem of low growth rate can be overcome with instability seeding by gravity waves and neutral wind enhancement of the growth rate [Miller, 1997; Kelley and Fukao, 1991].

[27] Medium Scale Traveling Ionospheric Disturbances (MSTIDs) are a phenomena frequently observed by SuperDARN radars which are closely linked to gravity waves. Work by Ogawa *et al.* [2009] and Suzuki *et al.* [2009] has examined MSTIDs in midlatitude SuperDARN data using the Hokkaido radar. Some of the radar backscatter which was used in these studies exhibited properties very similar to SAIS. Because of the propagation direction of the MSTIDs in these studies, it was suggested that the MSTIDs might have been generated by the Perkins instability. This can be achieved when finite amplitude F region plasma structures which are generated by gravity waves are amplified by the Perkins instability. The Perkins instability has a positive growth rate only in a narrow range of azimuths [Perkins, 1973], and it has been shown that in the nighttime midlatitude ionosphere, disturbances traveling in the Perkins direction are enhanced, while those propagating in other directions are damped [Miller, 1996; Kelley and Miller, 1997]. Kelley [2011] suggested that nighttime gravity waves could be generated by Joule heating. Future work on gravity waves and further examination of midlatitude ionospheric conditions could identify if the Perkins instability is indeed responsible for generating these decameter scale irregularities. Another possibility that must be considered is whether hybrid mechanisms are responsible for generating the bulk of the midlatitude irregularities observed as SAIS [e.g., Cosgrove and Tsunoda, 2004].

5. Summary

[28] In this paper we have analyzed the occurrence properties of a category of ionospheric scatter seen with the midlatitude SuperDARN radars during quiet times in the nightside ionosphere. The scatter is associated with low Doppler velocities and spectral widths and is distinctly subauroral. We have demonstrated an ability to select for SAIS events with data from the Blackstone SuperDARN radar, making possible statistical analysis of its occurrence and properties. Upon doing so, it is clear that SAIS is observed on field lines that map into the plasmasphere. It is also clear that the midlatitude ionosphere is quite active with irregularities, regardless of geomagnetic activity, and that the SuperDARN radars in this latitude region commonly make measurements within the region of the ionosphere that is conjugate to the inner magnetosphere, with a frequency of about 3 out of every 4 nights. We have characterized the occurrence of SAIS and its relation to the auroral oval boundary and plasmapause. Future work will consider the impact of propagation factors on observation of the irregularities, the sources of plasma instability that populate the midlatitude ionosphere with irregularities on the nightside, and the connection to plasma processes in conjugate regions of the plasmasphere. We note that the midlatitude SuperDARN radar observations of

irregularities and their motions provide a window on the electric fields in the subauroral ionosphere and conjugate region of the plasmasphere.

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