# Large-scale aspects and temporal evolution of pulsating aurora

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**Abstract.** Pulsating aurora is a common phenomenon generally believed to occur mainly in the aftermath of a substorm, where dim long-period pulsating patches appear. The study determines the temporal and spatial evolution of pulsating events using two THEMIS ASI stations, at Gillam (66.18 mlat, 332.78 mlon, magnetic midnight at 0634 UT) and Fort Smith, (67.38 mlat, 306.64 mlon, magnetic midnight at 0806 UT) along roughly the same invariant latitude. Parameters have been calculated from a database of 74 pulsating aurora events from 119 days of good optical data within the period from September 2007 through March 2008 as identified with the Gillam camera. It is shown that the source region of pulsating aurora drifts or expands eastward, away from magnetic midnight, for pre-midnight onsets and that the spatial evolution is more complicated for post midnight onsets, which has implications for the source mechanism. The most probable duration of a pulsating aurora event is roughly 1.5 hours while the distribution of possible event durations includes many long (several hours) events. This may suggest that pulsating aurora is not strictly a substorm recovery phase phenomenon but rather a persistent, long-lived phenomenon that may be temporarily disrupted by auroral substorms. Observations from the Gillam station show that in fact, pulsating aurora is quite common with the occurrence rate increasing to around 60% for morning hours, with 69% of pulsating aurora onsets occurring after substorm breakup.

## 1. Introduction

Pulsating aurora is often observed along the equatorial side of the auroral oval after substorm break up within a widespread region of diffuse aurora, and develops as irregularly shaped patches which over time begin to pulsate. The patchy structure, described in "The Last Rocket Club" by Thomas Mallon (Southwest Review, 1992) as "thin luminous gruel", is typical of pulsating aurora, which is characterized by quasi-periodic brightness modulations with periods ranging from 2 to 20 seconds, or 8 seconds on average [Royrvik and Davis, 1977]. Individual patches pulse out of phase with each other and may have slightly different periods. The patches, which can span 10s to 100s of kilometers, vary greatly in shape and size, with the shape changing on a timescale of minutes [Johnstone, 1978]. Streaming is often seen in the patches with brightening in one area that expands outward during the pulsation. Pulsating aurora is generally quite dim, often sub-visual, with a typical brightness in the range of 100s R - a few kR in the 427.8 nm emission.

The *International Auroral Atlas* (International Union of Geodesy and Geophysics (IUGG), 1963) describes the temporal variations of slowly varying auroral forms in several categories including pulsating, flaming, streaming, and fast auroral waves. *Pulsating* aurora is a quasi-periodic modulation of the intensity of extended forms. A separate phenomenon called *flickering* aurora tends to develop within discrete arcs and exhibits oscillations near 6-8 Hz and higher. *Flaming* aurora is an intensity modulation that tends to travel upwards along local magnetic field lines. Horizontal temporal changes are classified as *streaming* when traveling along an arc, or as *fast auroral waves* when appearing as a progression of arcs in latitude [Vallance Jones, A., 1974].

Thorough reviews of pulsating aurora have been presented by Davis [1978], Johnstone [1978], Johnstone [1983], Sandahl [1985] and Davidson [1990]. Pulsating aurora is generally thought to be caused by energetic electrons [Smith et al., 1980; McEwen et al., 1981], precipitated from the equatorial magnetosphere by pitch angle diffusion [Davidson, 1986b, a; Huang et al., 1990]. The equatorial location of the source region has been estimated based on two types of analysis: first, velocity dispersion analyses of sounding rocket observations of energetic electrons in conjunction with pulsating aurora (for example, Bryant et al. [1975]; Smith et al. [1980]; McEwen et al. [1981]; Yau et al. [1981] and Sandahl [1985]) and second, observations of magnetically conjugate pulsating aurora events (for example, Belon et al. [1969]; Gokhberg et al. [1970] and Davis [1978]). Several recent studies have shown cases of pulsating aurora with precipitating electron velocity dispersion indicating a nearer earth source region and/or a lack of magnetic conjugacy [Sato et al., 1998; Sato et al., 2002; Sato et al., 2004; Watanabe et al., 2007]; however, the majority of pulsating aurora studies have indicated an equatorial source.

The occurrence of pulsating aurora has long been associated with auroral substorms; numerous papers have discussed pulsating aurora in the context of substorm recovery phases, that is, after auroral breakup in the post-midnight local time sector [Akasofu, 1968; Duthie and Scourfield, 1977]. Oguti and Watanabe [1976] observed that the drift of the region of pulsating aurora may be related to the eastward drift of substorm-injected electrons and Akasofu [1977] proposed that pulsating aurora is caused by pitch-angle scattering of high energy, substorm-injected electrons. Since then, several studies have attempted to show a link between the substorm-injected electrons, measured by satellites near the equatorial magnetosphere, and the optical pulsating aurora measured by ground cameras [Nakamura et al., 1990; Nemzek et al., 1995; Suszcynsky et al., 1997]. However, this has often proved difficult due to a lack of satellite conjunctions with ground camera measurements of pulsating aurora.

## 2. Large-scale aspects of pulsating aurora

The usefulness of optical data is that it reveals the nature of auroral structures over many scales, both temporal and spatial, which is generally thought to reflect the dynamics of the source region. To a significant extent, auroral displays provide near real-time displays of the dynamic activity occurring at much higher altitudes.

In trying to understand what role pulsating aurora may play in magnetosphere-ionosphere coupling, certain properties of pulsating aurora events need to be characterized, including fundamental aspects regarding its global morphology and its large-scale spatial and temporal evolution. In spite of this apparent importance, studies that address the large-scale aspects have been very limited.

One important study by Cresswell [1972] presents a discussion of pulsating aurora and its relationship to substorms and diffuse aurora. The paper introduction presents an excellent overview of the state of knowledge of pulsating aurora at the time, noting that "The displays extend several hundred kilometers meridionally as well as several thousand kilometers zonally, so their behaviour must be associated with large scale magnetospheric processes"; however, no citation is provided to support this statement. On the other hand, a discussion citing the thesis of J. P. Heppner in 1954 notes that Heppner determined that pulsating aurora occurs mainly between the near-midnight region and the dawn sector, with an occurrence frequency that appears to peak near 64° magnetic latitude and to be quite low poleward of 66° and equatorward of 60°. The Heppner study used data only from College, Alaska, so the latitudinal coverage was limited and, of course, not much was said (or could be said) about the temporal evolution of the large-scale region.

Kvifte and Pettersen [1969] present results from a statistical study based on observations made from Tromsø, Norway, during the winter of 1967-68. Data were obtained from four photometers at 428 nm, each having a field-of-view of 10°, pointed to the south with elevations of 30° and 45°, towards zenith and to the north at 45°. Data were obtained from only 27 nights during the winter season. Note that a 10° field-of-view maps to approximately a 15 km patch in the ionosphere, assuming emissions at 90 km with the photometer pointed along zenith, so the coverage was limited to four distinct patches in this study. Latitudinal and longitudinal occurrence rates of pulsating aurora are determined with this arrangement and it is concluded that pulsating aurora events occur over the entire range covered (65° to 68° ILAT) and over all magnetic local times from pre-midnight to 0900 MLT, with occurrence rates ranging from less than 25% to greater than 75%.

A somewhat more extensive statistical study was carried out by Oguti et al. [1981], using data acquired with all-sky cameras during 34 nights in early 1980 from five stations, ranging from 61.5° to 74.3° in central Canada. Note that this was during a solar maximum interval. From this study it is concluded that the occurrence probability of pulsating aurora is approximately 30% near midnight but increases to 100% near 0400 MLT (though the data are limited by daylight, forcing the cameras to shut down in this region). Although it is noted that the amount of data is insufficient to provide reliable statistics, it is concluded that pulsating aurora occurs primarily between 61° (near the limit of their observing capability) and 70° and that there may be a weak peak in occurrences near 66°.

Royrvik and Davis [1977] consider aspects of pulsating aurora on smaller scales, noting that "all-sky camera data from Byrd Station demonstrate that the pulsating aurora can extend eastward from the darkside auroral oval around to the noon meridian or even beyond" (although a citation for this information is not provided). Note that, because of the relative orientations of the magnetic and geographic poles in the southern hemisphere, stations in the auroral zone remain in darkness 24 hours per day and can thus support optical observations in the dayside auroral zone.

Finally, Berkey [1978] present photometric and riometer observations obtained just after twilight (1300-1600 M.L.T.) at College, Alaska, and show the occurrence of pulsating auroras in the *afternoon sector*. The events are detected simultaneously using a 428 nm photometer and a riometer. By connecting the photometer output to a differentiating amplifier, they compare 428 nm emissions to sunlight (actually, to twilight). As the sun sets, a pulsating aurora signature is observed corresponding to riometer absorptions that were present before the optical signatures could be observed, due to sunlit conditions. With this arrangement, only a half dozen events were observed during the winter of 1967-68. Still, the results suggest that the pulsating aurora generation mechanism can operate on nearly global scales.

The purpose of the study presented below was to calculate statistics to better understand aspects of the generation of pulsating aurora (eg, using optical observations to learn about the source region). A description of the development and morphology of pulsating aurora from the perspective of THEMIS ground camera observations is presented.

## 3. Methodology

This study made use of THEMIS all-sky camera data from Gillam and Fort Smith stations. Figure 1 shows the locations of these cameras within the THEMIS array, each of which produces a "white light" (unfiltered) image of 256x256 pixels every 3 seconds. Each circle represents the extent of coverage in the ionosphere, based on emissions at 110 km altitude, so pulsating aurora emission (at a lower altitude) decreases the size of the circle. For observations along zenith, this corresponds to a spatial resolution of approximately 1 km, although this resolution is degraded dramatically for features low on the horizon. The sensitivity of the cameras is roughly 1 kR, integrated over all wavelengths within the passband of the instrument, thus the occurrence rates obtained in this study may be underestimated due to exclusion of very dim events. Note that in order to compare onsets at different locations, clear skies at both stations are required, thus the inclusion of data from multiple sites quickly reduces the number of events that can be observed.

For studies of longitudinal propagation, we use data from Fort Smith and Gillam stations. Although the fields-of-view of these cameras do not overlap in longitude, the gaps are tolerable. These stations are approximately 1.5 hours apart in magnetic local time (UT= 0500 and 0630 at magnetic midnight). The field-of-view of each camera spans $\sim 1$ hour, so the resulting coverage in MLT is the order of 2.5 hours.

Events were identified by the presence of a pulsating patch anywhere within the field-of-view of the camera. No effort was made to follow patch drift and, as noted above, the camera fields-of-view do not overlap. Therefore care must be taken when comparing onset times at adjacent stations to conclude whether a particular event has drifted or expanded from one camera to another. In some cases it is possible that pulsating aurora may have onset in separate, localized regions and simply appears to be a single, continuous event. For such events, THEMIS all-sky mosaic movies using images from the full THEMIS array have been analyzed. The inclusion of images from stations adjacent to Fort Smith and Gillam often provides a better indication as to the spatial and temporal continuity of the widespread region of pulsating aurora.

## 4. Results

The study was conducted using THEMIS all-sky camera data from Gillam and Fort Smith from September 2007 through the end of March 2008, which included 119 days of valid data with clear skies. Of these, 74 days contain pulsating aurora at Gillam (ILAT of 66°).

### 4.1. Spatial/temporal evolution

The statistical study includes an assessment of large-scale spatial/temporal evolution of pulsating aurora, as determined by comparing events observed both at Fort Smith and Gillam and noting time differences in the onsets of these events. Figure 2 shows the result. The vertical axis shows differences in onset times, with a positive time difference meaning that pulsating aurora was observed at Gillam first. Therefore, since Fort Smith is west of Gillam, a positive time difference suggests a westward expansion of the pulsating aurora due to a westward drift or expansion of the corresponding precipitating particle source region. This assessment provides a basic idea of the large-scale spatial/ temporal evolution of the region of pulsating aurora. Several of the events included in this analysis were chosen for further analysis using THEMIS ASI mosaic movies to better determine the evolution from the complete ASI array.

For this study, onset times were associated with the first occurrence of pulsating aurora in *any* portion of the all-sky camera fields-of-view. Note that the magnetic latitude of Gillam is 66.1°, while that of Fort Smith is 67.3°, which has not been considered in this analysis and could perhaps have some effect on the relative onset times if the shape or drift of the region of pulsating aurora depends on magnetic latitude. (Further research is being done to determine possible longitudinal effects using several stations along the same magnetic latitude.) Magnetic midnight at Gillam is at approximately UT=6.6 and at Fort Smith magnetic midnight occurs at UT=8.1, so the stations straddle magnetic midnight at 7.4 (0724) UT. Figure 2 shows that pulsating aurora events occurring before approximately 0900 UT tend to be observed at Gillam before Fort Smith. At around 0900 UT a transition occurs toward events which are observed at Fort Smith first.

Note that cloud coverage at Fort Smith during many of the events identified at Gillam resulted in their exclusion from Figure 2, leading to more pre-magnetic midnight events than would otherwise have been expected in this analysis (as compared to post-midnight events), since the onset of pulsating aurora is statistically more likely to occur after magnetic midnight (as shown later in Figure 4). Also, Figure 2 provides no information about the duration of the pulsating aurora events. Many of the events included continued for hours, as discussed below (see Figure 3).

One of the main conclusions of this work is that pulsating aurora *onsets* evolve (spatially) away from a region that is located nominally 1.6 hours after midnight, on average. That is, when ground stations are located in MLT regions earlier than this time, pulsating aurora *onsets* appear to migrate westward. The important implication is that pulsating auroral forms must not simply be signatures of injected electrons (as suggested by Oguti and Watanabe [1976]; Akasofu [1977]; Nakamura et al. [1990]; Nemzek et al. [1995] and Suszcynsky et al. [1997]), otherwise the onsets would tend to always drift eastward at these latitudes (as they do in regions later than 1.6 hours after midnight), consistent with the gradient-curvature drift of electron injections and their drift echoes. The observations have important implications for theories explaining the pulsation mechanism.

### 4.2. Event durations

The distribution of event durations, although clearly related to its generation mechanism, does not seem to have been quantified perviously in any statistical sense. As part of this study, this distribution has been estimated and is presented in Figure 3. Note that, since these data are from a single station and the time required for this station to move through the morning sector is comparable to the typical event duration, some aliasing is likely present. However, this too is further analyzed using THEMIS ASI mosaic movies. Since the sampling consists of a 1 second integration every 3 seconds, and pulsation periods in some cases can be 6 seconds or shorter, aliasing can show an incorrect apparent pulsation period, but the appearance would remain consistent with pulsating aurora. Since this is not a study of period there should be no net effect.

The bar graph in the foreground of Figure 3 (black bars) includes only events which exhibited a clear start and end time; whereas the graph in the background (gray bars) includes events where either the start/stop time was obscured by cloud cover or the event beginning/end could not be determined due to camera shut off for sunlight or patch intensity being too dim to detect. The latter group mainly consists of long duration, morning time events which are still present at the time of camera turn off. Mean and mode duration values were calculated from the full event list for better statistics and therefore provide a lower boundary for the estimate. Still, the distribution of durations shown in the figure provides a sense for how long pulsating aurora can be expected to last (i.e., the persistence of the source).

Of particular interest is the fact that the mode of the durations (90-120 minutes, all events; 30-60 minutes, clear start/stop) is somewhat comparable to the occurrence rate of substorm onsets (for a certain class of substorm, investigated by Borovsky et al. [1993], the most probable time between substorm onsets is shown to be 2.75 hours). Substorms are often observed to repeat on a timescale of 1 to 2 hours. This may suggest that, rather than being a part of the substorm recovery phase (lasting for tens of minutes), the pulsating aurora (often lasting for hours) may be disrupted or displace locally by quasi-periodic substorms. Pulsating aurora is often observed to begin during the recovery phase of a substorm and the occurrence of a substorm has an observable effect on pre-existing pulsating aurora (a topic of further study); however, the pulsating aurora typically persists long beyond the substorm recovery phase.

Also of note are the many events lasting for several hours, with durations which often are underestimated due to weather or camera turn on/off implying that these events extend into the dayside. With some events lasting for greater than 9 hours, it is clear that pulsating aurora is a long lasting phenomenon that is not confined to the substorm recovery phase. The long duration and spatial extent of the widespread region of pulsating aurora highlight the importance of the phenomenon as a means of magnetosphere-ionosphere coupling.

### 4.3. Spatial occurrence distributions and relationship to substorms

Figure 4 shows the occurrence distribution as a function of magnetic local time. Magnetic midnight is at the bottom of that figure, with dawn on the right-hand side. The dotted line shows the number of observable event times (times for which there are valid data, i.e. images acquired during periods of clear skies, etc.) and the dashed line shows the number of pulsating aurora events for each MLT bin. The dash-dot line shows the percentage of observable event times which during which there was pulsating aurora. Note that observable times are limited in the sense that in the dawn sector, sunrise causes the camera to be turned off. Therefore, statistics later than $\sim$ 0600 MLT become increasingly unreliable. In spite of this, a trend towards higher occurrence rates (see the dash-dot line in the plot) near dawn is clear.

The occurrence distribution determined with these data, maximizing at less than 60%, is less than that of both of Kvifte and Pettersen [1969] and Oguti et al. [1981], who observed occurrences reaching more than 75% and 100%, respectively, at these same latitudes. It is important to note, however, that both of these previous studies were based on data acquired near solar maximum, while our study used data from a time with minimal solar activity. Also note that the sensitivity of the THEMIS ground cameras may not be sufficient to detect dim (less than roughly 1 kR) pulsating aurora events and thus our occurrence rates may be slightly underestimated; although it is not clear how the sensitivity compares with that of the cameras used for the Oguti et al. [1981] study for pulsating aurora emissions.

As described above, pulsating aurora occurrences have been associated with the recovery phase of substorms. In this data set, based only on optical signatures of an expansion phase in the Gillam camera, we determined that 69% of the pulsating aurora onsets occur following substorm breakup, with a greater likelihood for observing pulsating aurora after midnight (54% probability versus a 14% probability before midnight). While the remaining events appear to evolve from a region of diffuse aurora, of course, it may well be the case that a substorm had developed further to the west and was simply not observed in the Gillam camera. However, analysis of THEMIS ASI mosaic movies for several long pulsating aurora events, with durations on the order of 6-8 hours in the Gillam camera, shows some instances of pulsating aurora with no obvious substorm precursor anywhere within the THEMIS ASI array.

A study of CARISMA magnetometer data was performed to identify a substorm precursor near Gillam station for each pulsating aurora event. For some events, no obvious substorm precursor was found. However, without coverage of the full auroral oval it cannot be said with absolute certainty that there was not an onset outside of the data coverage. For these events, the AE index was consulted.

The AE index for January 13, 2008 shows relatively little auroral activity until around 1215 UT when there is a large spike in AE, probably indicating a magnetic substorm. However, the onset of pulsating aurora on this date occurred at around 1018 UT, before any obvious substorm activity, at which time there is a small increase in the AE index. A similar situation arose on March 20, 2008 for a pulsating aurora event with an onset at around 0938 UT, well before the possible substorm aurora occurring at around 1215 UT. The AE index shows only weak auroral activity for November 27, 2007 with a small increase around the time of pulsating aurora onset at 0841 UT. (Note that for the above dates 8, 9, and 8 out of 12 stations were used in calculating the AE index.)

It is clear from the statistics that pulsating aurora events occur frequently, with occurrence rates increasing into the morning hours, and often lasting for several hours. This observation provides further evidence that pulsating aurora is not strictly a part of the substorm recovery phase but is a distinct phenomenon that may be temporarily effected by the occurrence of substorms.

## 5. Discussion and conclusions.

Data from the THEMIS ASI array were used in a statistical study of pulsating aurora to better understand the large-scale spatial and temporal evolution of the associated source region with important implications for existing hypotheses. Three main aspects were evaluated including the relative onset times at two, adjacent stations for each pulsating aurora event, the distribution of event durations, and the occurrence rate vs. MLT, each of which has provided information regarding the relationship between pulsating aurora and auroral substorms. The main conclusions of the paper are as follows:

1. The source region of pulsating aurora drifts or expands westward, away from magnetic midnight, for pre-midnight onsets; the spatial evolution is more complicated for post midnight onsets. This observation argues against the idea that the occurrence of pulsating aurora may be tied to the presence of substorm-injected electrons.

2. The duration of pulsating aurora events is highly variable with a most probable duration of 90-120 minutes which may be related to the most probable time between substorms. The distribution includes many events with durations on the order of hours. This may indicate that pulsating aurora is a long lasting phenomenon that may be interrupted locally or temporarily displaced by the development of auroral substorms.

3. The study shows that 31% of all clear optical data exhibit pulsating aurora and 69% of all optically observed pulsating aurora onsets at Gillam occur post substorm breakup. There is a far greater likelihood of observing pulsating aurora after magnetic midnight (54% probability versus a 14% probability before midnight). The frequency of events and the fact that only 69% of the events were preceded by substorm activity at Gillam (some without an obvious substorm precursor within the THEMIS ASI array) may also suggest that pulsating aurora is not strictly a substorm recovery phase phenomenon. Pulsating aurora may sometimes pre-exist a substorm and subsequent pulsating aurora often persists long beyond the substorm recover phase.

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**Figure 1.** Map showing the locations of THEMIS all-sky cameras. Data for this study include observations from Fort Smith (11) and Gillam (13) for longitudinal studies. Adapted from Donovan et al. [2006].

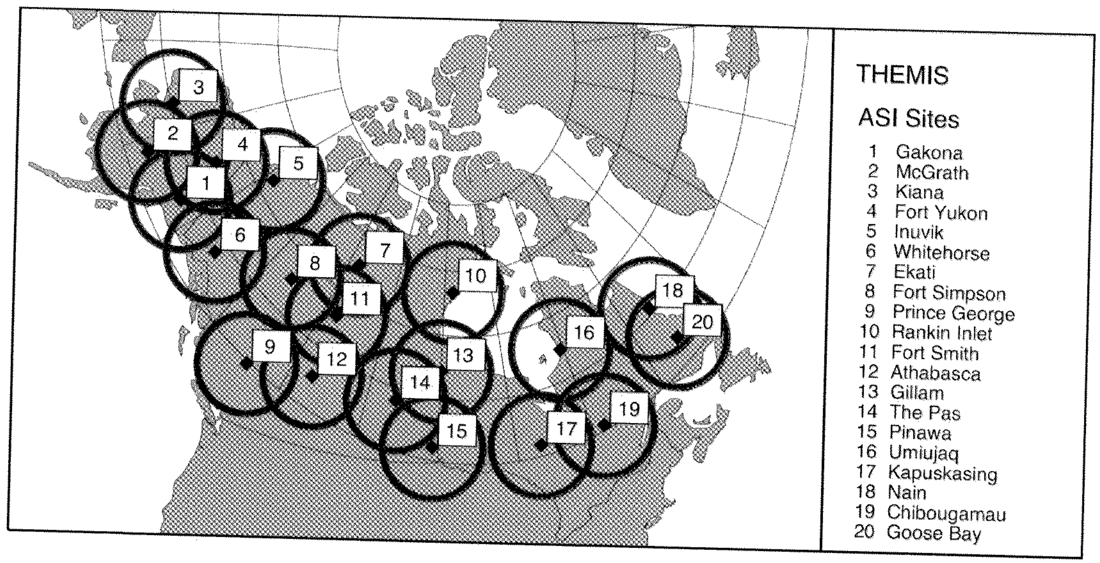
**Table 1.** Geographic and geomagnetic locations of primary stations.

| | Invariant | | UT of |
|---|---|---|---|
| Site Location | Lat (N) | Lon (E) | 2400 MLT |
| Gillam, Manitoba (13) | 66.1 | 333.9 | 0634 |
| Fort Smith (11) | 67.3 | 306.7 | 0807 |

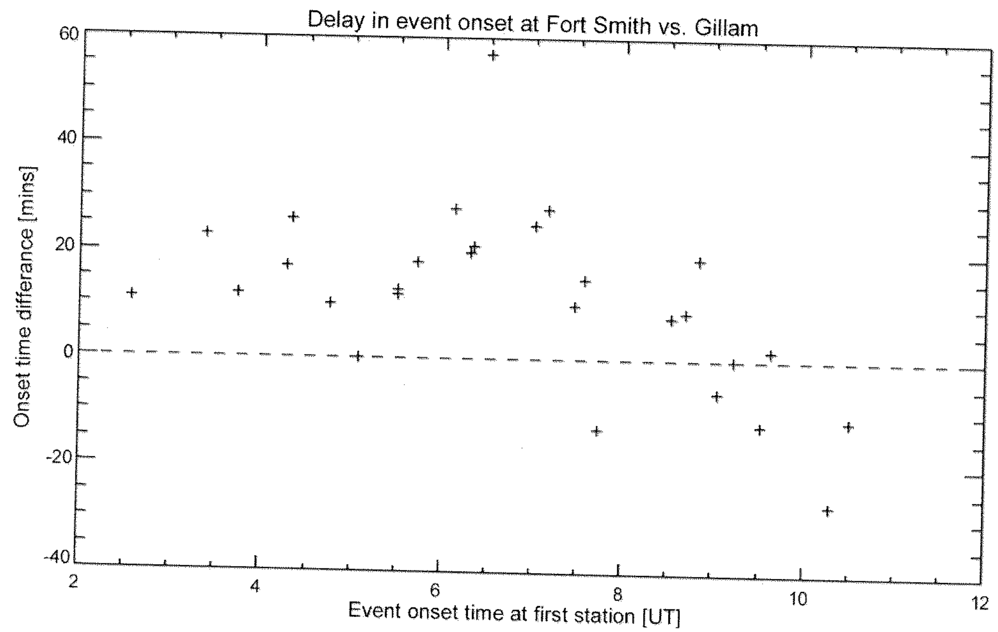
**Figure 2.** Time differences in onsets of pulsating aurora at Gillam and Fort Smith. The vertical axis shows differences in onset times of pulsating aurora observed at Gillam versus Fort Smith, with a positive time difference meaning that pulsating aurora was observed at Gillam first. The implication is that onsets evolve (spatially) away from a region that is nominally 1.6 hours after magnetic midnight (see explanation in the text).

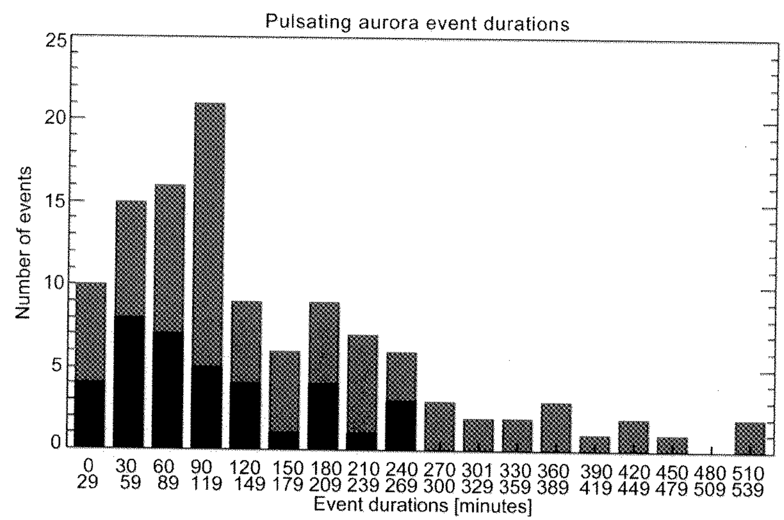
**Figure 3.** Distribution of event durations, as observed from a single camera at Gillam (gray includes all observed events, black includes only events with clear start and stop times).

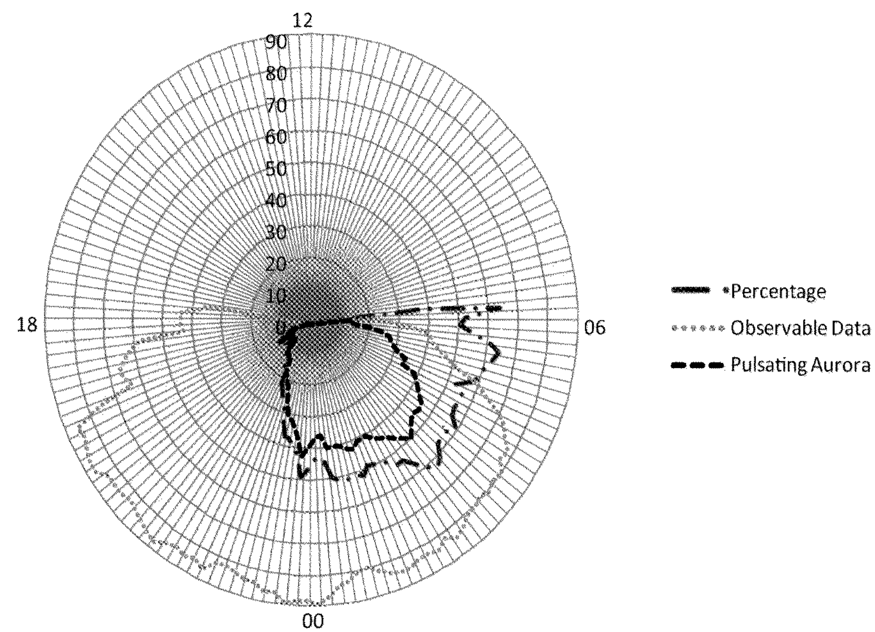
**Figure 4.** Plot of occurrence rate vs. MLT with midnight at the bottom. The dotted line shows the number of observable event times and the dashed line shows the number of pulsating aurora events for each MLT bin from as early as just before 1800 to around 600 MLT. The dash-dot line shows the percentage of observable events which are pulsating; note that this percentage increases dramatically near magnetic midnight to around 50% and continues to increase to around 60% by around 0300 MLT and remains high into the morning hours.



THEMIS
ASI Sites
1 Gakona
2 McGrath
3 Kiana
4 Fort Yukon
5 Inuvik
6 Whitehorse
7 Ekati
8 Fort Simpson
9 Prince George
10 Rankin Inlet
11 Fort Smith
12 Athabasca
13 Gillam
14 The Pas
15 Pinawa
16 Umiujaq
17 Kapuskasing
18 Nain
19 Chibougamau
20 Goose Bay


Delay in event onset at Fort Smith vs. Gillam
Onset time differance [mins]
Event onset time at first station [UT]
60
40
20
0
-20
-40
2
4
6
8
10
12


Pulsating aurora event durations
Number of events
25
20
15
10
5
0
0 29
30 59
60 89
90 119
120 149
150 179
180 209
210 239
240 269
270 300
301 329
330 359
360 389
390 419
420 449
450 479
480 509
510 539
Event durations [minutes]


12
90
80
70
60
50
40
30
20
10
0
18
06
00
Percentage
Observable Data
Pulsating Aurora