Superposition of Auroral Brightness, Plasma Velocity, and their Covariance During Substorms

M F Wilcox & W A Bristow

Penn State University Department of Meteorology and Atmospheric Sciences

Contact Information:
mfw56@psu.edu

Introduction

Auroral substorms are dynamic space weather events driven by magnetospheric energy release, resulting in rapid variations in auroral emissions and plasma flow. In this study, we performed a Superposed Epoch Analysis (Superposition) that aligns the substorm onset in both space and time to identify common patterns across multiple auroral events. By averaging auroral brightness, plasma velocity, and their covariance, we show trends that reveal the characteristic evolution of these parameters before, during, and after substorm onset.

This approach reveals the average spatial and temporal evolution of these quantities during substorms, highlighting systematic trends that may be obscured in individual cases due to variability. Our findings contribute to a clearer understanding of the fundamental processes governing auroral substorms and their role in space weather variability.

Key Points:

- Use of observations to find and select auroral substorms
- Analysis of the evolution of plasma velocity, auroral brightness, and their covariance in auroral substorms
- Creation and analysis of a superposition of auroral brightness, plasma velocity, and their covariance during substorms

SuperDARN Radar Network

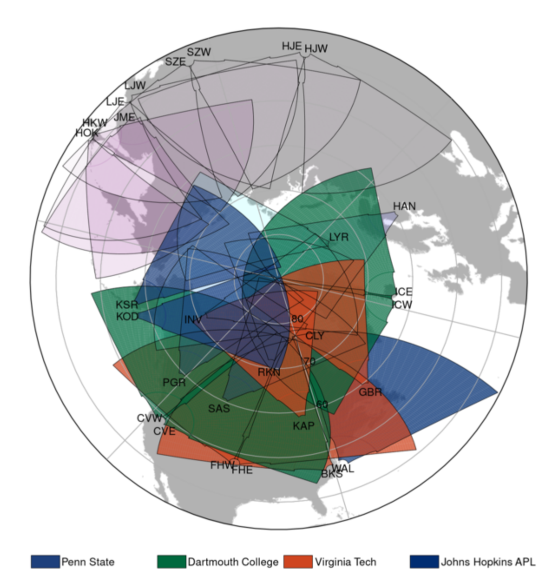

Figure 1: Current SuperDARN network fields of view in the northern hemisphere

SuperDARN is a global-scale radar network designed to measure plasma density irregularities in the ionosphere, providing large-scale estimates of high-latitude plasma motion (ion winds). The network records data every two minutes and currently has 19 sites to date.

Figure 1 shows the field of views for all sites. The different colored shading corresponds to which institution oversees the operation of that radar. In the northern hemisphere, Penn State oversees the operation of radars on Kodiak (KOD) and King Salmon (KSR)

THEMIS All-Sky Imagers

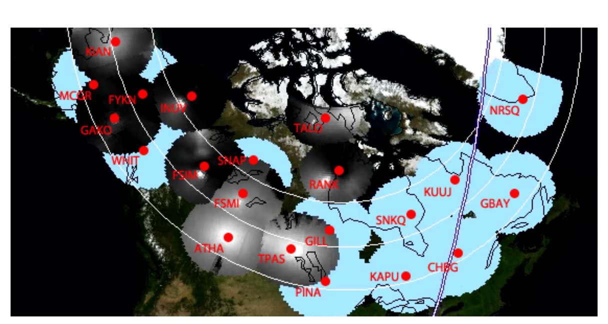

Figure 2: Current THEMIS-ASI field of views in the northern hemisphere

THEMIS ASI is a ground-based imager array which spans from eastern Canada into western Alaska. Each camera observes white light aurora by taking images in three second intervals. The array consists of twenty cameras, each with a 1 kilometer resolution at the zenith.

Figure 2 shows the field of views for the ASI imagers across the continent with abbreviated labels for each camera based on location. A blue circle indicates the imager is turned off and anywhere there is a black and white image, the imager is on. There are other all sky imagers not associated with THEMIS which are not plotted on the figure.

Events

The superposition was conducted using ten carefully selected substorm events. These events were chosen based on three main criteria: the solar cycle phase, the visibility of auroral arcs or features, and the availability of plasma velocity data. All events were from Solar Cycle 24 (which peaked in April 2014) and occurred between 2011 and 2015. Each event includes two-minute-interval data spanning from 30 minutes before to 30 minutes after substorm onset. The data region for each event covers ±5° of latitude from the substorm onset latitude and ±2 magnetic local time (MLT) hours from the substorm onset MLT.

Substorm 1 (2013-02-02)

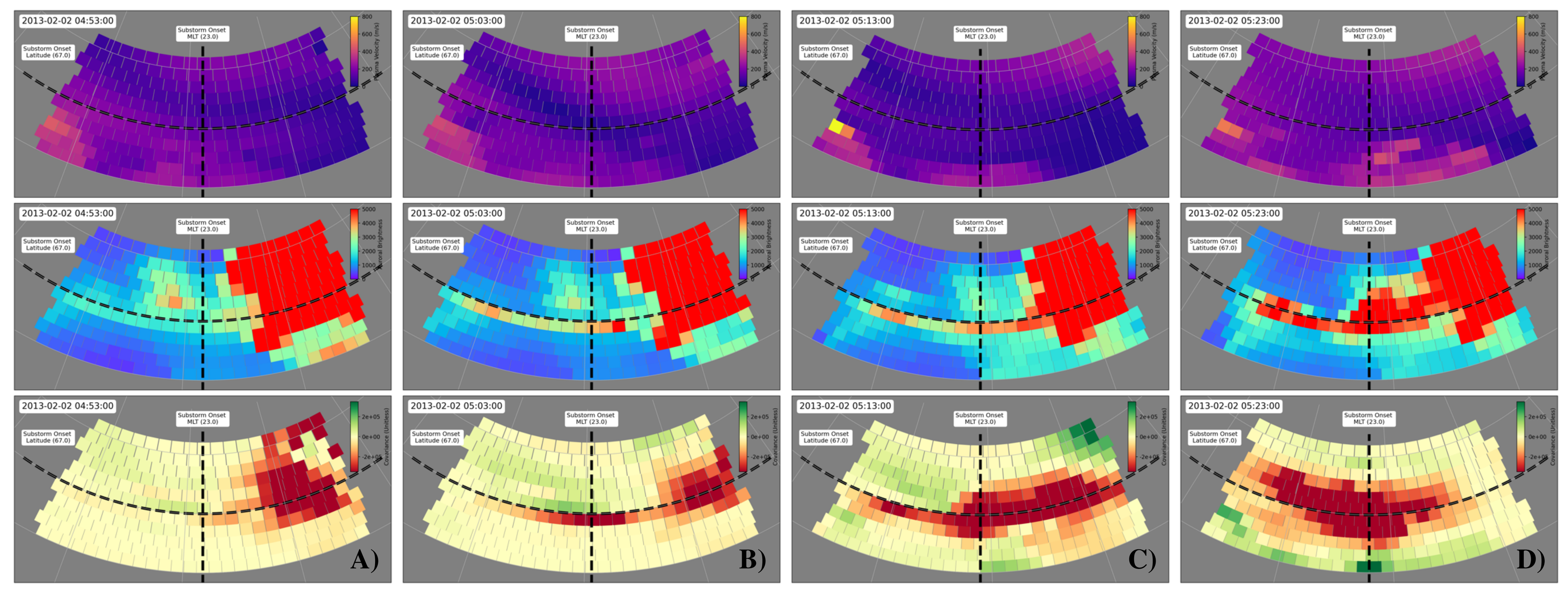

Figure 3: Sector plots of the substorm from 2013-02-02, showing plasma velocity magnitude (top panel), auroral brightness (middle panel), and their covariance (bottom panel). The panels shown are spaced 10 minutes apart, and panel B) highlights the substorm onset. Dashed lines indicate the substorm onset latitude and longitude. Substorm onset happened at 5:03 UTC

Substorm 2 (2014-03-21)

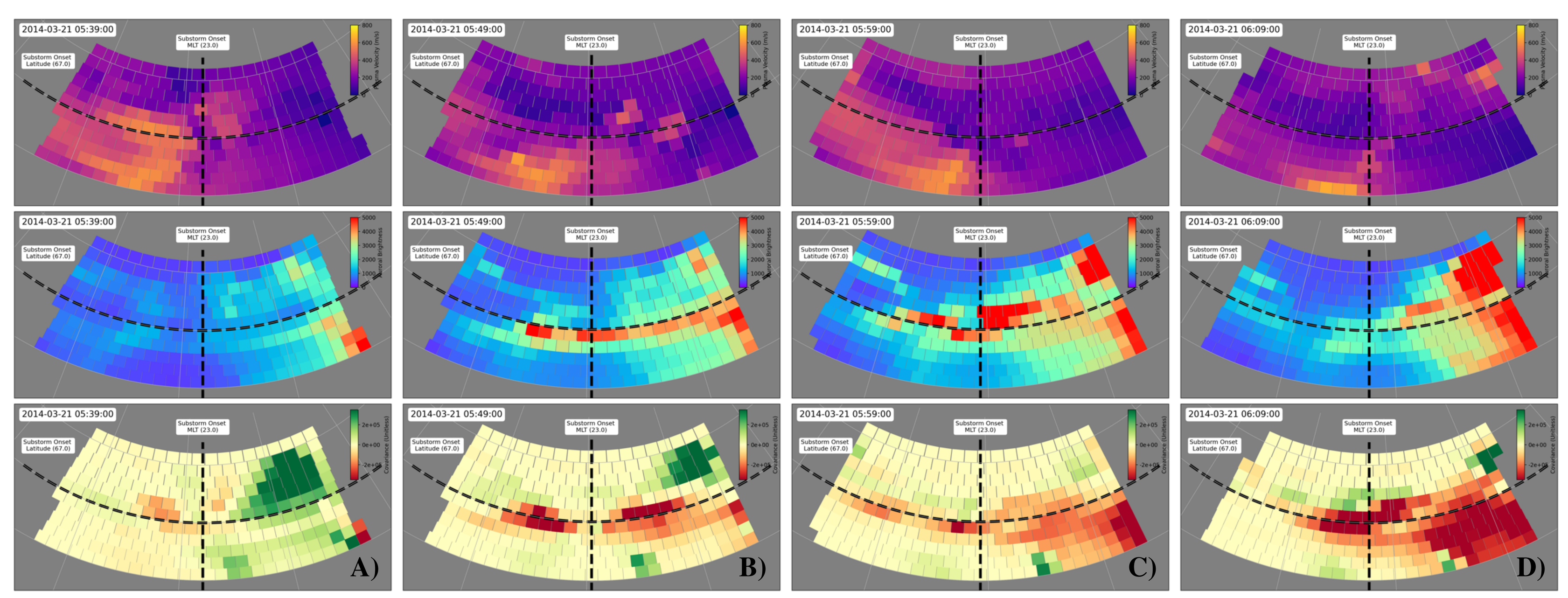

Figure 4: Sector plots of the substorm from 2014-03-21, showing plasma velocity magnitude (top panel), auroral brightness (middle panel), and their covariance (bottom panel). The panels shown are spaced 10 minutes apart, and panel B) highlights the substorm onset. Dashed lines indicate the substorm onset latitude and longitude. Substorm onset happened at 5:49 UTC

The two figures above show typical substorm behavior which includes an equatorially moving auroral arc followed by rapid brightening of the aurora and simultaneous rapid decrease of plasma velocities in the region of bright aurora. This behavior leads to strong negative covariance in the region of bright aurora and can be seen in both events and is expected from prior knowledge of substorm behavior.

Event 1 Features

- Visible decrease in plasma velocity in bright aurora region
- The auroral arc and its rapid brightening after substorm onset are also shown
- Higher plasma velocities are visible equatorward of the bright aurora
- A large region of negative covariance, caused by the rapid brightening and accompanying velocity decrease, is apparent
- Higher plasma velocities (750 m/s) at 04:01 UTC in the region where the auroral arc forms are not shown
- Note: The large red region on the right side of the auroral brightness panel is not aurora—it is an error in one of the THEMIS imagers

Event 2 Features

- Initially, there are higher velocities in the region where the auroral arc forms, which then decrease as the substorm progresses
- High velocities persist equatorward of the substorm onset throughout the event
- Like in Figure 3, there is a large region of negative covariance in the bright aurora region
- Not shown: High plasma velocities (1000 m/s) located -3 MLT along the substorm onset latitude, which persist for the duration of the substorm

Results

Events for the superposition were aligned by the substorm onset latitude and MLT. The latitude was set to the average onset latitude across all ten events (66.4°), while the MLT was set to 19.2, corresponding to the zero longitude line at the average onset time. The superposition region, similar to the individual event regions, spanned ±5° latitude from 66.4° and ±2 MLT from 19.2 MLT. Data from each event were mapped onto this superposition grid and then averaged. The two-minute data intervals, spanning from 30 minutes before to 30 minutes after substorm onset, were also preserved in the superposition.

10 Event Superposition

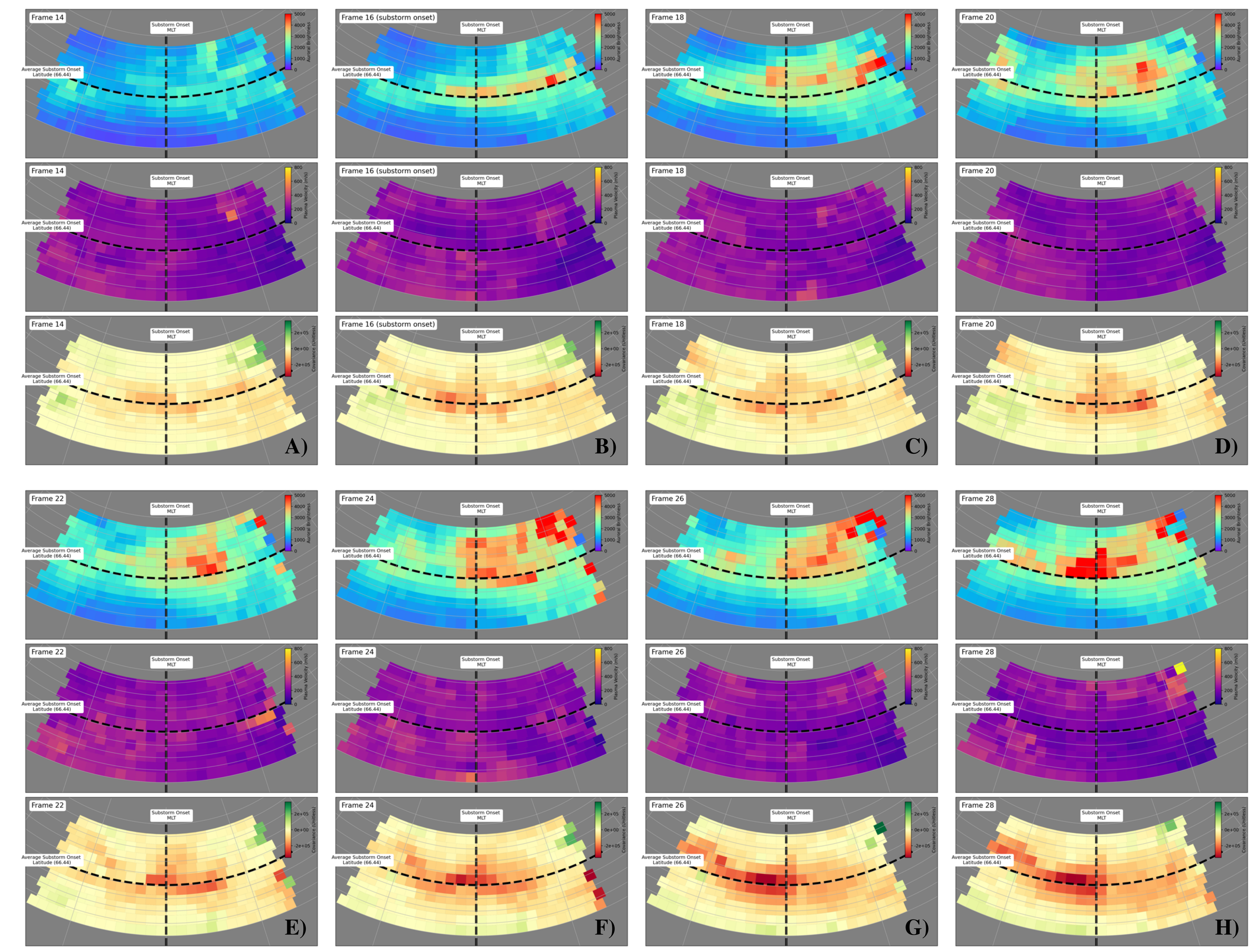

Figure 5: Sector plots of the 10 event substorm superposition showing auroral brightness (top), plasma velocity (middle), and the covariance between them (bottom). The panels are spaced two minutes apart, and panel B) marks substorm onset. Dashed lines indicate the average substorm onset latitude and onset MLT.

In the superposition, the values are distributed across the region, but the characteristic features of an individual substorm remain evident. The brightness still shows the formation of an auroral arc with rapid brightening following the substorm onset. Likewise, a region of negative covariance—stronger to the west of the onset location, as seen in the 2013-02-02 event and other events in this dataset—is present. Although the velocity profile is less distinct than in individual events, there is still a region of lower velocities where the bright aurora is observed.

Conclusions

- Auroral brightness, plasma velocity magnitude, and their covariance profiles resemble that of an induvidual substorm but arent as strongly defined as the induvidual events
- Substorm behavior is consistent across multiple different events regardless of onset time or location
- Plasma velocity values don't appear as high as we think they should and it is currently unclear as to why, but the shown behavior is what is expected from substorms

Forthcoming Research

- Refine list of auroral substorms by using events from solar cycle 25.
- Create sector plots showing plasma velocity vectors in order to analyze how velocity direction evolves along the latitude of substorm onset as well as poleward and equatorward of the substorm.
- Expand sector region westward as many events have high plasma velocities further to the west of the substorm onset location.