A Superposed Epoch Analysis of SuperDARN Plasma Convection, THEMIS-ASI Auroral Brightness, and Their Covariance During Substorms

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Introduction

Auroral substorms produce significant changes in ionospheric plasma convection and auroral precipitation, both of which contribute to energy deposition in the ionosphere–thermosphere system. Previous studies using SuperDARN and auroral observations have demonstrated a strong connection between plasma flows and auroral activity, but the quantitative relationship between plasma convection and auroral brightness remains poorly constrained. Improving our understanding of this relationship could lead to more accurate estimates of Joule heating and thermospheric response during geomagnetic activity.

- Plasma convection and auroral brightness are key drivers of ionospheric energy deposition during substorms.
- Statistical studies have shown that changes in plasma flow are closely linked to auroral brightening, expansion, and recovery-phase dynamics.
- Existing empirical models typically represent electric fields and auroral precipitation independently.
- The covariance between plasma velocity and auroral brightness has not been extensively characterized.
- This study uses SuperDARN and THEMIS observations to quantify the evolution of plasma velocity, auroral brightness, and their covariance during substorms.

Research Questions and Objectives

Research Questions:

- How does the aurora evolve before, during, and after substorm onset?
- How does ionospheric plasma velocity evolve during substorms?
- What is the covariance between plasma velocity and auroral brightness during substorms?
- How representitive are these relationships across multiple substorm events when viewed through a superposed epoch analysis?

Objectives:

- Use THEMIS ASI array to identify typical brightening and expansion patterns relative to substorm onset.
- Use SuperDARN network to investigate how convection patterns develop and persist throughout substorm lifecycle.
- Compute the covariance for each event and conduct a superposed epoch analysis to identify common features.
- Evaluate where and when covariance is the strongest and determine its usefulness for estimating Joule heating.

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 $\pm 5°$ latitude from the substorm onset latitude and ± 2 magnetic local time (MLT) east and ± 5 MLT west from the substorm onset MLT.

Substorm 1 (2013-03-16)

Substorm 2 (2014-03-21)

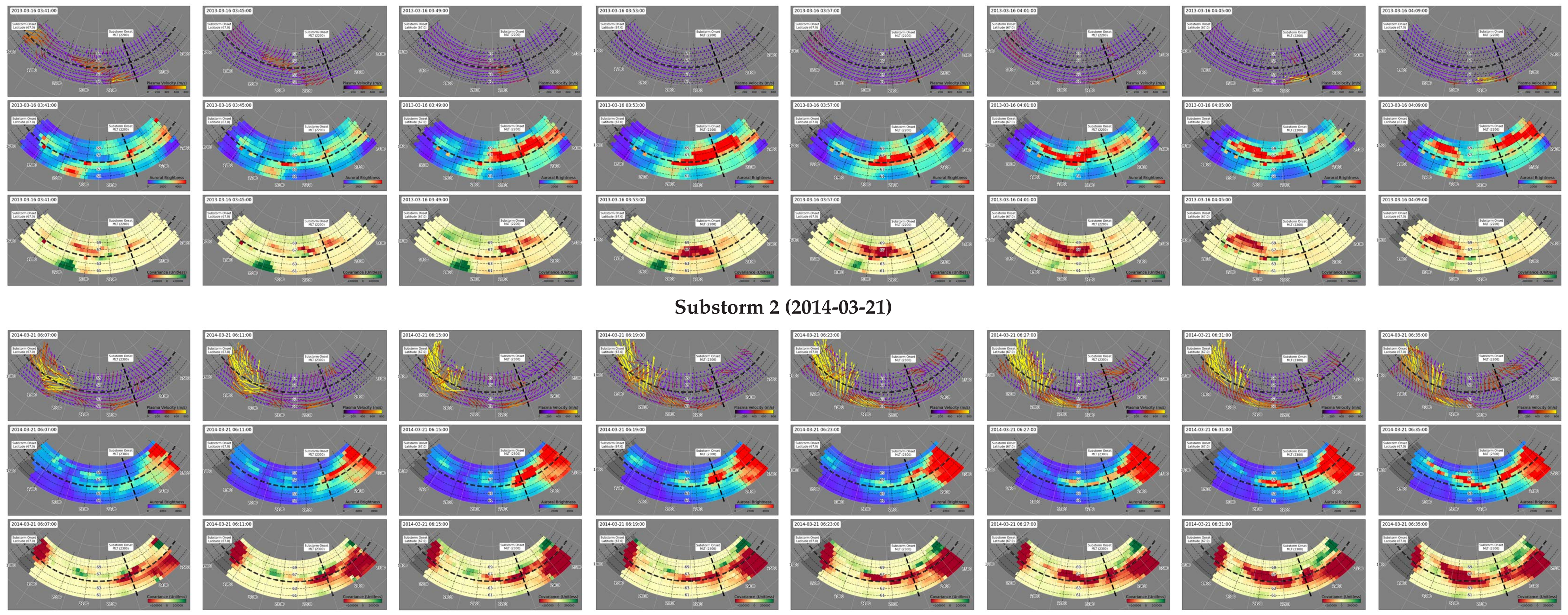

Figure 2: Sector plots of two individual events (one on each row) showing plasma velocity (top), auroral brightness (middle), and the covariance between them (bottom). The panels are spaced 4 minutes apart. Dashed lines indicate substorm onset latitude (horizontal) and onset MLT (vertical).

The two individual substorm events show typical substorm behavior which includes an equatorially moving auroral arc followed by rapid brightening of that arc 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, which is seen in both events and is expected from prior knowledge of substorm behavior.

Event and Superposition Animations

QR code to view event GIFs (may have to download to view):

QR code to view superposition GIF (may have to download to view):

Materials & Methods

This study combines observations from the Super Dual Auroral Radar Network (SuperDARN) and NASA's THEMIS All-Sky Imager (ASI) array to examine ionospheric plasma convection and auroral brightness during auroral substorms. Together, these datasets enable simultaneous characterization of ionospheric electric fields (via plasma convection) and conductivity (via auroral brightness).

Substorm events were identified using THEMIS ASI keograms, which track auroral evolution along a north–south slice through each imager. Events were selected based on data quality (minimal cloud contamination and sufficient coverage across multiple stations) and clear substorm signatures, defined by an equatorward-moving auroral arc followed by rapid brightening and poleward expansion across the field of view.

SuperDARN observations were analyzed using range–time plots of line-of-sight velocity. Ionospheric ground scatter was removed, and only auroral-zone plasma velocities were retained. Substorm signatures were identified through enhanced nighttime flows and sharp velocity changes near onset, consistent across multiple radar beams and local time sectors.

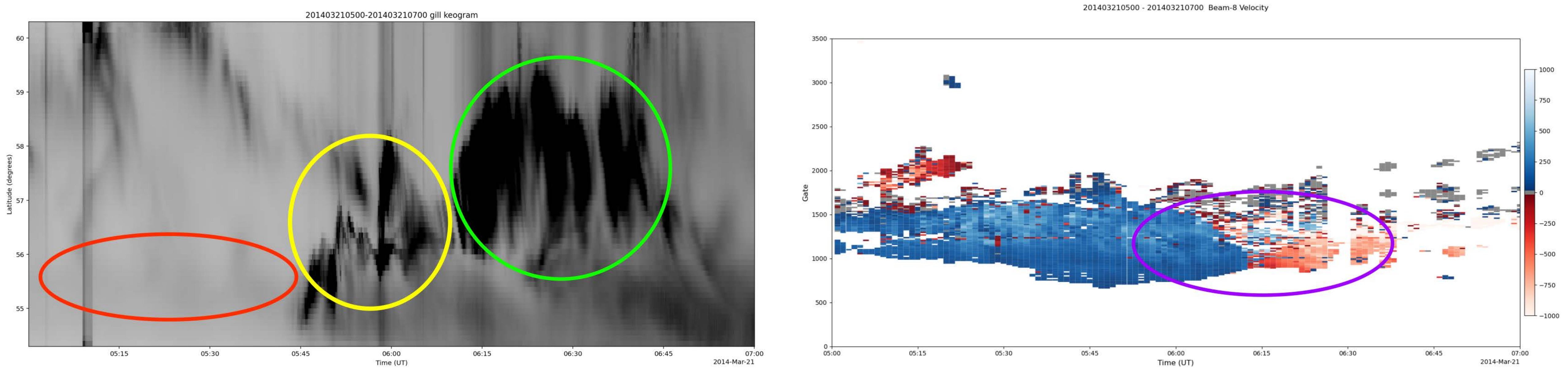

Figure 1: Keogram from the THEMIS all-sky imager in Gillam (left) and a range–time plot of line-of-sight velocity from beam 8 of the Kodiak SuperDARN radar (right) on 21 March 2014, showing the interval surrounding substorm onset. The keogram illustrates the equatorward motion of the auroral arc (red), followed by a small-scale breakup of the arc (yellow), and subsequent rapid auroral brightening and poleward expansion (green). The RTI plot shows the equatorward progression of a high-velocity region prior to onset, as well as a sharp change in line-of-sight velocity near substorm onset (purple).

Conclusions and Broader Impacts

Conclusions:

- A superposed epoch analysis of 10 solar cycle 24 substorms was used to characterize the average evolution of plasma convection, auroral brightness, and their covariance using SuperDARN and THEMIS observations.
- The superposition preserved key substorm features, including poleward and westward auroral expansion, persistent plasma flows west and equatorward of onset, and the emergence of negative covariance near the brightest auroral regions.
- Auroral brightness, plasma velocity, and covariance were weaker and more spatially diffuse than in individual events due to averaging, but their overall temporal and spatial behavior remained consistent.
- The strong correspondence between auroral brightness and negative covariance suggests covariance may provide a useful observational constraint linking ionospheric electric fields and conductivity.

Broader Impacts:

- Improved forecasting of thermospheric expansion and atmospheric drag on LEO satellites
- Enhanced satellite orbit prediction and collision avoidance capabilities
- Better understanding of ionospheric conditions that affect communication and navigation systems
- New observational constraints for future ionosphere-thermosphere models
- Improved space weather forecasting and resilience of critical technological infrastructure

Future Research

- Investigate particle energy–time spectrograms during substorm onset and expansion phases to better understand the relationship between particle acceleration and ionospheric plasma flows.
- Determine whether observed reductions in plasma velocity coincide with inverted-V electron spectra, Alfvén wave acceleration signatures, or both.
- Compare how different acceleration mechanisms influence auroral morphology, plasma convection, and the development of covariance.

Superposed Epoch Analysis

Individual event grids were aligned using each substorm onset latitude and MLT. Events were mapped using AACGM coordinates and shifted to a common reference location (66.1° latitude, 335° longitude). Plasma velocity, auroral brightness, and covariance values were then averaged within each grid cell to create composite maps that highlight common substorm evolution while reducing event-to-event variability.

Superposition

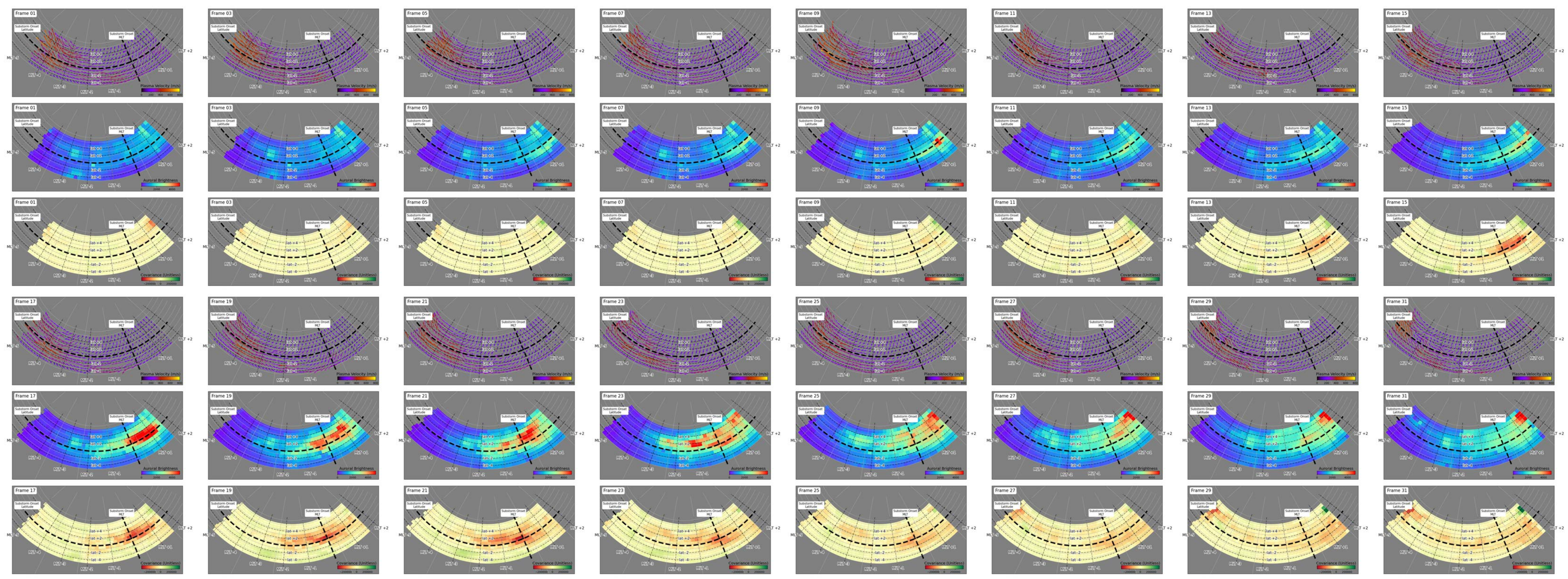

Figure 3: Sector plots of the 10 event substorm superposition showing plasma velocity (top), auroral brightness (middle), and the covariance between them (bottom). The panels are spaced 4 minutes apart. Dashed lines indicate the average substorm onset latitude (horizontal) and onset MLT (vertical).

- Auroral brightening begins near the onset latitude and initially develops east of onset MLT.
- Brightest aurora expands poleward and westward, producing broad distribution after onset.
- Auroral features are weaker and more diffuse than individual events due to averaging, and the growth phase arc is not preserved.
- Enhanced plasma velocity flows persist west of onset MLT throughout the interval and appear equatorward after onset.
- Reduced velocity magnitudes and a transition towards mostly southward flow near the region of bright aurora.
- Peak velocities are lower than individual events (~600 m/s vs. ~800 m/s).
- Negative covariance develops within the brightest auroral regions and strengthens after onset.
- Covariance expands poleward and westward alongside the evolving aurora.
- Although reduced in magnitude by averaging, the strong spatial correspondence between auroral brightness and covariance is preserved.