Global Navigation Satellite Systems Observations of the Ionosphere During Strong Thermal Emission Velocity Enhancement

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Introduction

- Strong Thermal Emission Velocity Enhancement (STEVE) is an arc-like optical emission in the pre-midnight subauroral ionosphere during substorms. (Fig. 1a) (Nishimura et al., 2023).
- In the Northern hemisphere, STEVE appears south of where aurora typically occur and can stretch on average ~2145 km (Gallardo-Lacourt et al., 2018).
- STEVE is associated with subauroral ion drifts (SAID), extreme temperature enhancements and large density gradients.
- Generally, STEVE lacks particle precipitation.
- It is not understood how the density evolves or whether STEVE has significant impacts on GNSS.

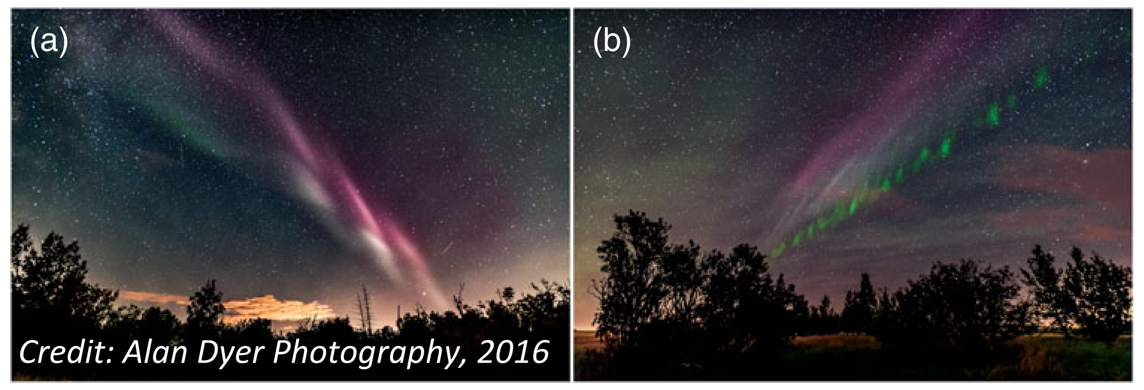


Figure 1 (a-b). STEVE without picket-fence (1a) and with picket-fence (1b) on 2016-09-03 in Strathmore, Canada.

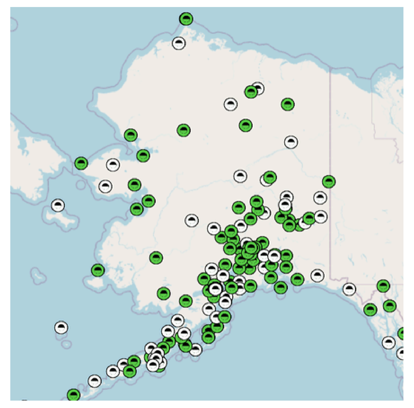
Methodology

This study aims to quantitatively:

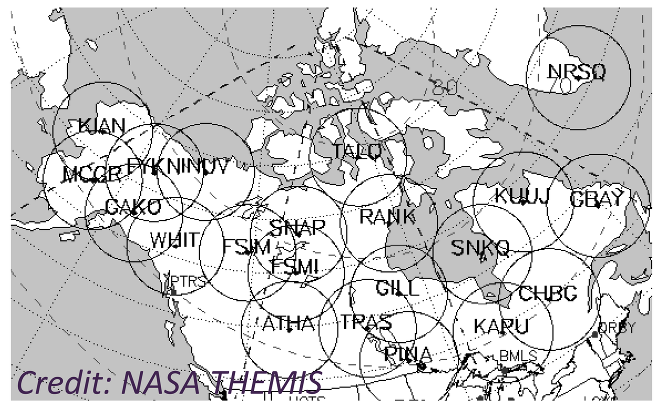
1. Determine how density structures vary during STEVE.
2. Determine how much STEVE creates errors in GNSS positioning and scintillation.
3. Understand why GNSS positioning errors could occur under the ionospheric plasma density structures around STEVE.

We are motivated to research GNSS and STEVE to better understand how STEVE impacts communication and navigation systems.

UNAVCO NOTA GNSS Receivers



THEMIS All-Sky Imagers



Identify: We searched for STEVE events through **15 years**' worth of imagery data. We found and studied **6 events** in total but selected the **2008-03-26** event to present.

Investigate: We used the Space Physics Environment for Data Analysis, programmed procedures, and processed data to:

1. Calculate TEC and compare to ASI data to find changes in TEC structures during STEVE.

2. Calculate PPP as a measure of GNSS positioning: compare to TEC to find errors caused by STEVE in GNSS.

3. Calculate phase and amplitude scintillation indices with VTEC and PPP to identify signal fluctuations.

Verify: We compared the data on the day of STEVE and a day without STEVE to find STEVE-related variations. We used the location and timing to determine the connection between TEC, PPP and scintillation. We repeated these steps for each event.

Results 1: Evolution of Substorm and STEVE on 2008-03-26

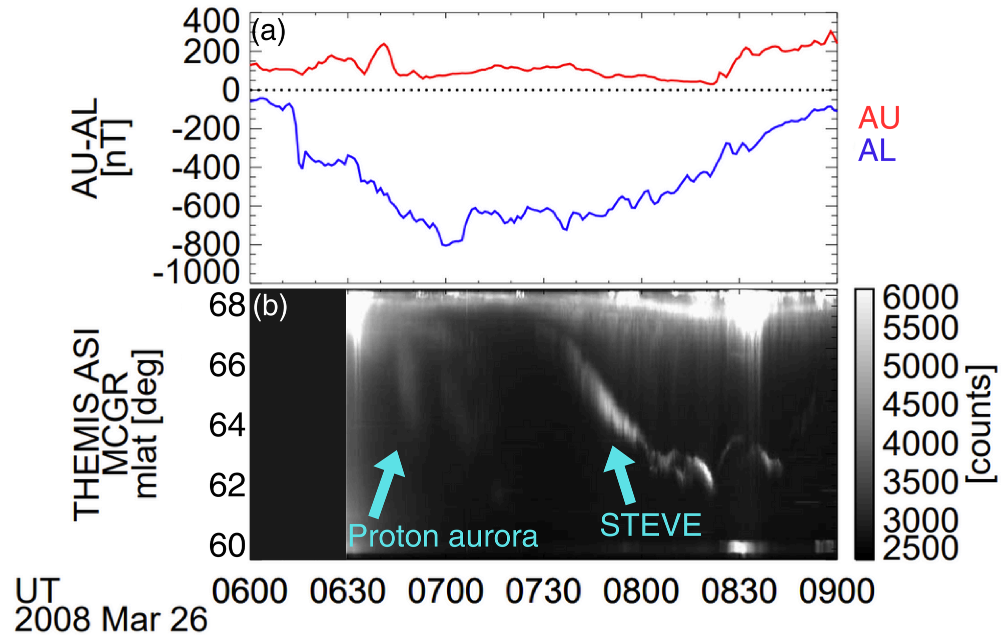


Figure 2 (a-b). AU/AL indices and THEMIS ASI keogram of STEVE on March 26th, 2008.

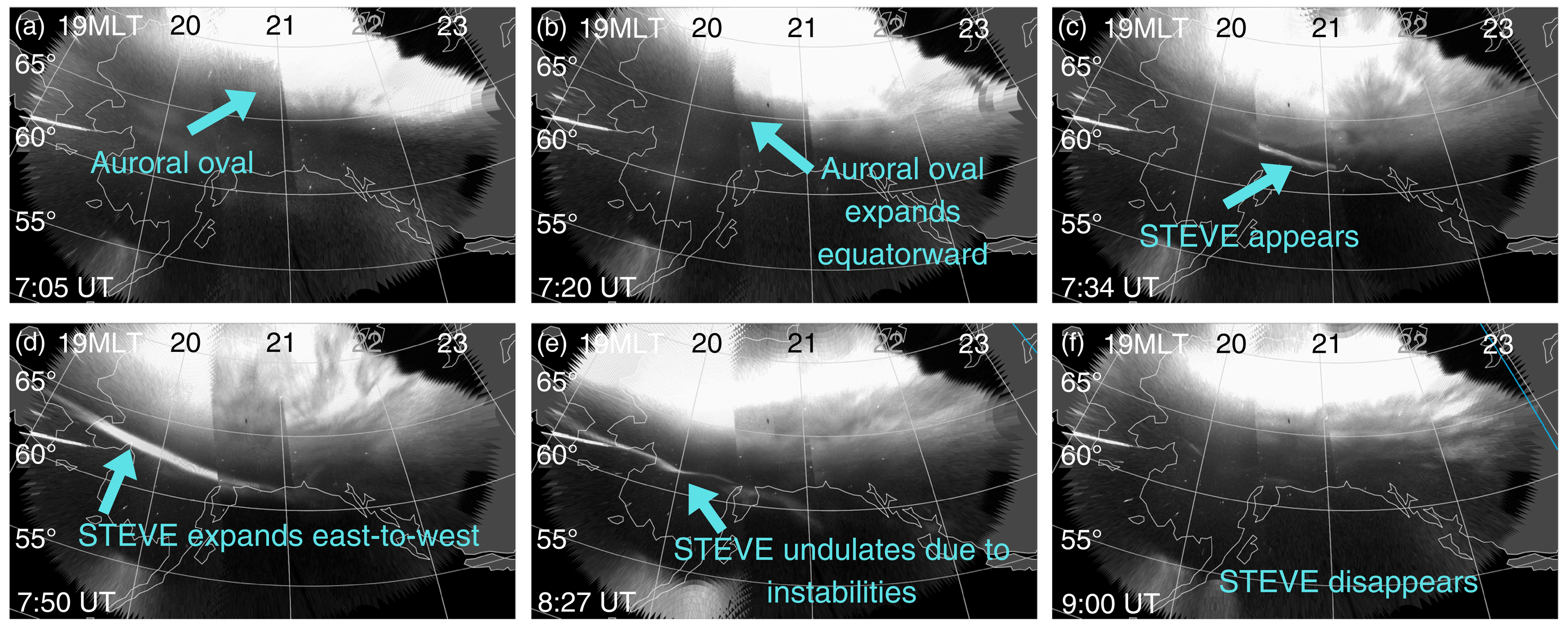


Figure 3 (a-f). THEMIS ASI snapshots of STEVE over Alaska at 200km altitude on March 26th, 2008.

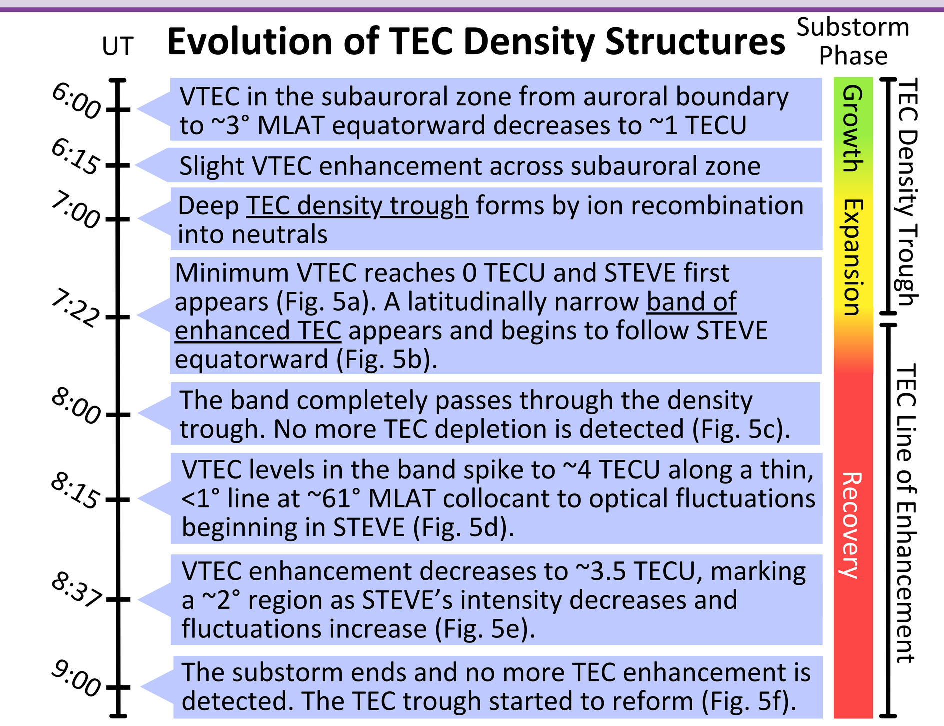


Figure 4. Timeline of TEC structures over STEVE in Fig. 5.

Results 2: TEC Temporal and Spatial Distribution

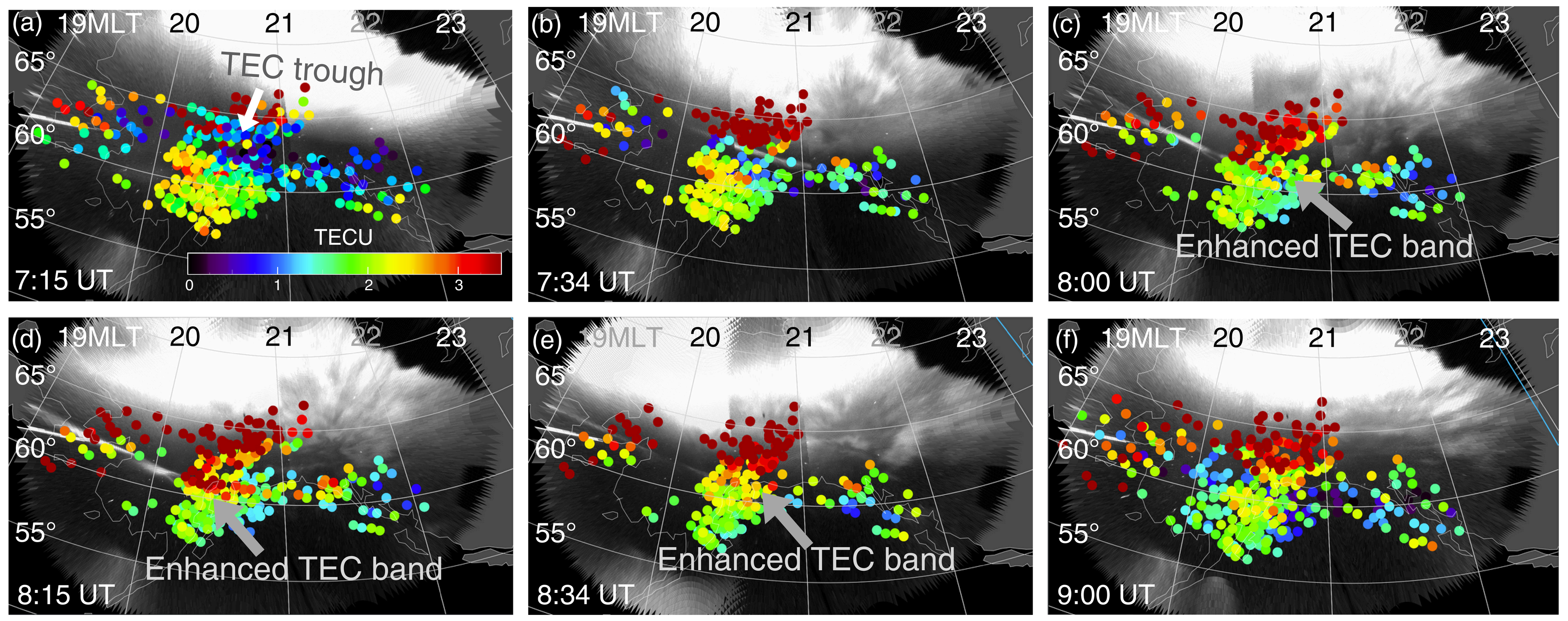
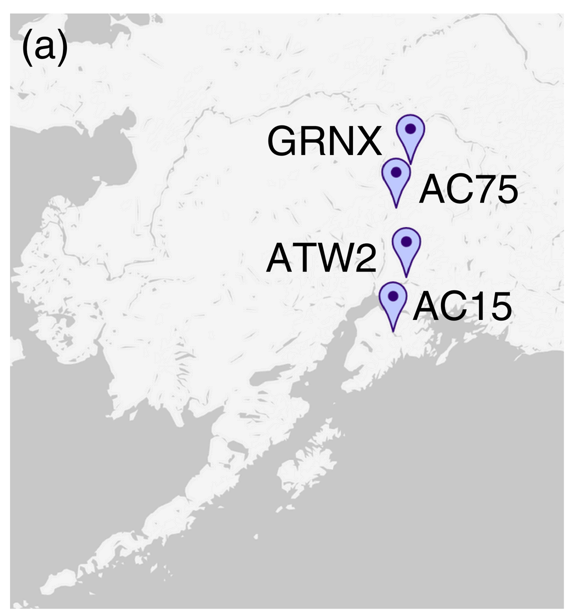


Figure 5 (a-f). Vertical TEC (VTEC) measurements of STEVE overlaid on THEMIS ASI snapshots plotted at 200 km altitude. VTEC data was calculated from 77 NOTA stations ranging from ~65.0° to ~59.5° latitude. A density trough initially stretched the full length of STEVE with a width of ~3° MLAT. **A highly-localized band of enhanced TEC passed through STEVE and filled the density trough.**

Results 3: TEC and PPP Time Variance



$$P = \sqrt{E^2 + N^2 + U^2} - \sqrt{E_0^2 + N_0^2 + U_0^2} - P_0$$

Equation used to calculate PPP variance

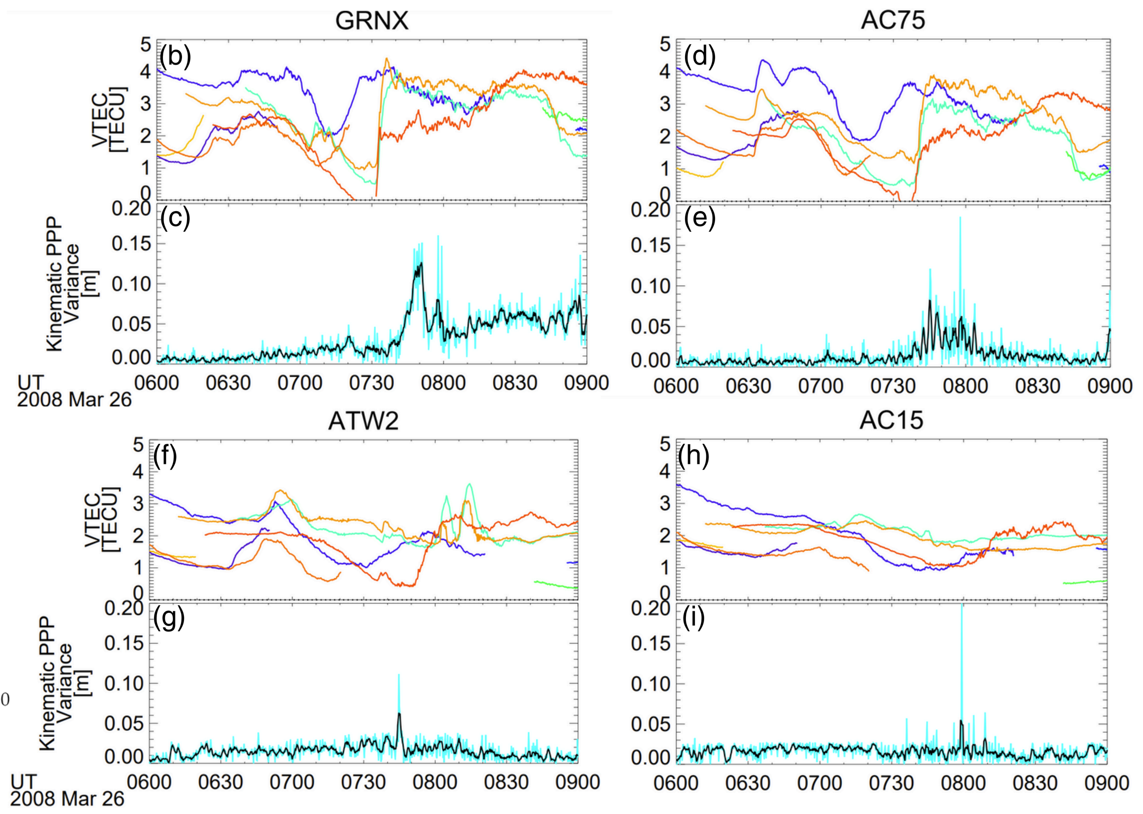


Figure 6 (a-i). Location of 4 sampled stations. VTEC, PPP variance (blue line), and the moving average (black line) over 1 minute of PPP variance were calculated on a 15-second sample rate for GRNX (b-c), AC75 (d-e), ATW2 (f-g), and AC15 (h-i). **PPP variance spiked during intense plasma gradients at STEVE.**

Results 4: Phase and Amplitude Scintillation

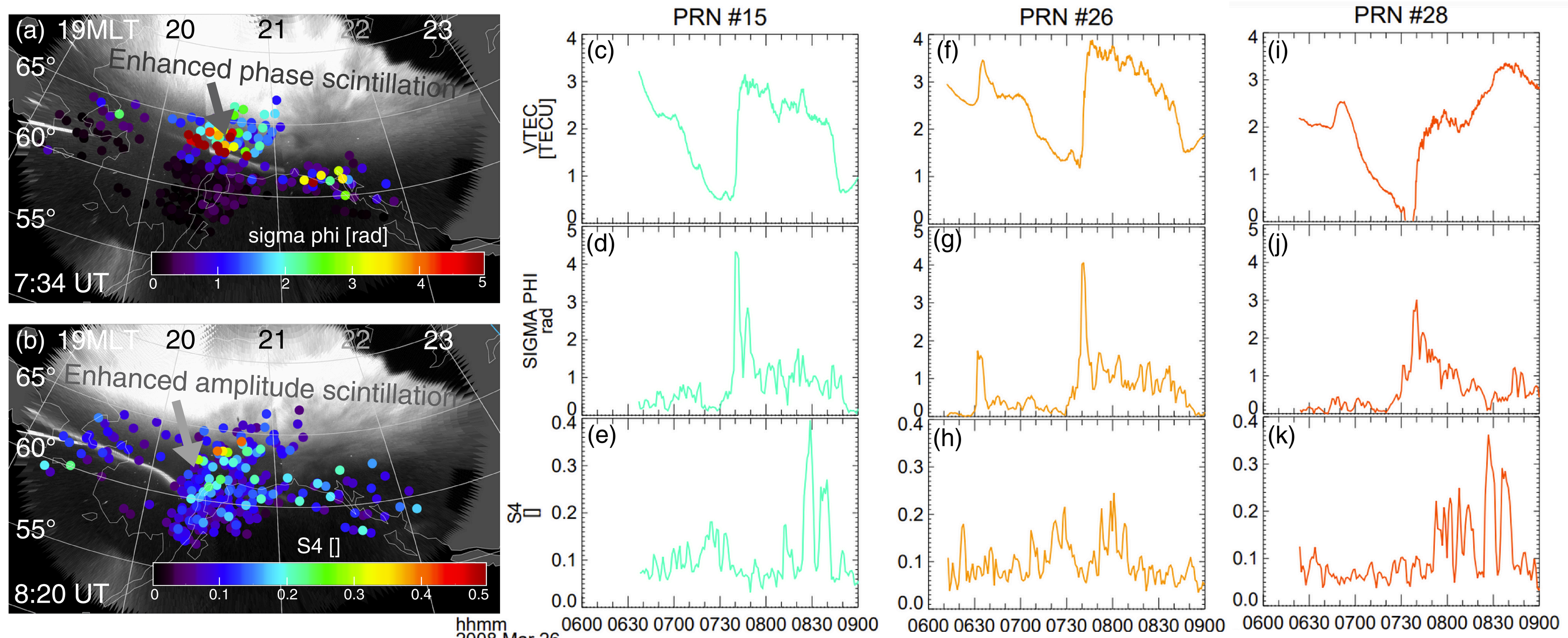


Figure 7 (a-k). Scintillation overlaid on THEMIS ASI snapshots (a-b). VTEC & 3-min phase/amplitude scintillation indices were calculated for satellites PRN 15 (c-e), 26 (f-h), and 28 (i-k) for station AC75. **Phase scintillation spiked during intense plasma gradients and corresponded to rapidly fluctuating TEC structures over STEVE.**

Discussion

Questions remaining:

- What does drive TEC enhancement around STEVE?
- How does TEC/PPP/scintillation vary at the 1-second timescale?

Potential causes of the unexpected TEC enhancement:

- Plasma drift along the poleward electric field in the lower ionosphere (Pedersen drift, Zettergren and Semeter, 2012)
- Low-energy electron precipitation (Nishimura et al., 2019)
- Neutral wind convergence (Liang et al., 2021)
- Instability (such as gradient drift instability, Kelvin-Helmholtz instability, and temperature gradient instability) that modifies density structure in the trough (Rathod et al., 2021)

Conclusions

- Combined THEMIS ASI observations with collocant GNSS measurements to determine and understand the variation of ionospheric density structures, GNSS positioning errors, and scintillation during STEVE.
- Identified narrow VTEC enhancement directly associated with STEVE after a typical TEC density trough
- Detected significant levels of phase scintillation and variance in GNSS positioning error
- Suggested energetic particle precipitation, Pedersen drift, and neutral winds may drive the unexpected TEC enhancement

Future work:

- Numerical simulations
- Statistical studies
- Studies with higher sample rate data (1 Hz) on 2016-05-08 and 2014-08-21