A local-scale data assimilation approach for reconstructing boundary conditions to drive physics-based simulations of auroral events

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ABSTRACT

The high-latitude auroral ionosphere and its dynamics play a crucial role in our understanding of space weather phenomena. The auroral system is incredibly complicated in that it involves exchange of mass, momentum, and energy with both the magnetosphere and thermosphere, exemplifying the concept of a complex "system of interacting systems" often used to describe the geospace environment. Ground- and space-based instruments offer crucial insights into specific ionospheric parameters but cannot provide a complete picture of the ionospheric dynamics at play for any given event due to limited fields of view and sampling. This necessitates the use of physics-based models for developing a detailed understanding of various processes at play in the system; however, local-scale models of auroral dynamics require accurate boundary conditions to preserve realism. This study adopts a data assimilation approach for producing two-dimensional reconstructions of ionospheric potential and precipitation boundary conditions that are then used as inputs to a physics-based model to simulate the ionospheric dynamics near auroral features. We present multiple auroral events occurring during a campaign that included measurements from the Poker Flat Incoherent Scatter Radar (PFISR), co-located digital all-sky camera (DASC), magnetometers, and the Super Dual Auroral Radar Network (SuperDARN), which were operated in conjunction with nightly overpasses of the Swarm satellite constellation. These data are used to produce 2D ionospheric potential reconstructions via the inversion method of Local Mapping of Polar Ionospheric Electrodynamics (Lompe), extracting quantities such as convection velocities, electric potential, field-aligned currents, and electric fields. These inverted data are then used to drive the Geospace Environment Model of Ion-Neutral Interactions (GEMINI) to generate volumetric and time-dependent simulations of the events, including plasma thermal and electrodynamic quantities. Event dates are chosen based on data availability, distinct event types, and favorable conjunctions between PFISR and Swarm—our main diagnostics for plasma flow. The demonstrated process of data analysis, reconstruction, and modeling has the potential to deepen our understanding of auroral physics and its implications both at local and global scales in terms of ionospheric density and temperature structure, preconditioning for instabilities in the ionospheric plasma, and coupling to neutral atmospheric heating and acceleration.

INTRODUCTION

- The ionosphere and our ability to have an accurate description of its coupling to space play a huge role in our understanding of space weather phenomena
- Both ground and space are equipped with instruments that can explain different parameters of state parameters but do not give a full picture of the state of the ionosphere on their own; combining different types of measurements with different variations of statistical models, conductance maps, and numerical methods provides us with the ability to yield a realistic picture of ionospheric electrodynamics in localized regions
- Having an appropriate model to assess quantities that are either difficult/impossible to physically measure gives way to drive simulations for ionospheric events within physics-based models and exploit under- or incorrect estimation of such quantities (i.e. Joule heating)
- Electrodynamic inputs for simulations allows for high spatial and temporal resolutions and physically accurate outputs giving a streamlined way to take auroral observations from data on instruments to a body of simulated events
- The data used throughout this study is from the Swarm-over-Poker 2023 (SoP23) campaign, a crowd-sourced campaign organized by Dr. Kristina Lynch at Dartmouth college; ~six weeks of auroral events were observed by PFISR in conjunction with the Swarm satellite constellation and co-located ground instrumentation
- The primary purpose of this project is to evaluate data from the Poker Flat incoherent scatter radar (PFISR) and co-located instruments for multiple nights during the SoP23 campaign to obtain an understanding of local-scale electrodynamics surrounding PFISR, using data assimilative and high-resolution modeling techniques

METHODS

MATHEMATICAL FRAMEWORK

- Local Mapping of Polar Ionospheric Electrodynamics (Lompe) is an inversion tool that estimates magnetic field propagation from the ground into space, field-aligned currents, and conductance measurements to relate ionospheric electric fields, *F*-region plasma convection velocities, ground magnetic field disturbances, and space magnetic field disturbances [4]
- The Heinselman and Nicolls, 2008 method is used to compare to the flow results of the Lompe reconstructions; each measurement represents a sample of the vector field as a dot product of the geometry vector with the velocity field, plus associated error from the line-of-sight velocity estimate [1]
- The Geospace Environment Model of Ion-Neutral Interactions (GEMINI) is a multi-purpose, three-dimensional ionospheric model that is used to describe dynamics and processes in the ionosphere and is comprised of a fluid system of differential eqs that describe the dynamics of ionospheric plasma; these equations are coupled via electrostatics of auroral and neutral currents with a steady-state assumption of the current continuity equation [6]

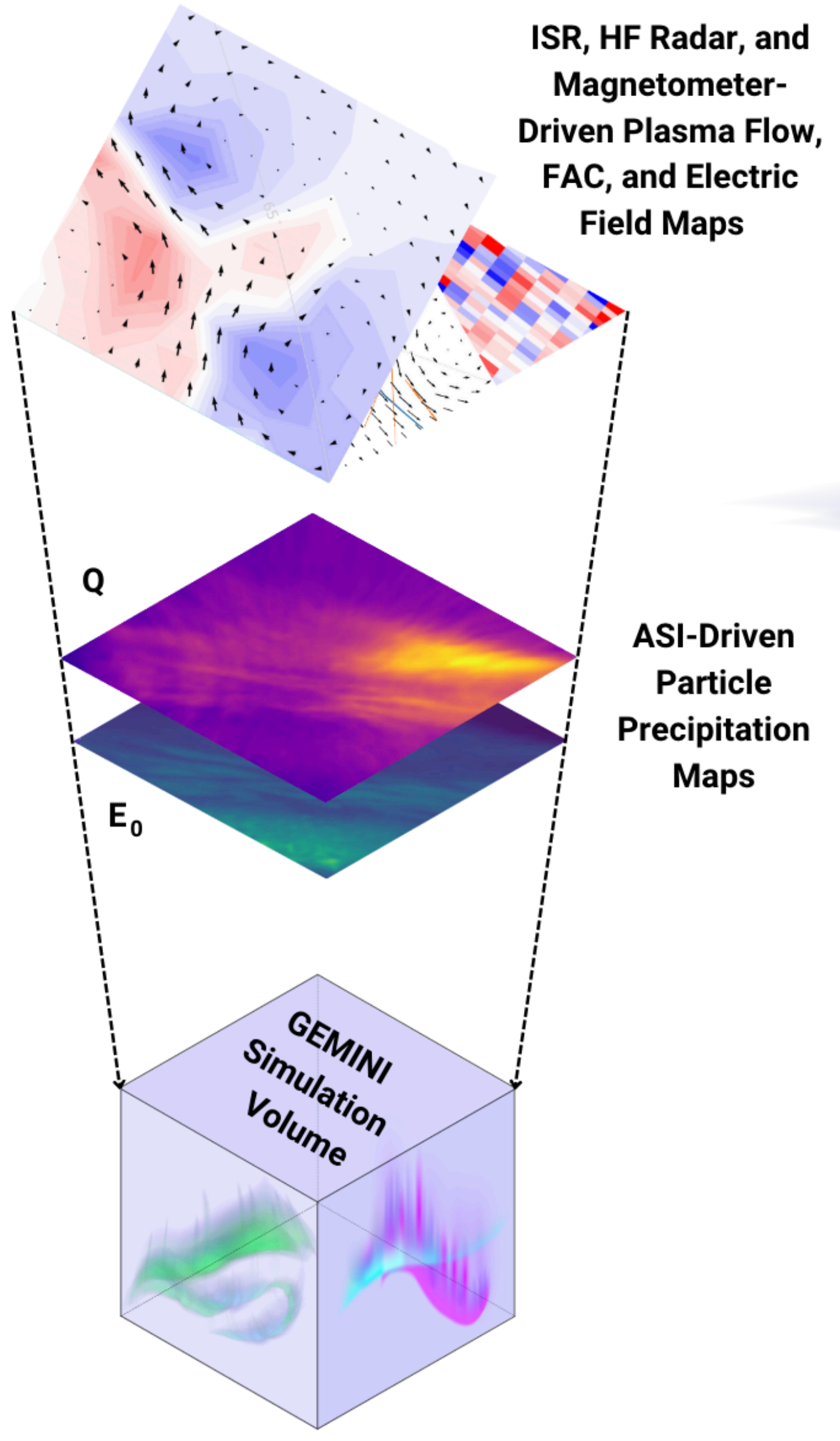


Figure 1: Display of information that flows down into the GEMINI simulation volume; the Lompe outputs are extracted, and either electric field or field-aligned currents and the ASI inversions of *Q*, *E0*, σ_P, and σ_H are funneled into GEMINI functions and are inserted into the GEMINI simulation volume as perturbations on a previously heated and equilibrated ionosphere.

OBSERVATIONAL TECHNIQUES

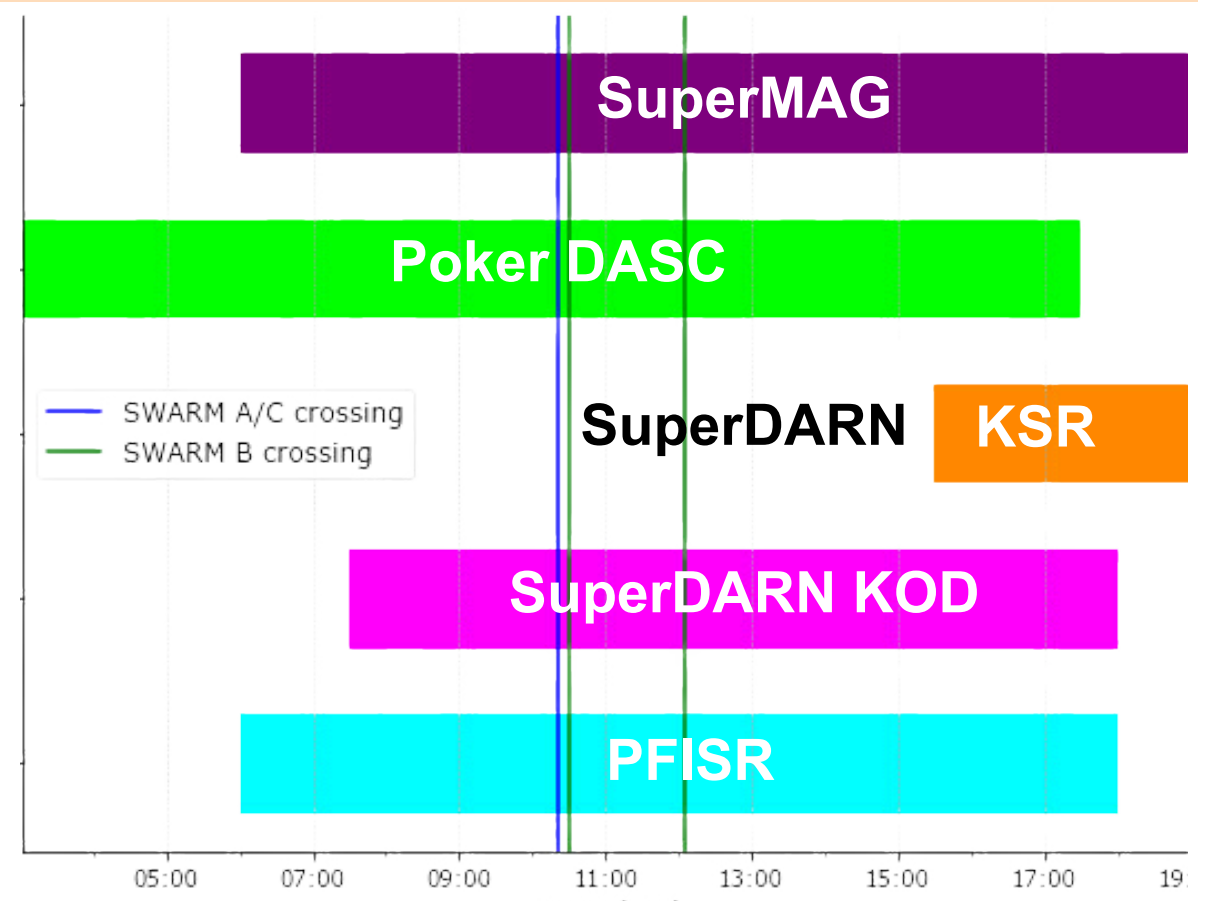
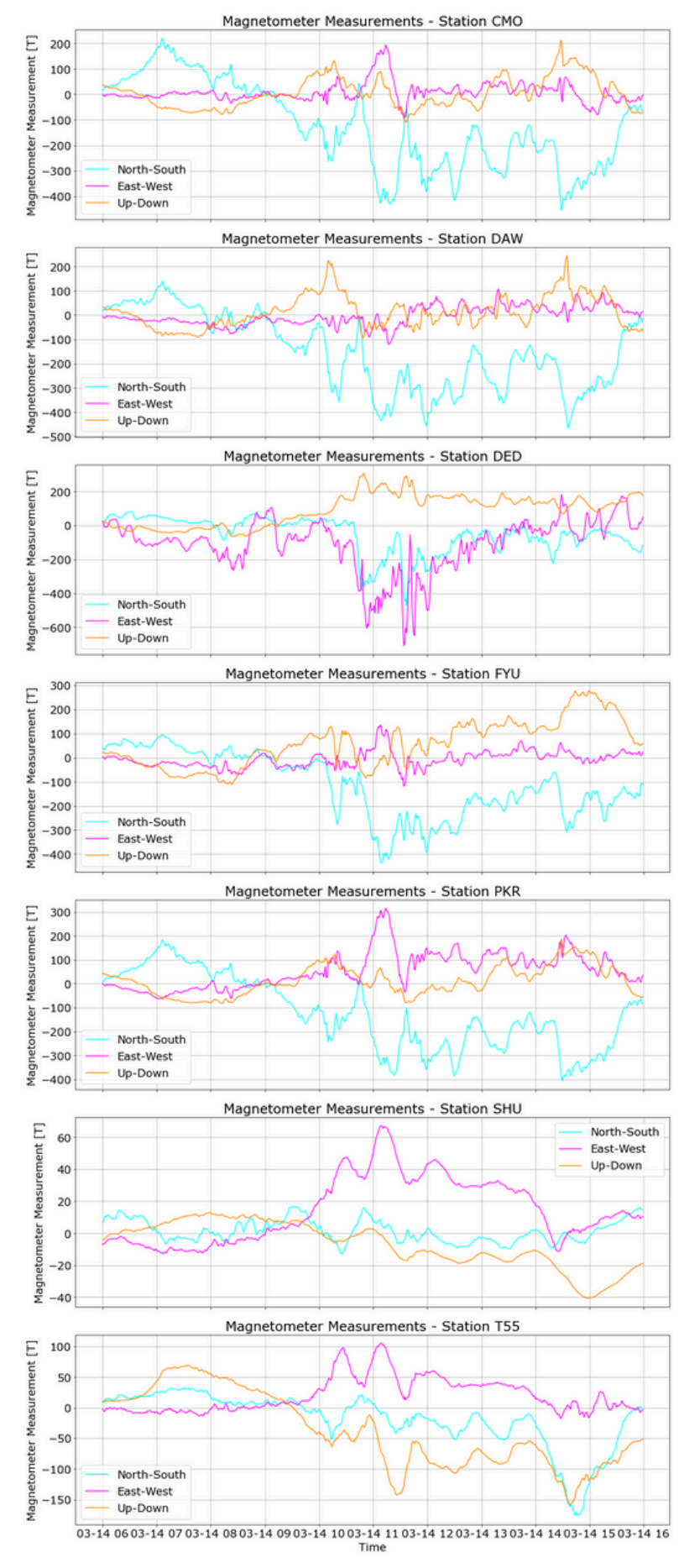


Figure 2: Example of planning model reconstructions around an event based off of data availability; every available source of data is placed in an event table and Swarm crossings are marked as to determine the highest data density times for a given event date and Lompe reconstructions are performed with the available data.



The following instruments/ measurements were used throughout the SoP23 campaign as Lompe, vvels, and GEMINI inputs:

- PFISR - ion flows
- SuperDARN (KOD, KSR) - ion flows
- SuperMAG - ground magnetic fields
- SWARM A, B, and C - space magnetic fields
- Poker DASC - particle precipitation

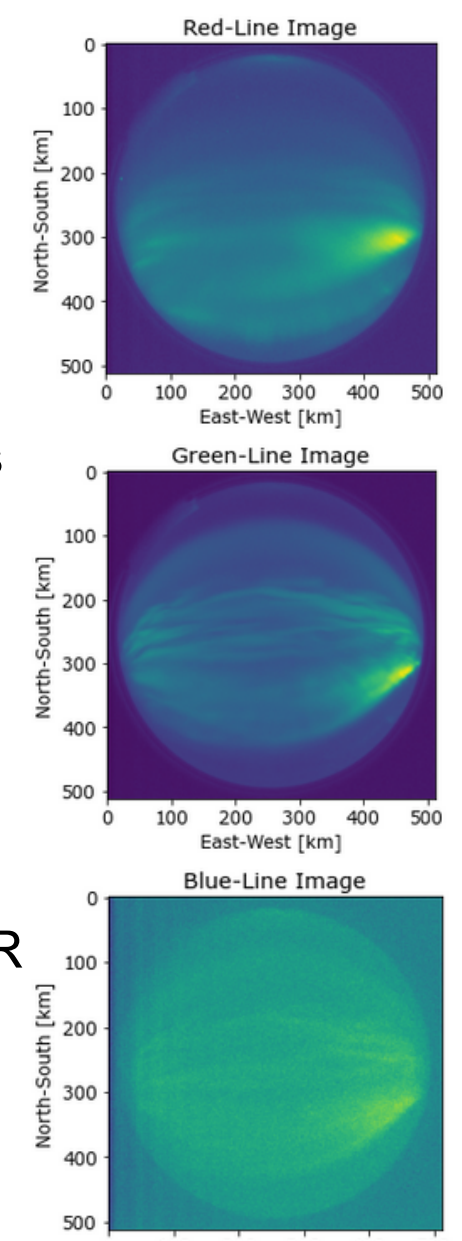
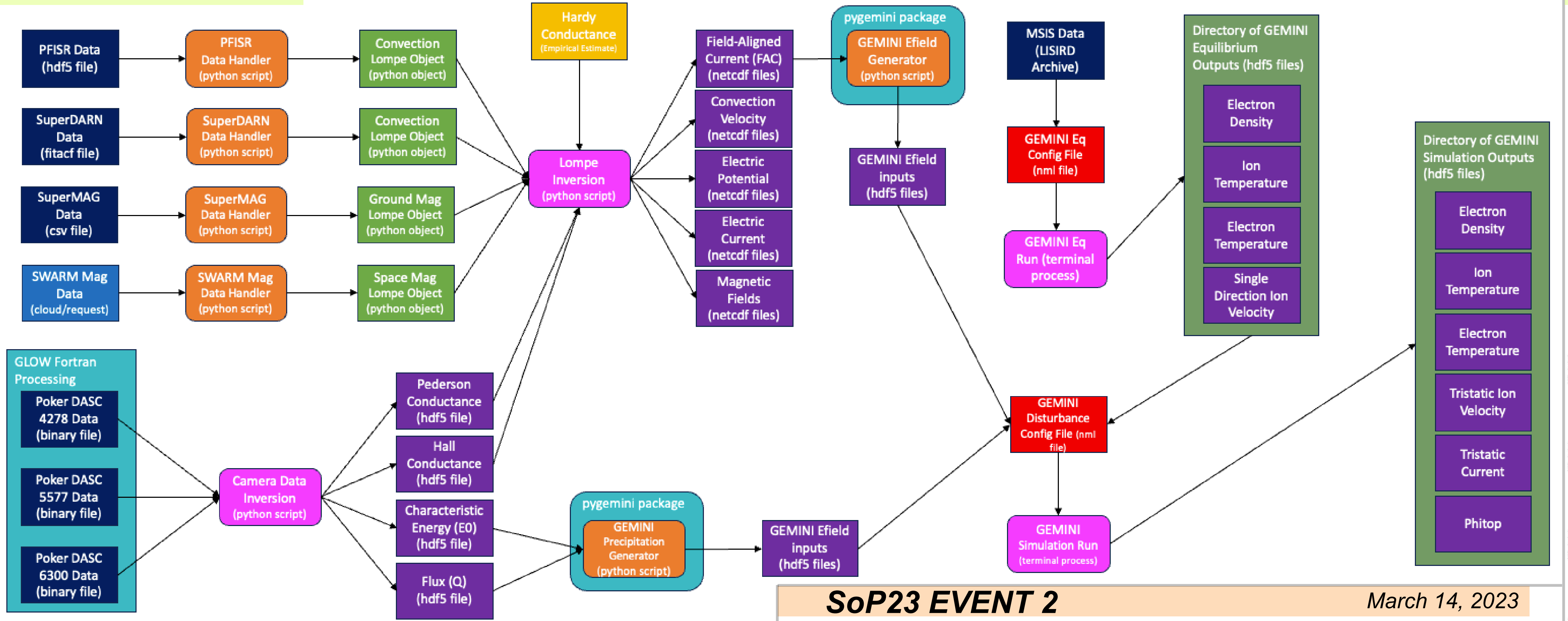


Figure 3 >: Red, green, and blue-line DASC imagery from the PFRR ASI (March 14, 2023 event); this observed imagery is later used to determine particle precipitation information.

< Figure 4: N, E, U ground magnetometer measurements from the SuperMAG ground system (March 14, 2023 event), used as inputs for the data-driven process; every SuperMAG magnetometer within the state of Alaska that was on at the time of the event was used.

MODELING



PFISR Data (hdf5 file) → PFISR Data Handler (python script) → Convection Lompe Object (python object)

SuperDARN Data (fitacf file) → SuperDARN Data Handler (python script) → Convection Lompe Object (python object)

SuperMAG Data (csv file) → SuperMAG Data Handler (python script) → Ground Mag Lompe Object (python object)

SWARM Mag Data (cloud/request) → SWARM Mag Data Handler (python script) → Space Mag Lompe Object (python object)

Hardy Conductance (Empirical Estimate) → Lompe Inversion (python script)

Lompe Inversion (python script) → Field-Aligned Current (FAC) (netcdf files); Convection Velocity (netcdf files); Electric Potential (netcdf files); Electric Current (netcdf files); Magnetic Fields (netcdf files)

Field-Aligned Current (FAC) (netcdf files) → pygemini package: GEMINI Efield Generator (python script) → GEMINI Efield inputs (hdf5 files)

GLOW Fortran Processing: Poker DASC 4278 Data (binary file); Poker DASC 5577 Data (binary file); Poker DASC 6300 Data (binary file) → Camera Data Inversion (python script) → Pederson Conductance (hdf5 file); Hall Conductance (hdf5 file); Characteristic Energy (E0) (hdf5 file); Flux (Q) (hdf5 file)

pygemini package: GEMINI Precipitation Generator (python script) → GEMINI Efield inputs (hdf5 files)

MSIS Data (LISIRD Archive) → GEMINI Eq Config File (nml file) → GEMINI Eq Run (terminal process) → Directory of GEMINI Equilibrium Outputs (hdf5 files): Electron Density; Ion Temperature; Electron Temperature; Single Direction Ion Velocity

GEMINI Disturbance Config File (nml file) → GEMINI Simulation Run (terminal process) → Directory of GEMINI Simulation Outputs (hdf5 files): Electron Density; Ion Temperature; Electron Temperature; Tristatic Ion Velocity; Tristatic Current; Phitop

Figure 5: Scripting Architecture for the Lompe + GEMINI Pipeline

	No Mag	SuperMAG	SWARM Mags	2+ Mags	Poker DASC	Poker DASC and Mag(s)
No Flows	0	1	1	1	0*	1
PFISR Flows	2	3	3	3	2	5
SuperDARN Flows	1	2	2	3	1	4
SWARM Flows	1	2	2	3	1	4
Multiple Flows	3	4	4	4	3	6

Table 1: Data Availability Modeling Matrix; this matrix helps to determine the strength of a Lompe model run depending on the available data inputs. The scores range from 0-6, where 0 indicates that a Lompe model inversion cannot be performed with the available data, and a 6 indicates that the Lompe model inversion includes ample data to perform an inversion. A score of 3 or above is considered to be adequate for model inversion. A score of 0* indicates that while a Lompe inversion may not be performed, precipitation inputs for GEMINI may still be generated independent of Lompe.

RESULTS

SoP23 EVENT 1

February 12, 2023

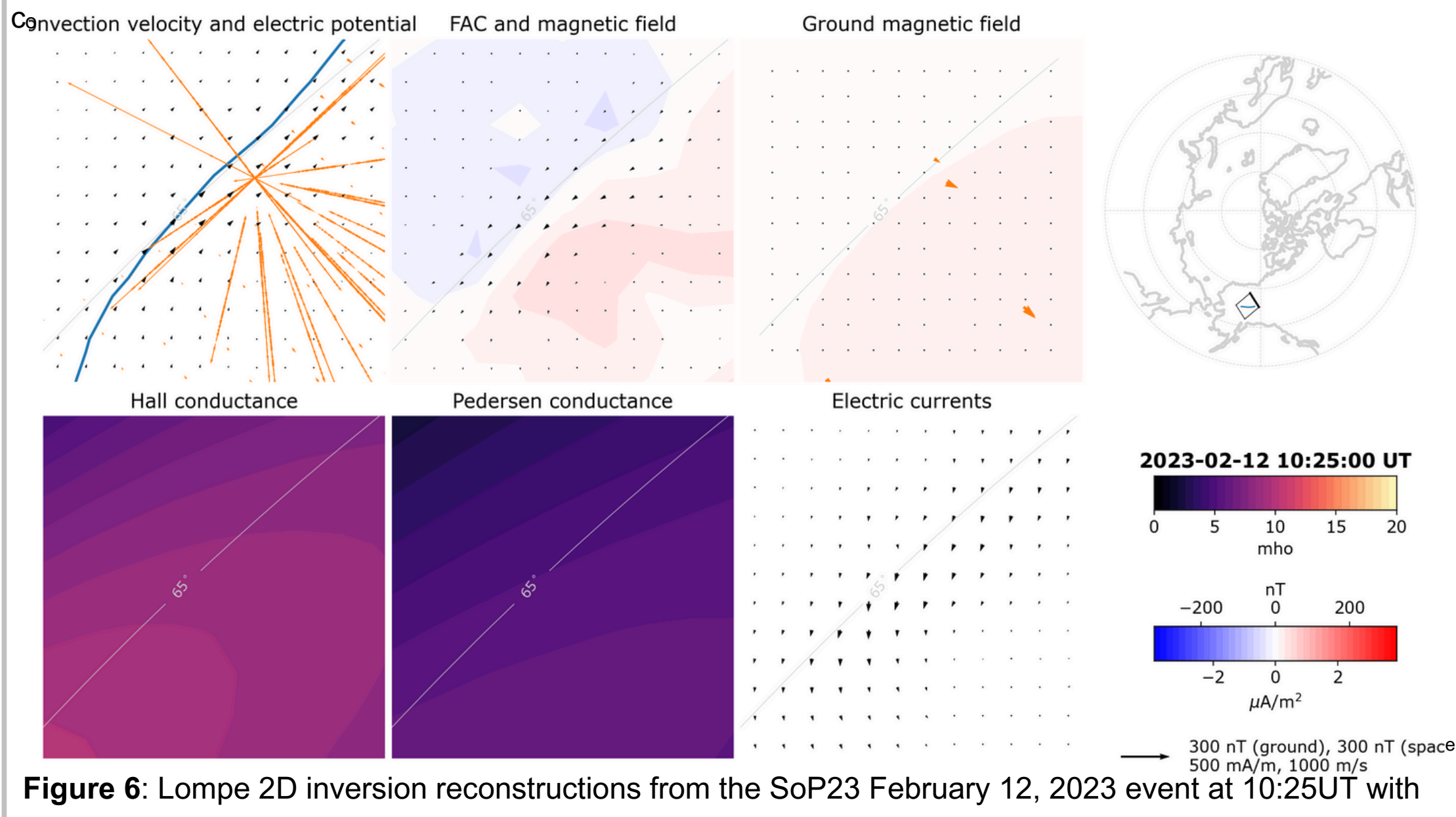


Figure 6: Lompe 2D inversion reconstructions from the SoP23 February 12, 2023 event at 10:25UT with PFISR, SuperDARN KOD, and SuperMAG inputs.

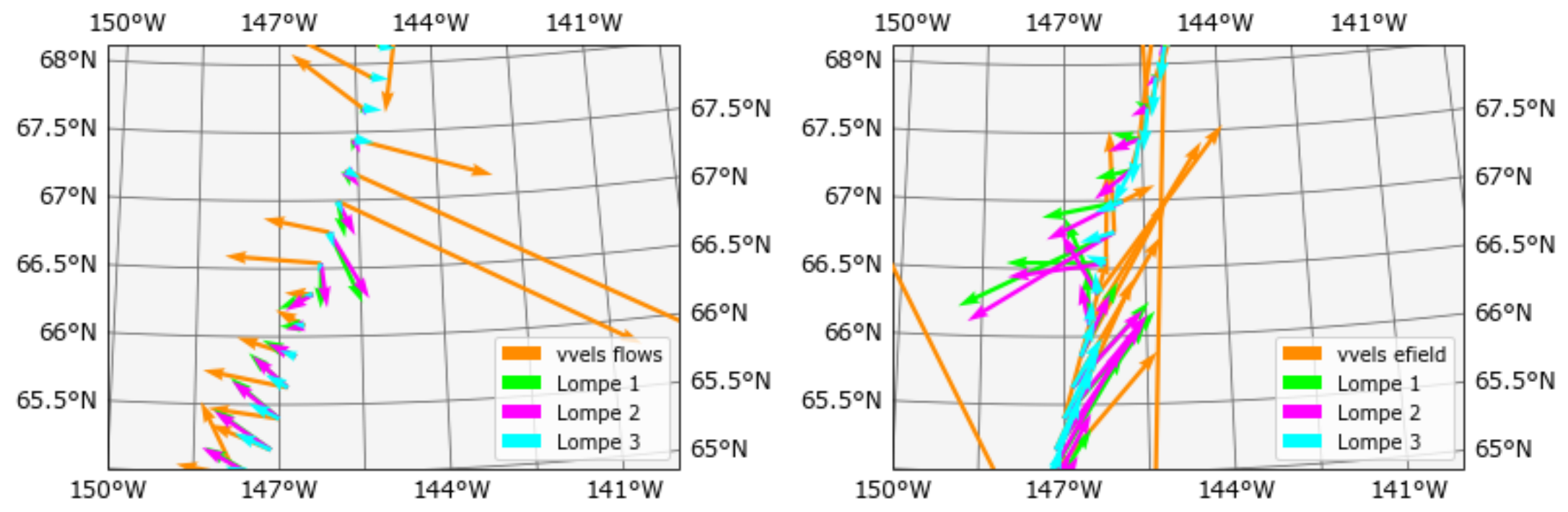


Figure 7: Lompe vs. vvels comparisons, where Lompe 1 = PFISR inputs only, Lompe 2 = PFISR and SuperMAG inputs, Lompe 3 = PFISR, SuperDARN, and SuperMAG inputs; left: plasma flows, right: efields

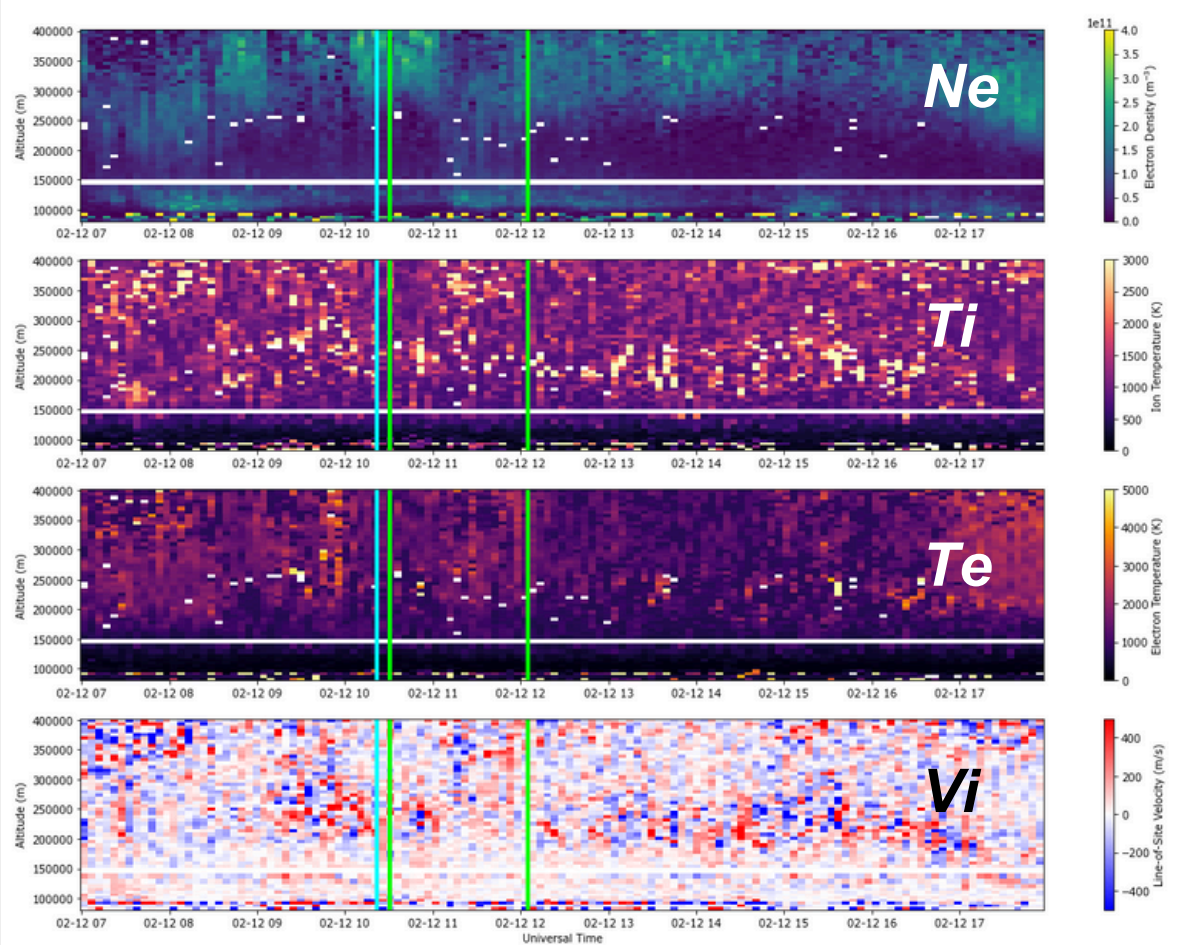


Figure 8: PFISR plasma parameters with SWARM crossings (blue = A/C, green = B) for SoP23 Event 1.

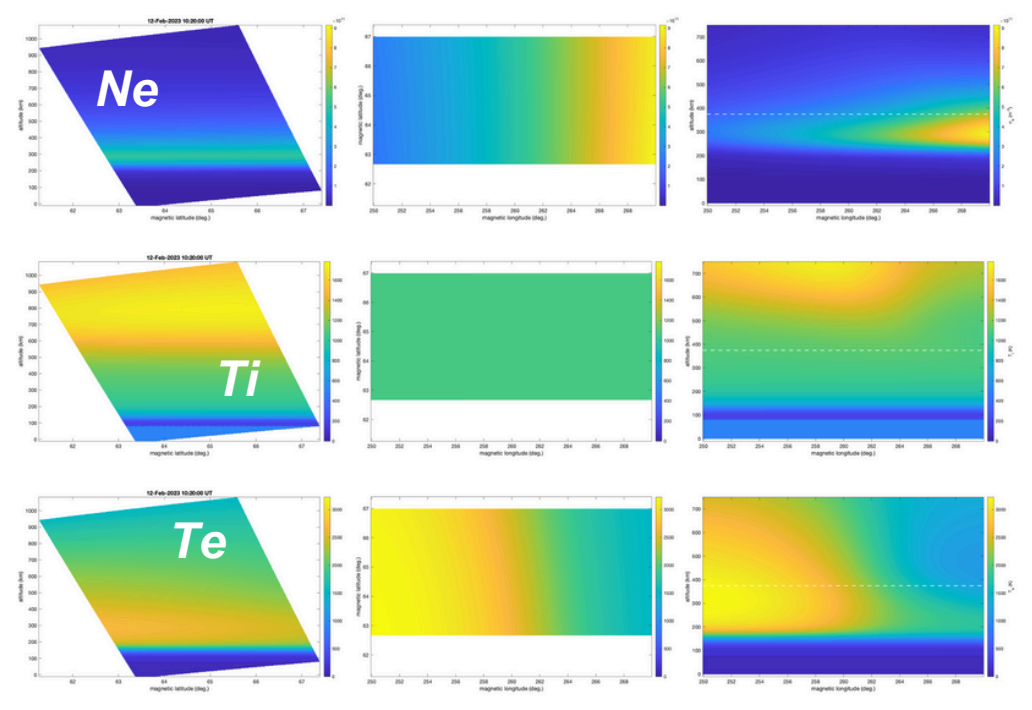


Figure 9: GEMINI *Ne*, *Ti*, and *Te* outputs (MSIS-driven); left column = alt (km) vs mlat (deg); middle = mlat vs mlon (deg); right = alt vs mlon; particle precipitation maps will later be used to drive these plasma parameters.

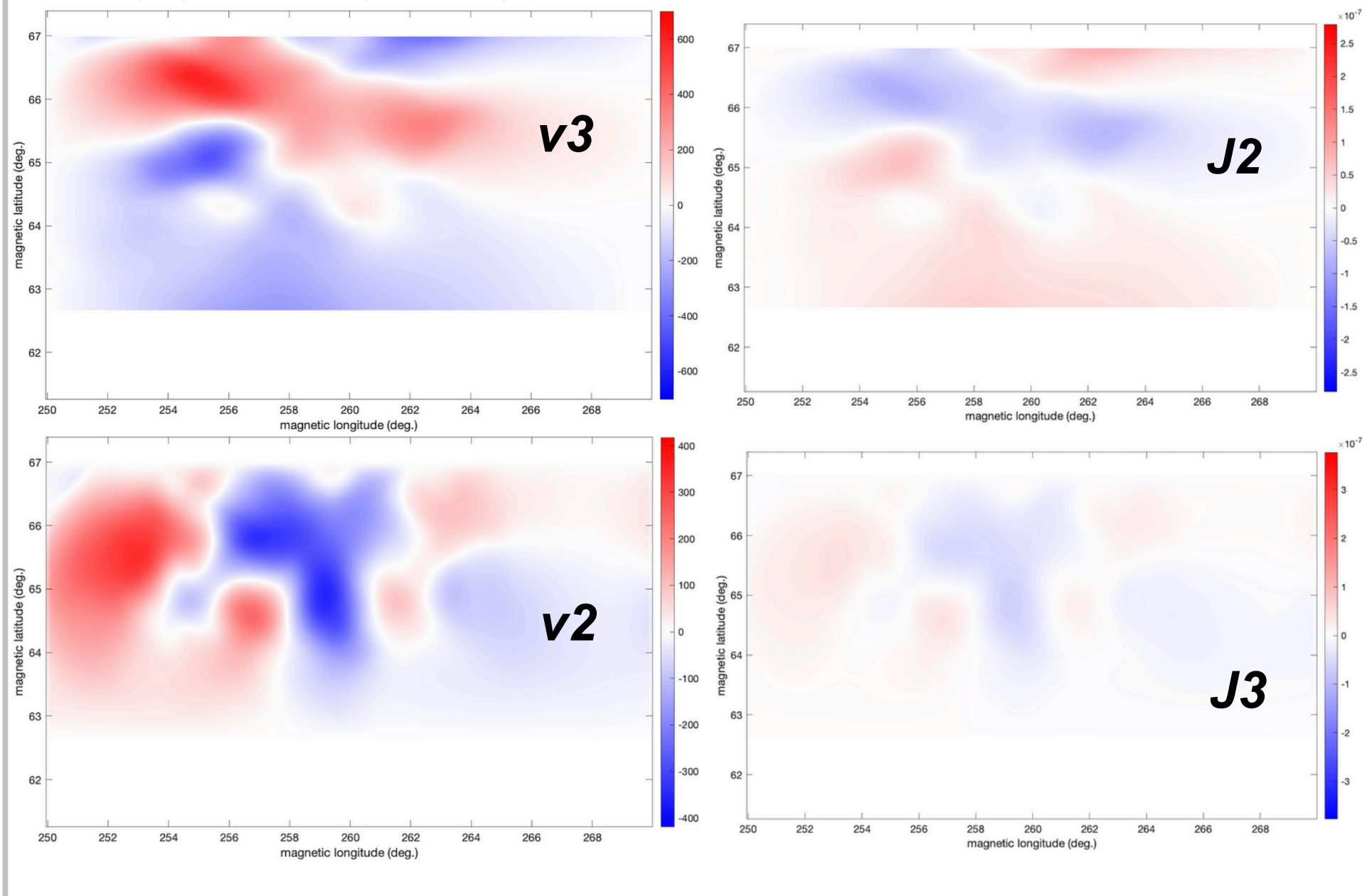


Figure 10: GEMINI velocity and current outputs for SoP23 Event 1. The velocity and current components are calculated within GEMINI using the Lompe FAC outputs, which are driven by real data inputs.

SoP23 EVENT 2

March 14, 2023

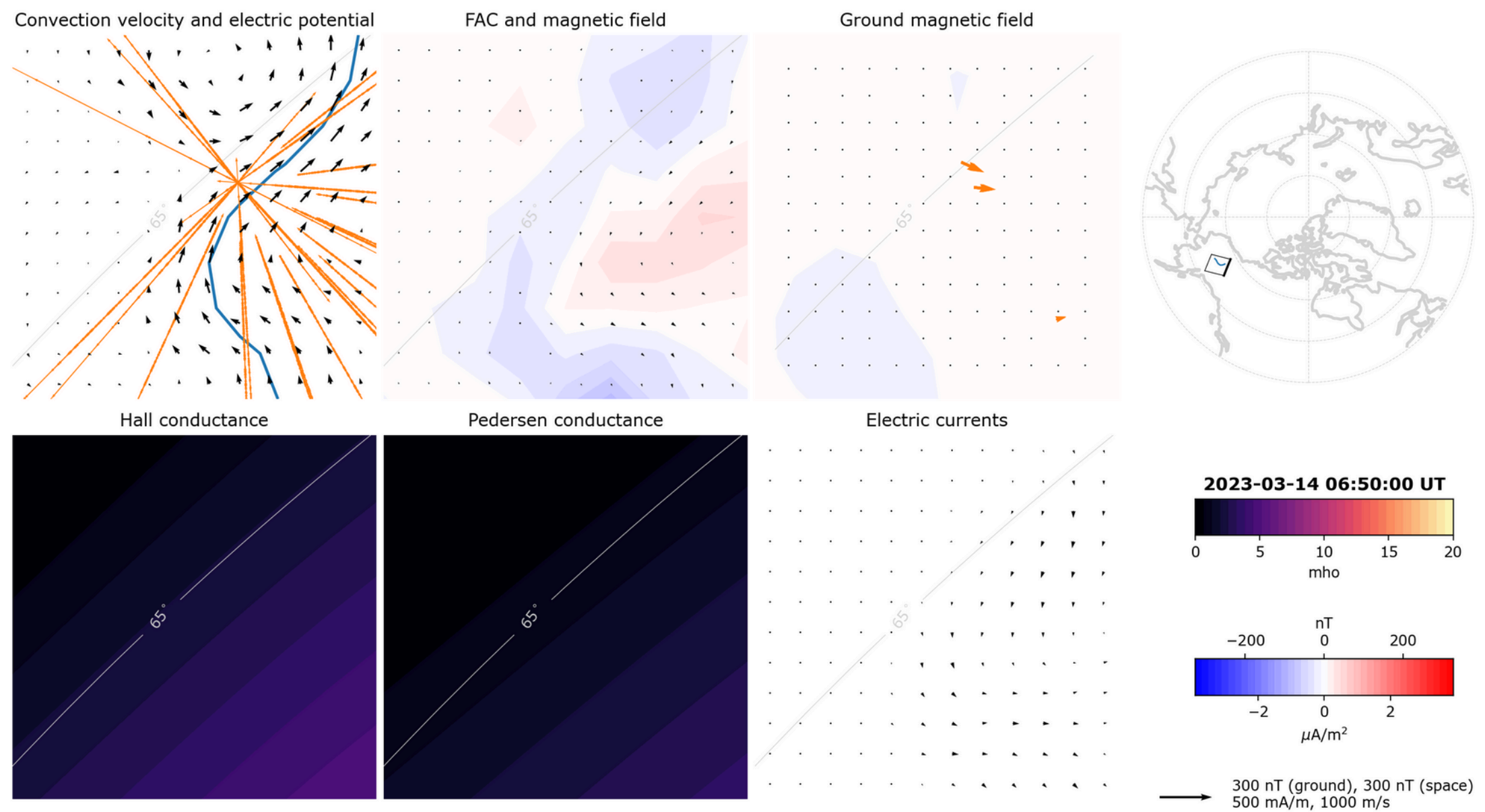


Figure 11: Lompe 2D inversion reconstructions from the SoP23 March 14, 2023 event at 6:50UT with PFISR and SuperMAG inputs.

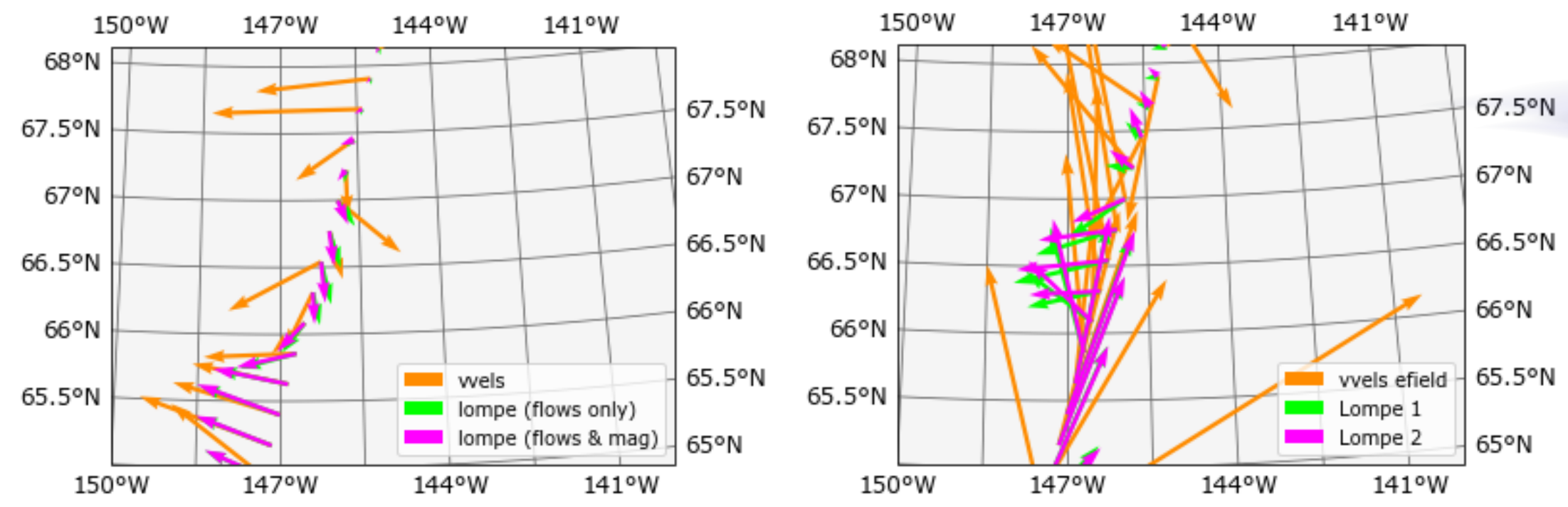
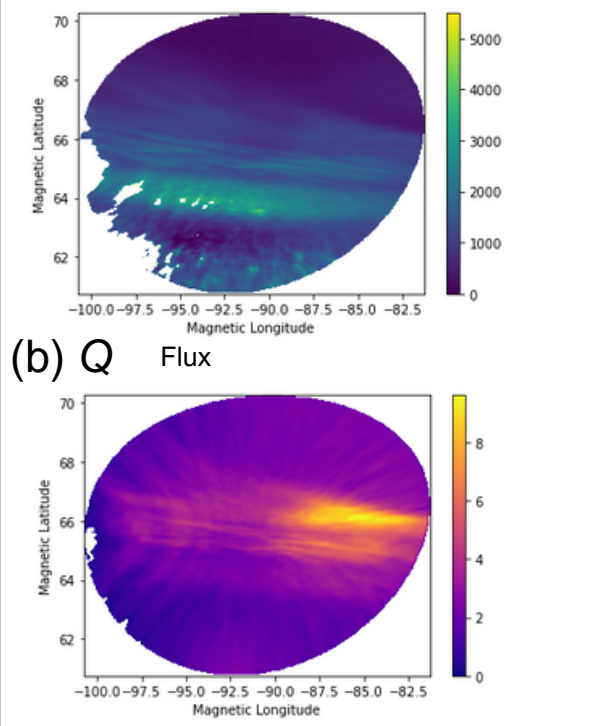


Figure 12: Lompe vs. vvels comparisons, where Lompe 1 = PFISR inputs only, Lompe 2 = PFISR and SuperMAG inputs; left: plasma flows, right: efields



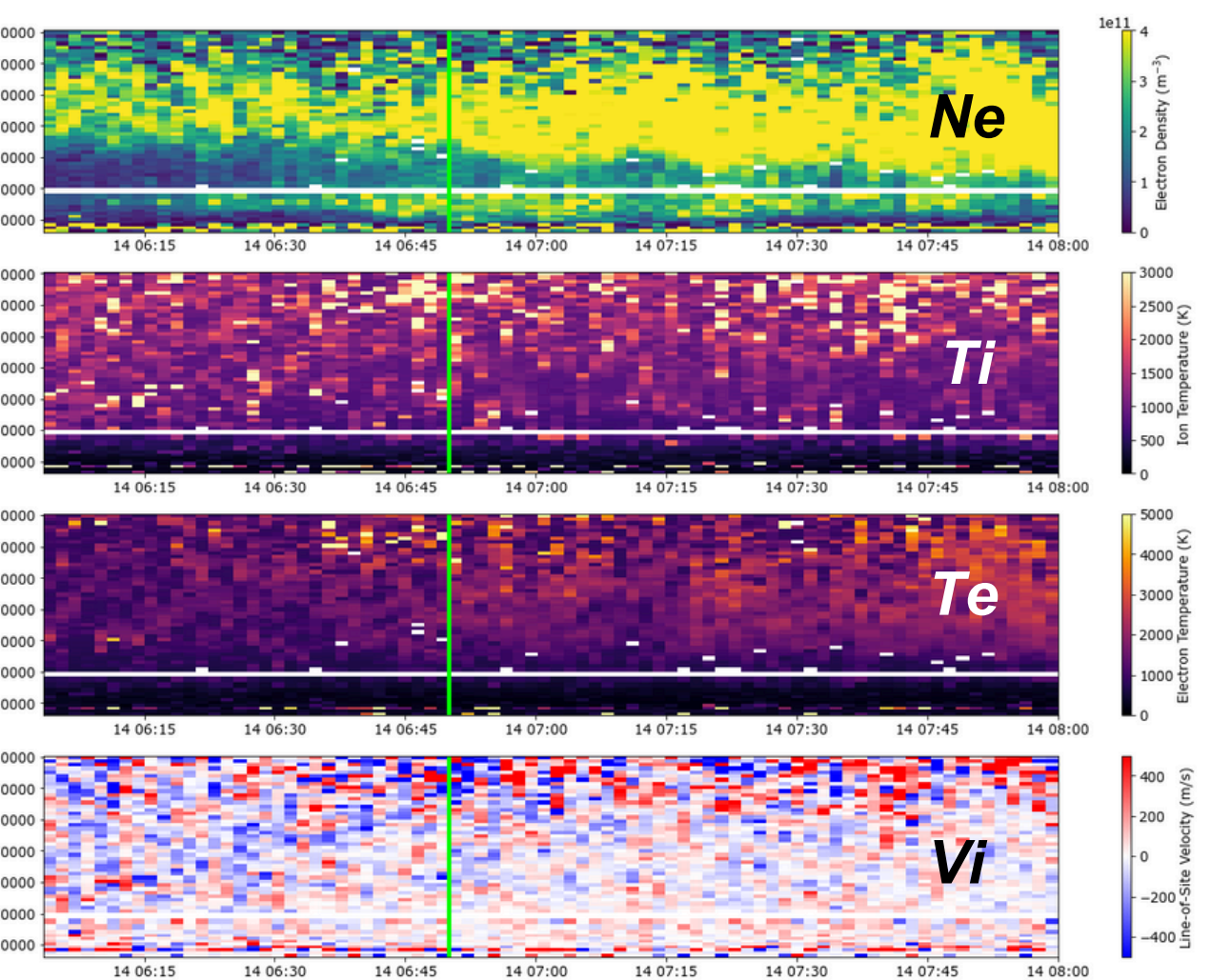


Figure 13: PFISR plasma parameters with Swarm crossings (green = Swarm B)

Figure 14: Inverted DASC imagery from the March 14 SoP23 event (mlat vs mlon); image inversion process courtesy of Alex Mule at DU

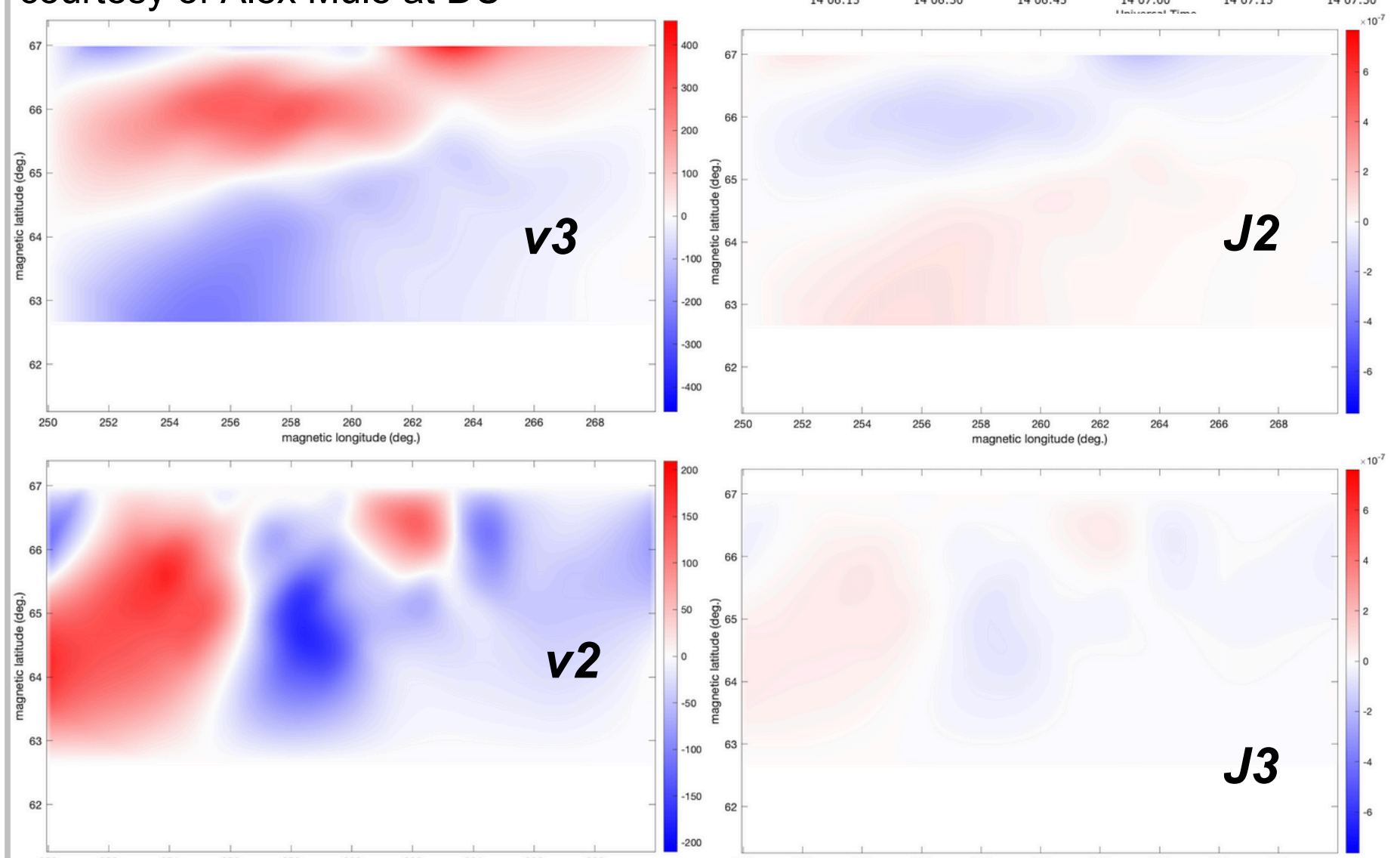


Figure 15: GEMINI velocity and current outputs for SoP23 Event 2. The velocity and current components are calculated within GEMINI using the Lompe FAC outputs, which are driven by real data inputs.

SoP23 EVENT 3

March 19, 2023

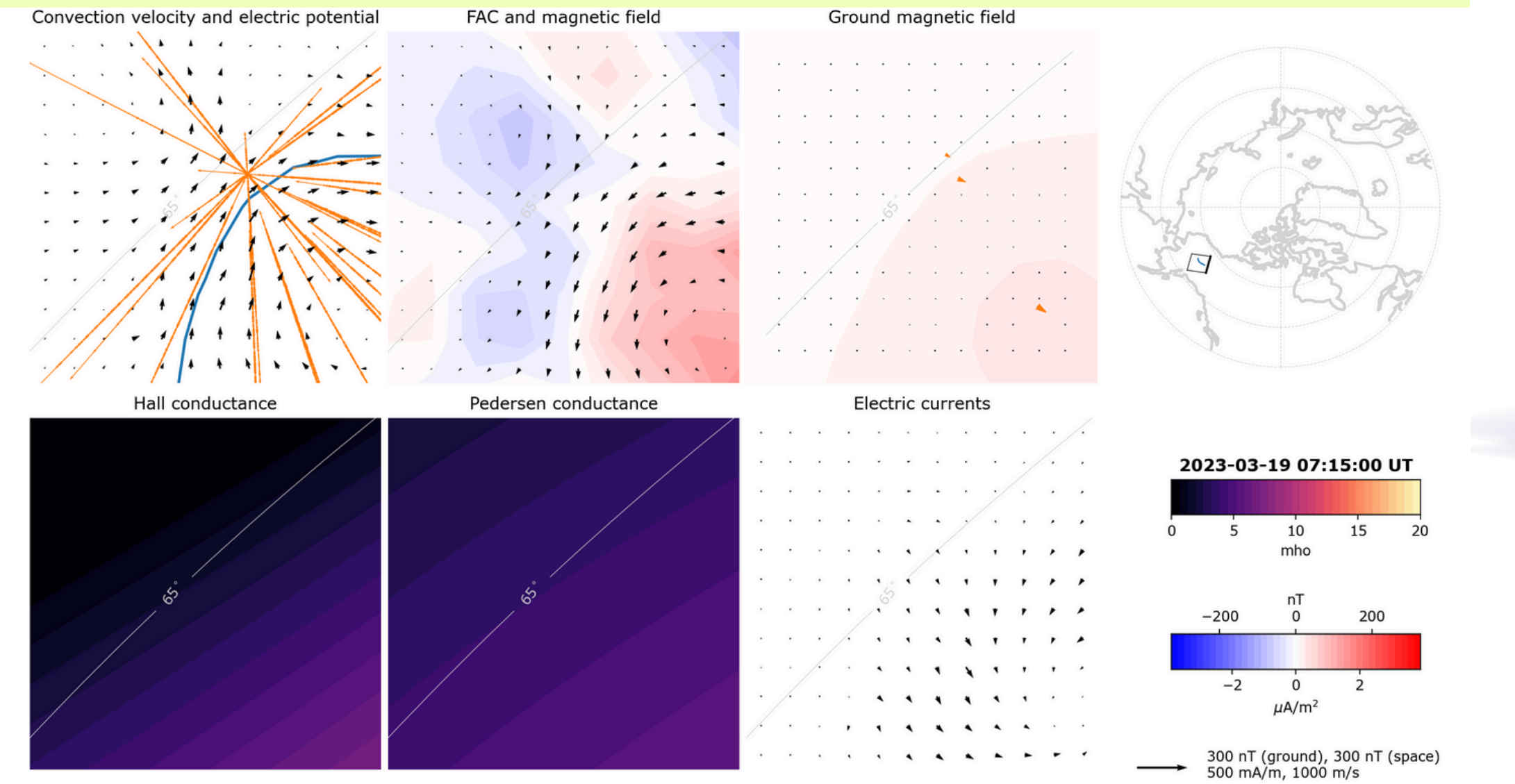


Figure 16: Lompe 2D inversion reconstructions from the SoP23 March 19, 2023 event at 7:15UT with PFISR and SuperMAG inputs

SoP23 EVENT 3 (continued)

March 19, 2023

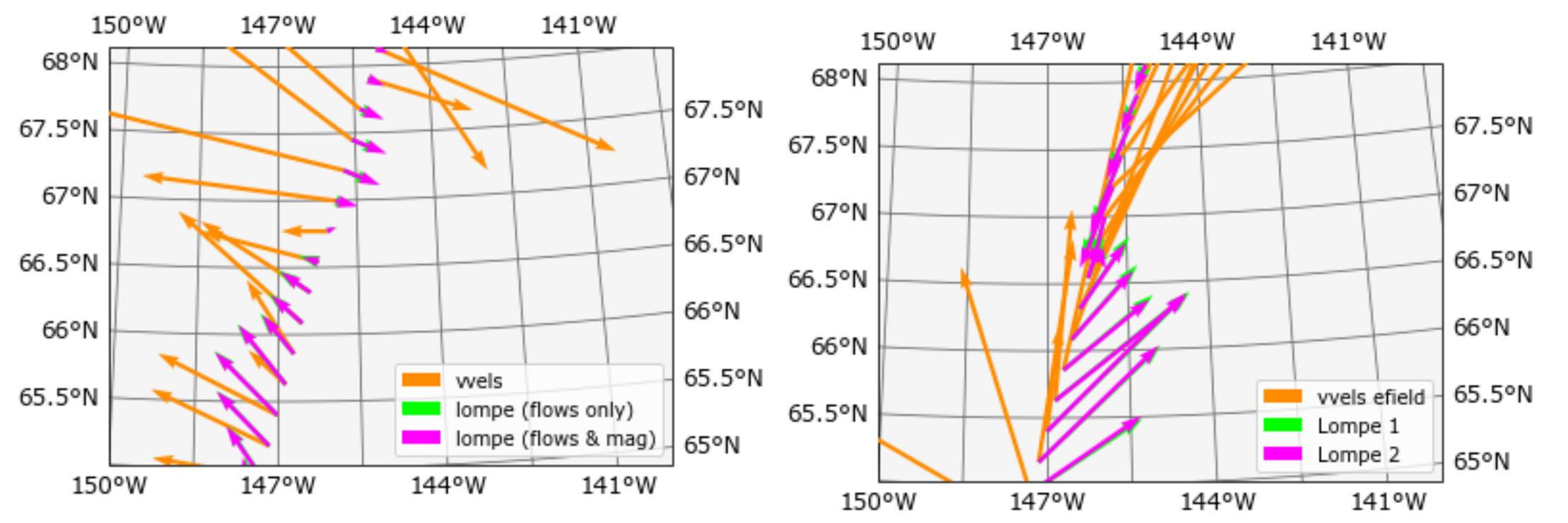


Figure 17: Lompe vs. vvels comparisons, where Lompe 1 = PFISR inputs only, Lompe 2 = PFISR and SuperMAG inputs; left: plasma flows, right: efields

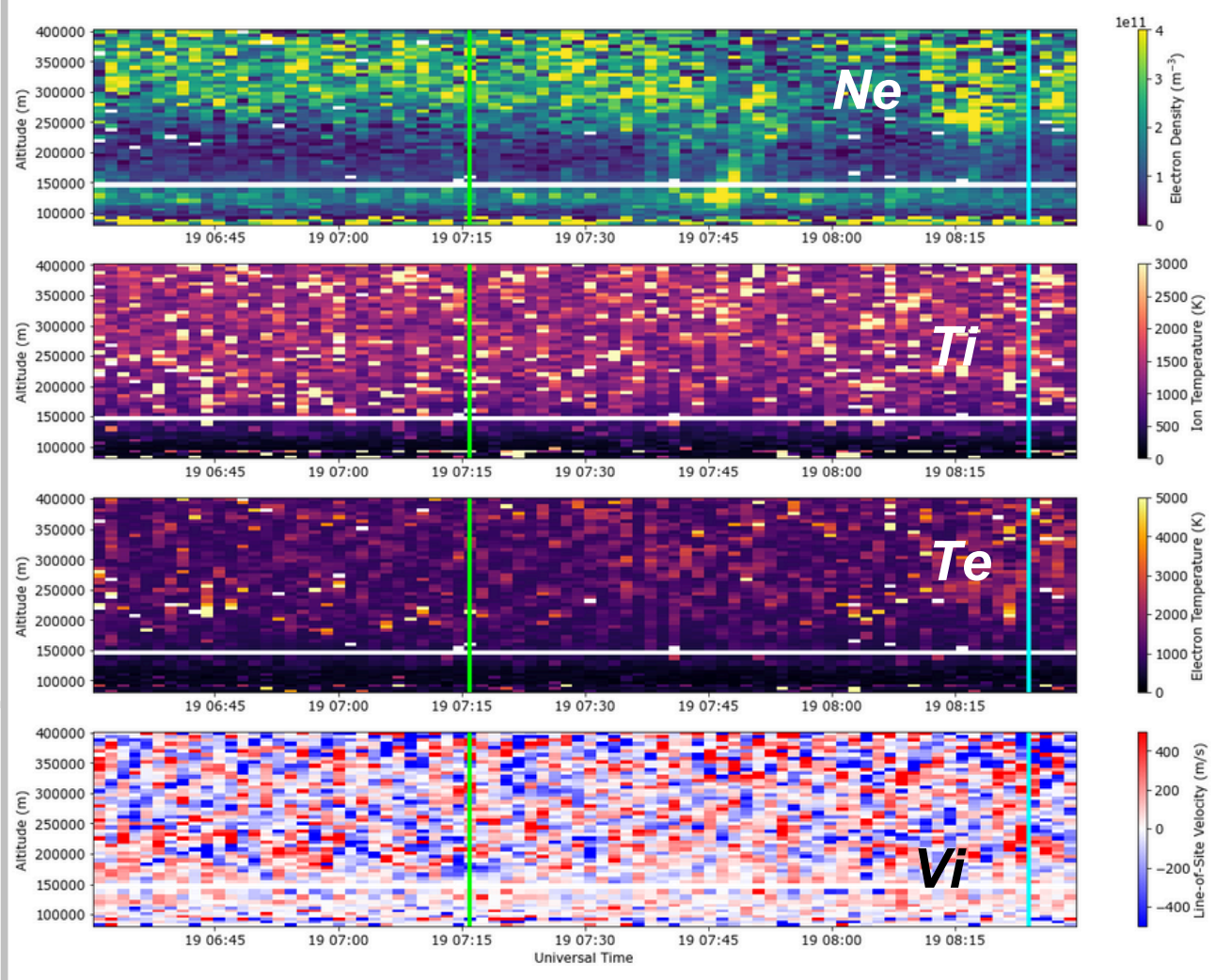


Figure 18: PFISR plasma parameters with Swarm crossings (green = Swarm B)

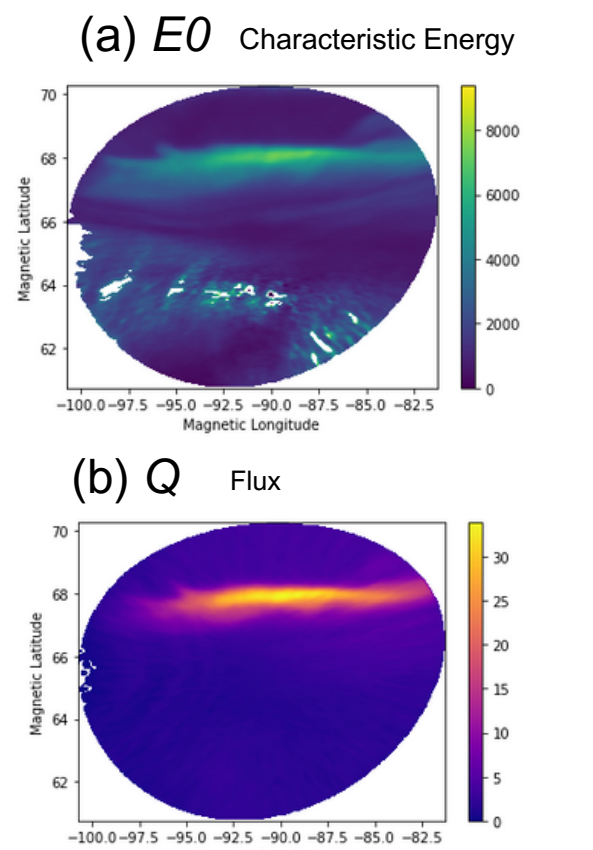


Figure 19: Inverted DASC imagery from the March 19 SoP23 event (mlat vs mlon); image inversion process courtesy of Alex Mule at DU

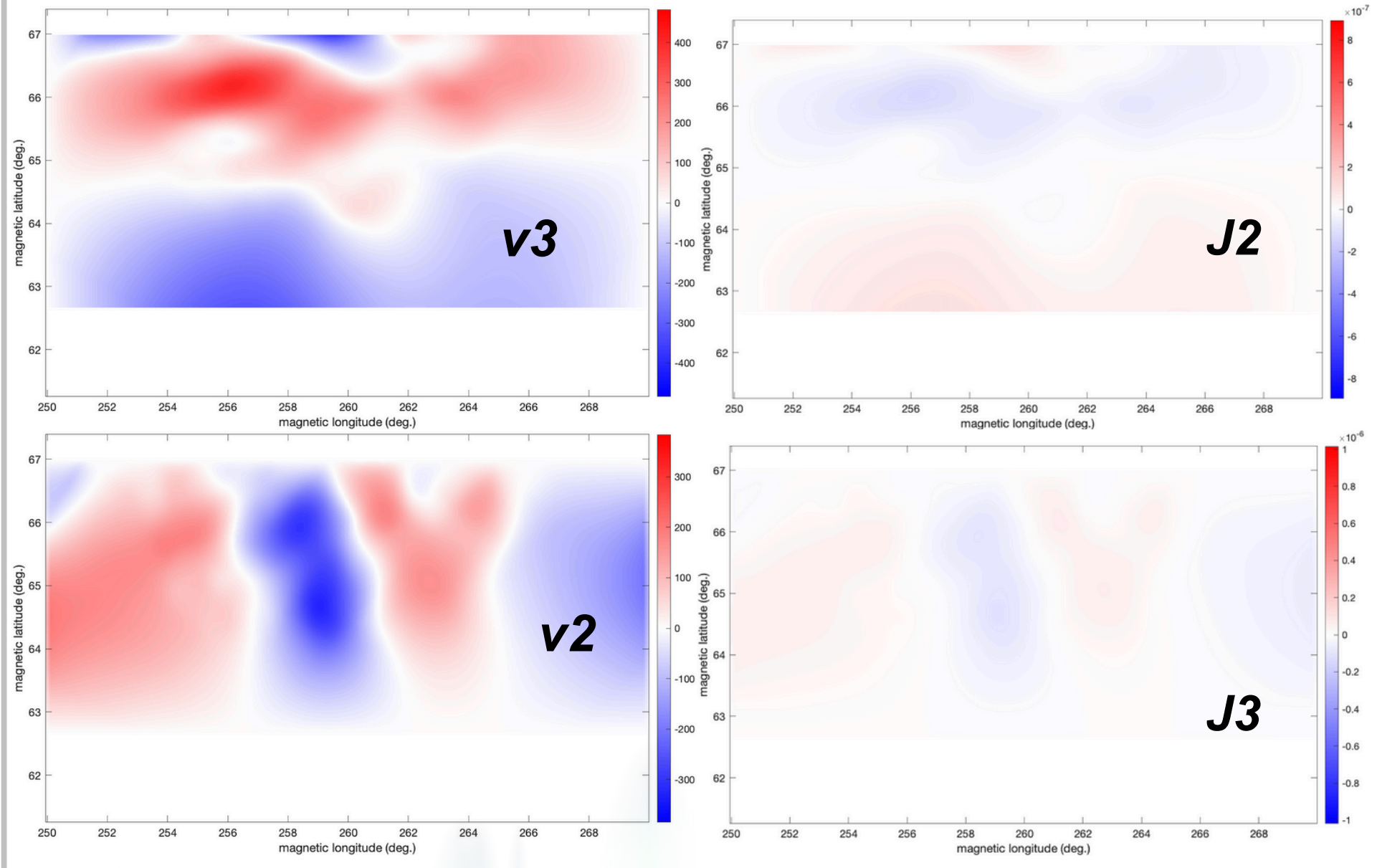


Figure 20: GEMINI velocity and current outputs for SoP23 Event 3. The velocity and current components are calculated within GEMINI using the Lompe FAC outputs, which are driven by real data inputs.

DISCUSSION

- Compared to statistical and empirical models, this local-scale assimilation approach offers refined spatial and temporal resolutions that are crucial for capturing the dynamic and rapidly changing conditions of auroral features.
- While these findings look to address the issues associated with capturing small- and meso-scale structures within ionospheric modeling, they are subject to the limitations of the observational data and the assumptions embedded within the GEMINI model; the spatial resolution and temporal coverage of input data can constrain the model's ability to generalize to unobserved conditions, and the computational demands of high-resolution, local-scale modeling necessitate significant resources, limiting the applicability for real-time forecasting (i.e. if it would be of interest to perform real-time analysis to call a sounding rocket launch with the dynamics at that moment in time).
- Future work will include:
  - The integration of additional data sources (such as from future sounding rocket missions or high-frequency artificially induced measurements from stations like HAARP)
  - Incorporating Swarm flows and magnetometer measurements for Lompe reconstructions
  - Driving GEMINI with the camera inversion inputs alongside the FAC inputs so that *Ne*, *Ti*, and *Te* can be influenced by real data as opposed to MSIS—this process has been done before (see Figs. 21 & 22), though the previous version used a different process for performing the camera data inversions and was not used with accompanying FAC inputs
  - Integration of Lompe and pygemini (GEMINI python plug-in) to perform self-consistent updates between the 2D reconstructions and the model outputs

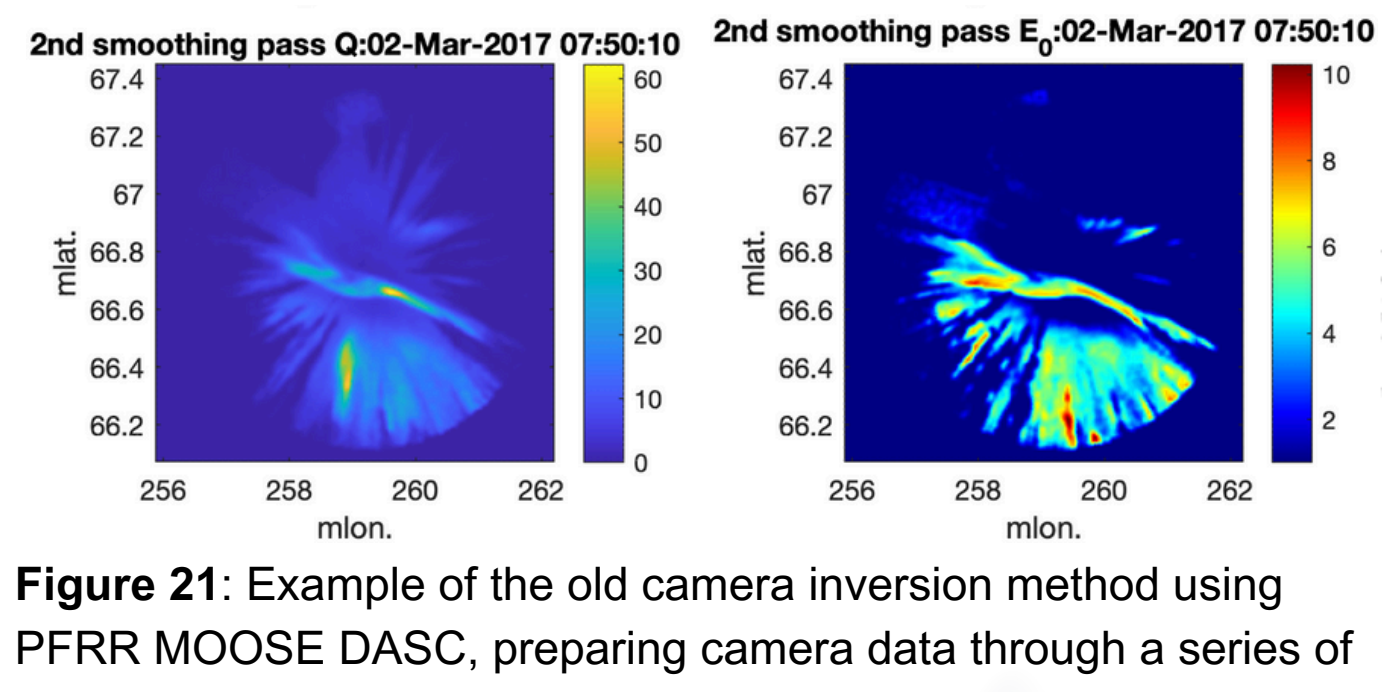


Figure 21: Example of the old camera inversion method using PFRR MOOSE DASC, preparing camera data through a series of smoothing and interpolations before inputting to GEMINI simulation volume. Plotted in MLAT [deg] vs. MLON [deg].

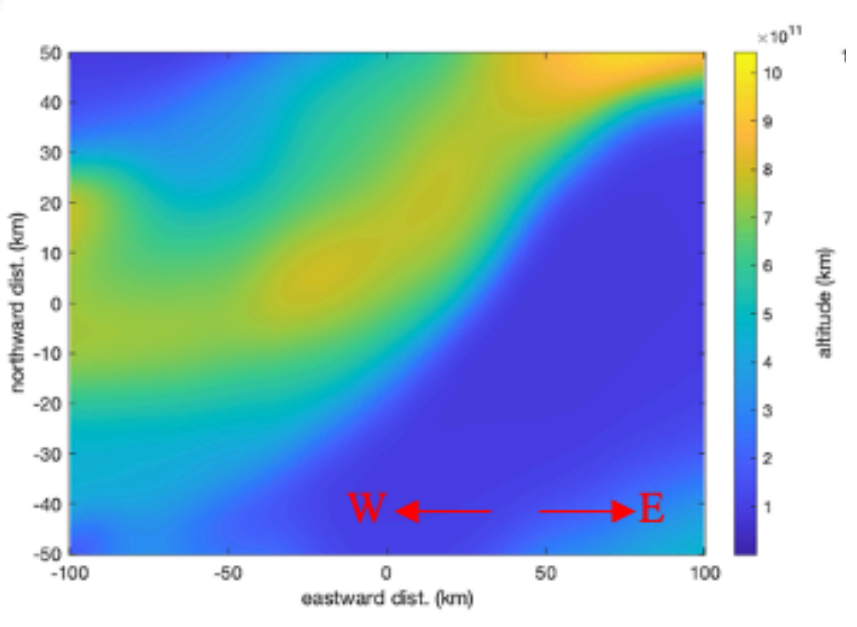


Figure 22: Example of GEMINI electron density output using ASI particle precipitation maps from older method. Plotted in Northward Distance [km] vs. Eastward Distance [km].

CONCLUSION

- This study has demonstrated the effectiveness of local-scale data assimilation in understanding the ionospheric responses to auroral stimuli through the spatial and temporal abilities of the GEMINI model afforded by data-driven inputs, providing insight into the mechanisms of energy transfer and electromagnetic interactions within the auroral ionosphere.
- The modeling capabilities developed through this study have direct implications for improving predictions of space weather effects.
- To build on the foundation laid by this research, future efforts will focus on exploring adaptive modeling techniques that can dynamically adjust to changing data inputs.
- Ultimately, we have demonstrated a process of data analysis, reconstruction, and modeling that has given us the ability to deepen our understanding of auroral physics.

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