Temporal and Spatial Evolution of the E/F-region Ionosphere

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Outline

Introduction

- Motivation
- Experiment Design
- Initial Observations

E-Region

- Sporadic-E

Plasma Line

- Observation + Analysis

F-Region

Summary and Conclusions

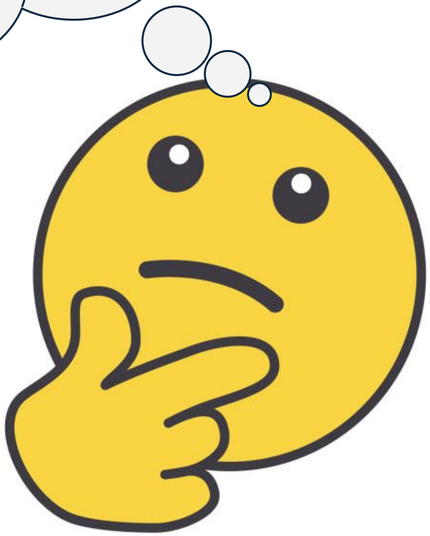
Craig Heinselman

Motivation

General Interest Areas

- Travelling Ionospheric Disturbances (TIDs)
- Decaying Layers
- Sporadic E (Es) Layers
- Transition between E and F Regions
- F-region Advection

What if we aimed to understand a general evolution of the ionosphere as opposed to focusing on phenomena that may or may not happen?



The goal of this experiment is to gain a general understanding of how the E and F regions examining the temporal and spatial evolution of the E/F-region Ionosphere.

Experiment Setup

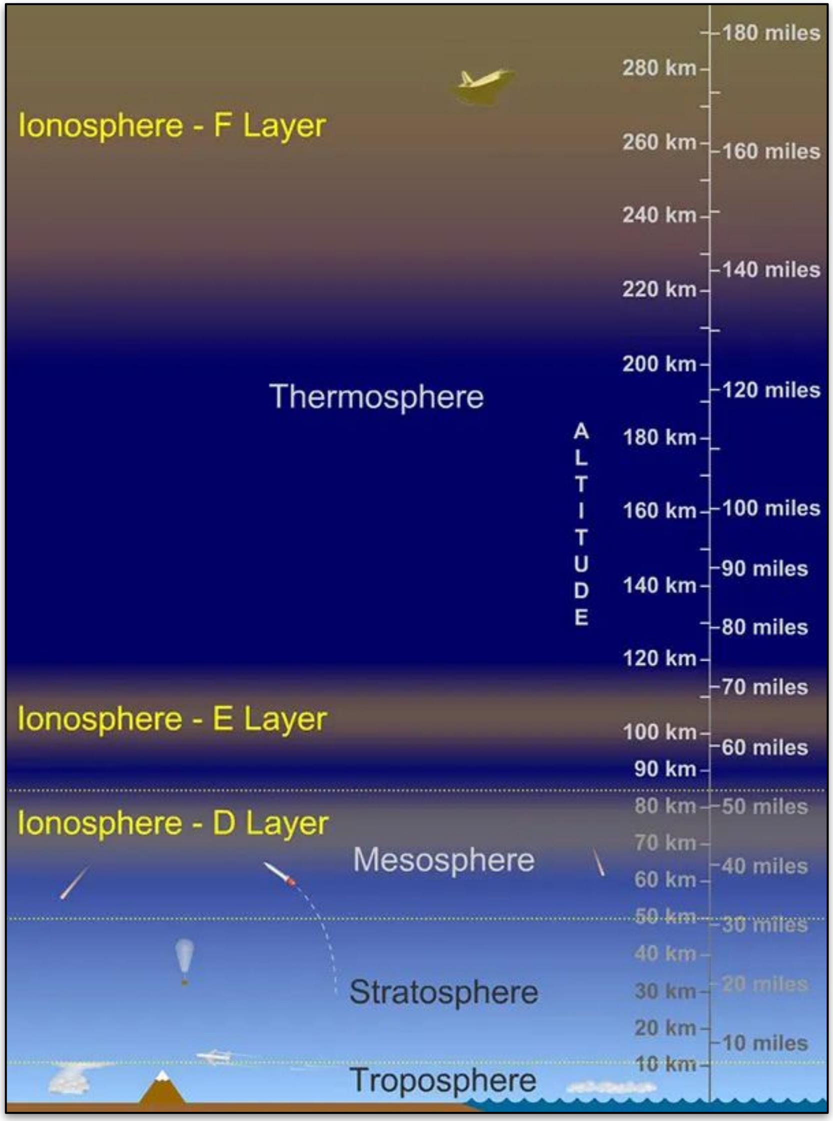
E and F Region Observations

PFISR2 Mode

- Long Pulse (F-region)
- Alternating Codes (E-Region)

Long Pulse (480 μs):
Good for F-region observations where there is a larger scale height and the electron density is lower.

Alternating Code:
Good for E-region observations where the scale height is smaller and more structure is present.

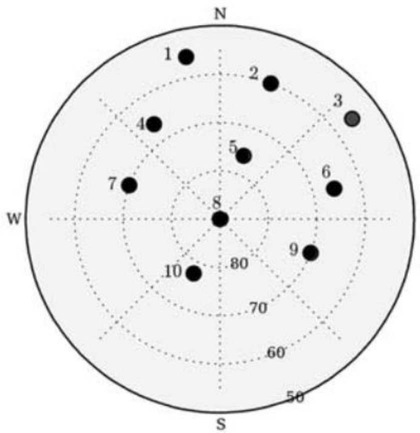


UCAR

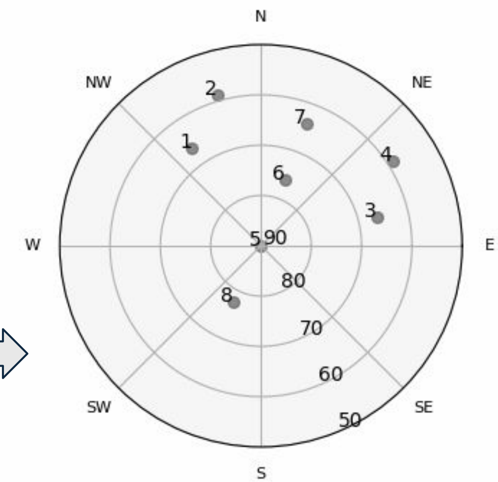
Experiment Setup

Temporal and Spatial Observations

- 8 Beams
- Daytime Experiment
- 5 min ≥ Integration Time ≥ 1 min



Nicolls and Heinselman, 2007



Spatial Resolution

Beams selected to be similar to Nicolls and Heinselman, 2007 (TIDs).

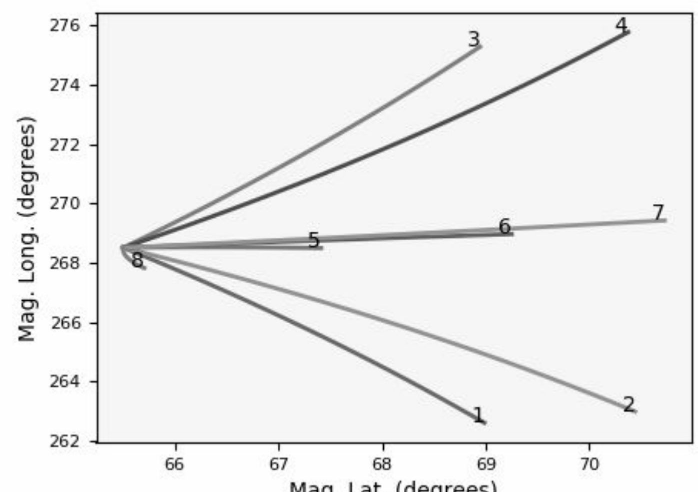
- *Increasing the number of beams gives a higher spatial resolution at the cost of a lower temporal resolution.*

Temporal Resolution

Daytime Experiment

- Better signal to noise ratio due to the higher densities allowing for shorter integration.

Use shorter integrations times since temporal resolution decreases with increasing integration time.

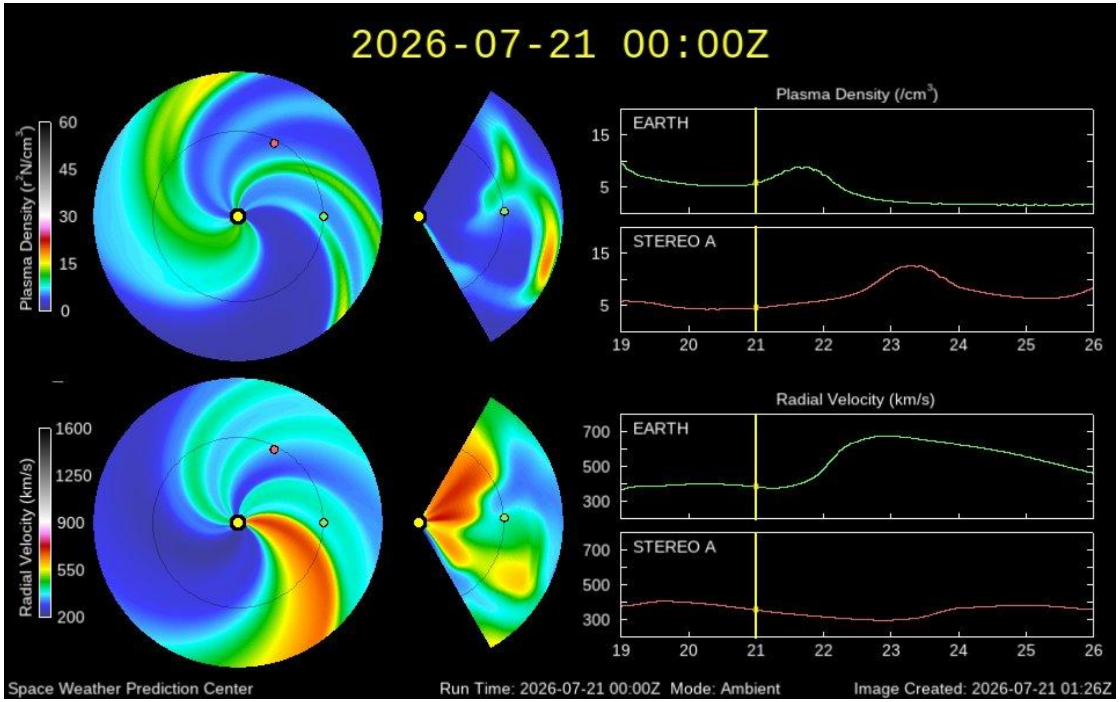


Experiment Conditions

Experiment Start: 2026-07-21 00:00:00 UT
(2026-07-20 16:00:00 AKDT)

Experiment End: 2026-07-21 02:00:00 UT
(2026-07-20 18:00:00 AKDT)

In general, conditions were quiet and stable with little to no geomagnetic activity. This timeframe is a good measure of background ionospheric conditions that could be used to compare with predicted elevated conditions in the near future.



SWPC WSA-Enlil Model

Conditions

- No Solar Flares or CMEs Prior or During the Experiment
- No Proton Events
- Quiet Geomagnetic Conditions
  - Kp = 1
  - Ap = 4

Data Products

15 Data Files

- 6 Alternating Code
- 6 Long Pulse
- 3 Long Pulse Vectors

E-Region

F-Region

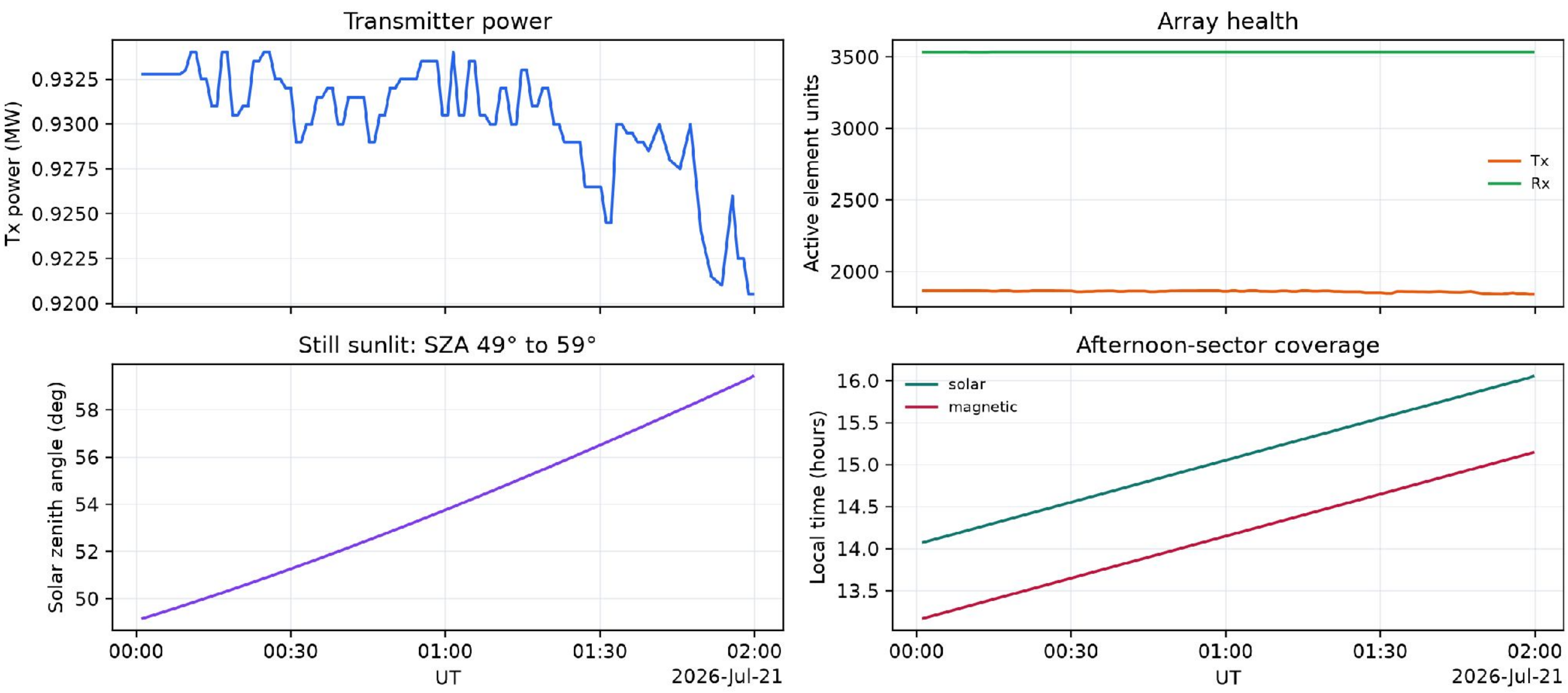
Product	Parameters	Available Integration Times [min]
Alternating Code (AC)	N_e, T_e, T_i, v_{los}	**1**, **3**, **5**, 10, 15, 20
Long Pulse (LP)	N_e, T_e, T_i, v_{los}	**1**, **3**, **5**, 10, 15, 20
LP Vectors	v_{vels}	**1**, **3**, **5**

The radar was stable, and the ionosphere remained sunlit

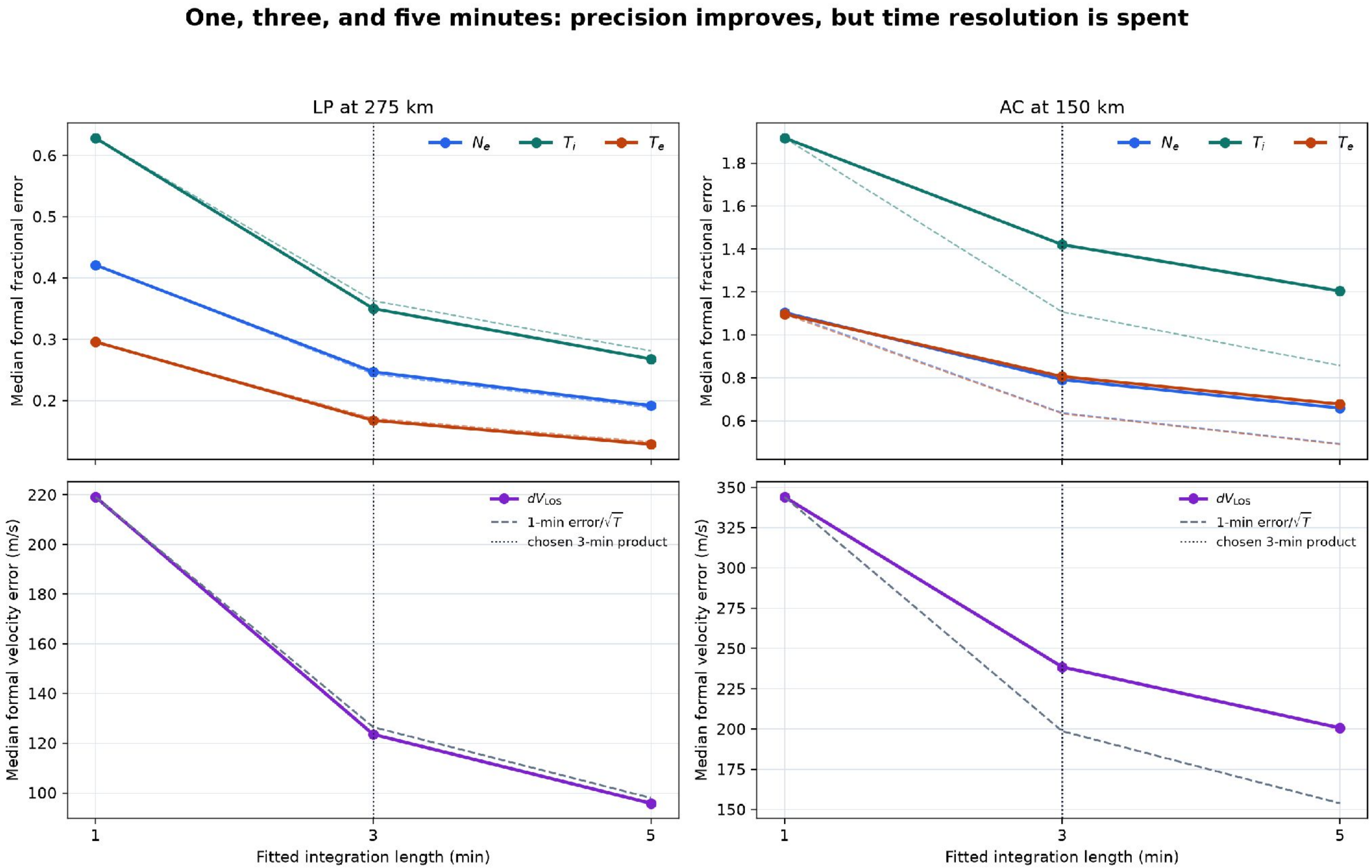
Experiment	20260721.001
Mode	PFISR2: LP + AC
Interval	00:01–01:59 UT
Beams	8
Mean power	0.930 MW
Local solar time	14.07–16.05 h
Solar zenith	49.2–59.4°

- LP: primary F-region product.
- AC: E/lower-F product; noisier here.
- Separate 1-, 3-, and 5-min fits.

Run quality and observing geometry



The radar was stable, and the ionosphere remained sunlit

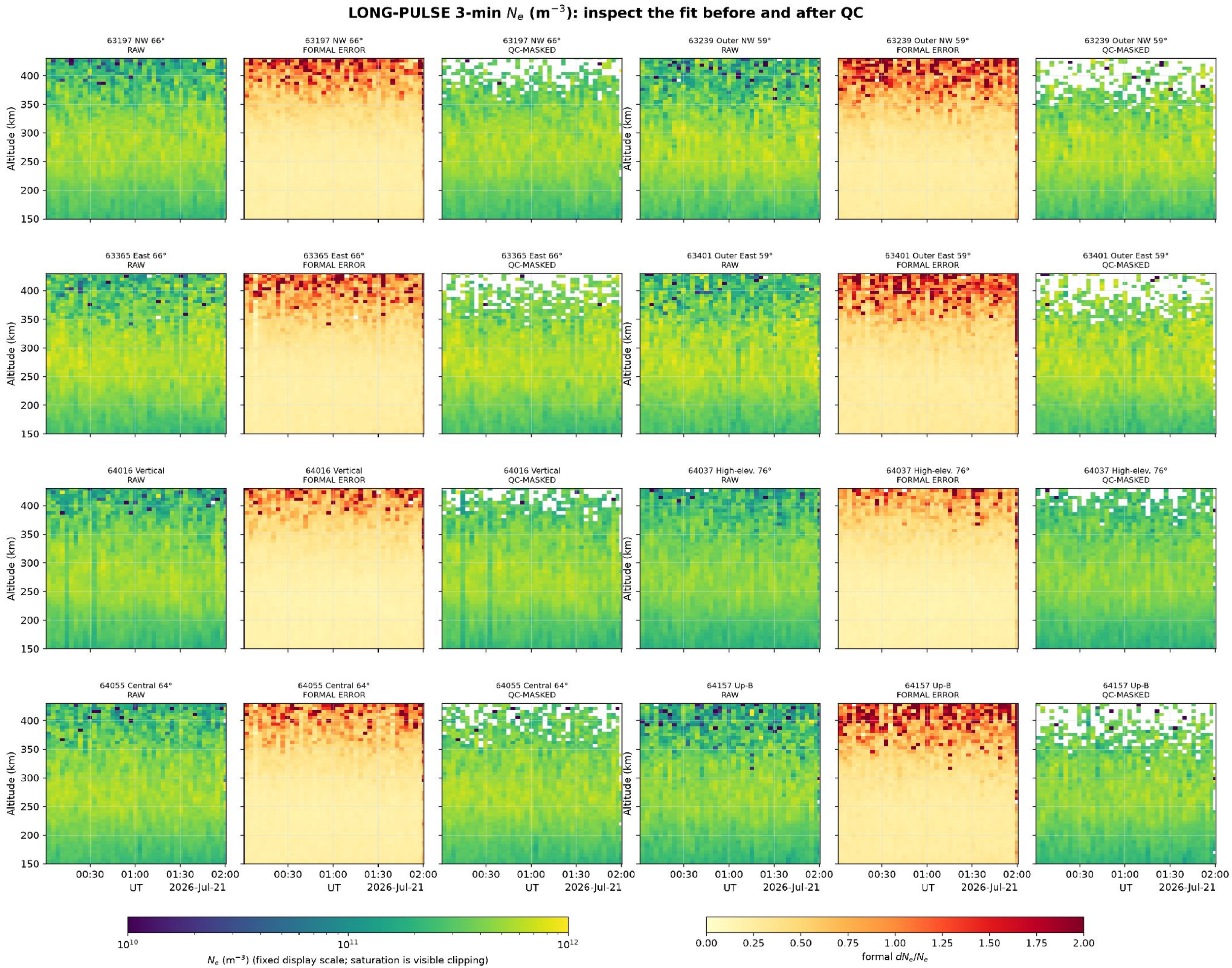


Dashed: 1-min formal error scaled by 1/sqrt{T}
LP: follows ideal scaling within a few percent
AC:AC has lower SNR
Choice: 3 min balances precision and time resolution

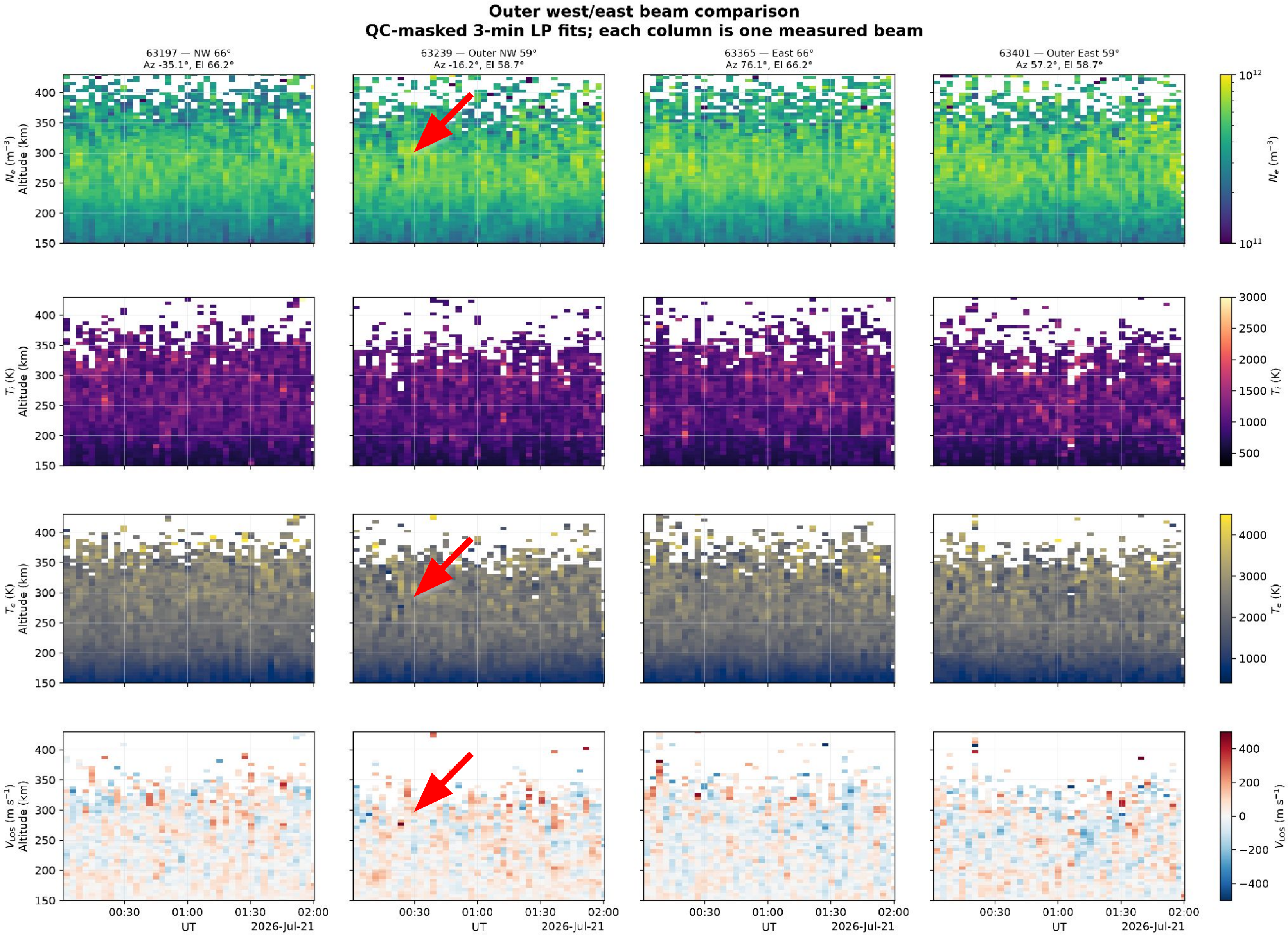
$$\frac{\sigma_S}{S} = \frac{1}{\sqrt{K}}\left(1 + \frac{1}{\mathrm{SNR}}\right)$$

F-region structure remains stable after QC

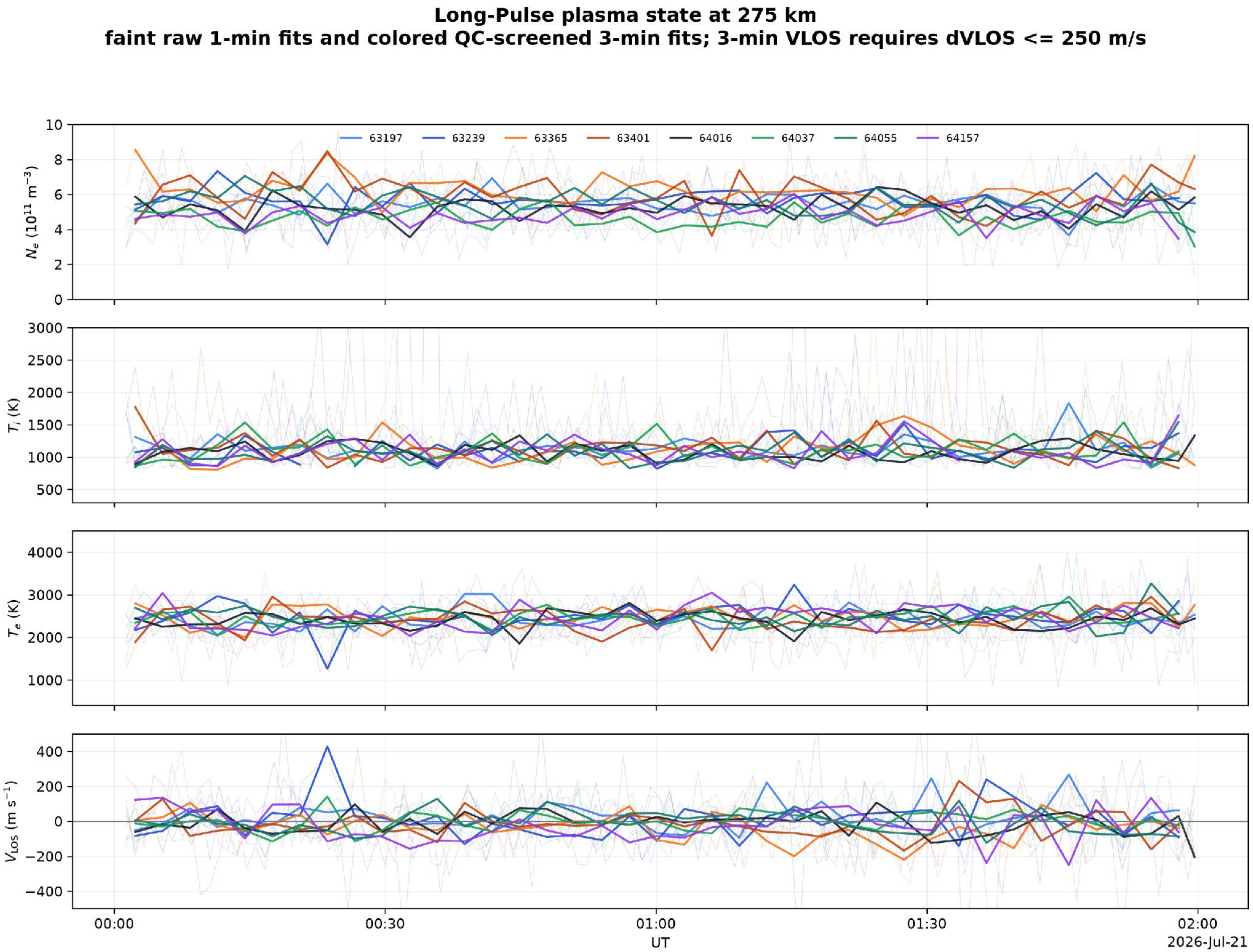
QC: finite N_e>0 and dN_e/N_e < 0.9
Stable F-region maximum near 250–320 km



Eight-beam LP comparisons



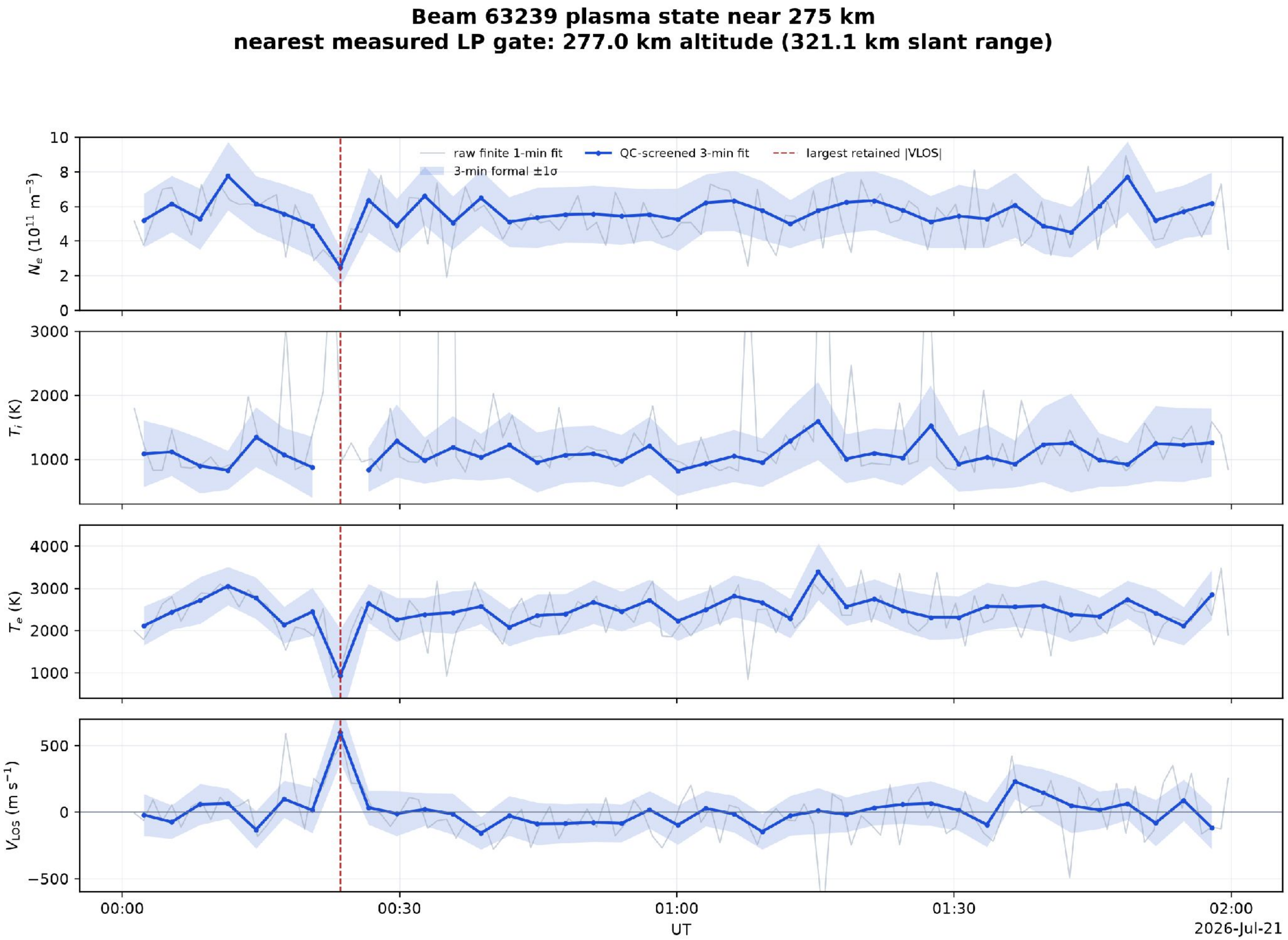
The velocity excursion occurs in only one beam



63239 at 00:23 UT

Beam 63239 only
One three-minute record
No multibeam coherence

Large formal errors

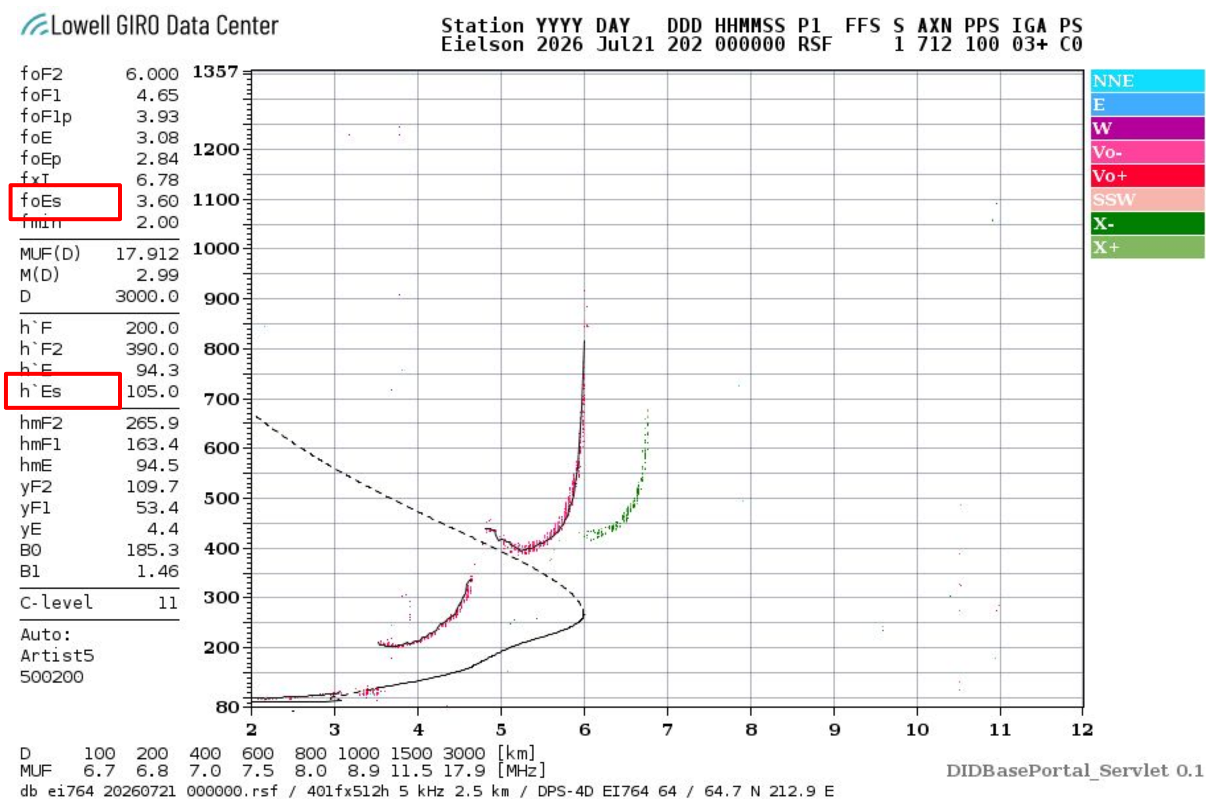


- $N_e = (2.49 \pm 1.08) \times 10^{11}\ \mathrm{m}^{-3}$
- $T_i \approx 2742 \pm 2327$ K: rejected
- $T_e = 931 \pm 1109$
- $V_{\mathrm{LOS}} \approx 599 \pm 227$m/s.
- Gate power SNR: 0.116.
- Single beam and narrow altitude interval.

Comparison of PFISR and Digisonde During Sporadic E Event

Motivation

- Can PFISR observe the evolution of a Digisonde-observed sporadic E (Es) event?
- Compare the temporal evolution of E-region electron density measured by PFISR with Digisonde observations.



Digisonde

Measured:

- foEs (critical frequency)
- h'Es (virtual height)

Derived:

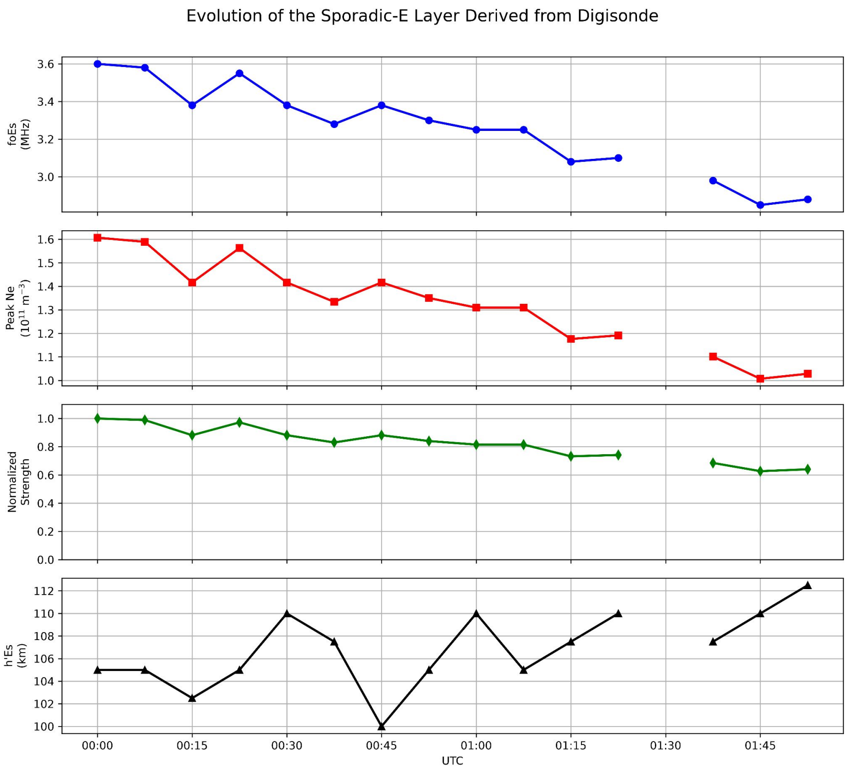
$$N_e = 1.24 \times 10^{10}\,(\text{foEs})^2$$

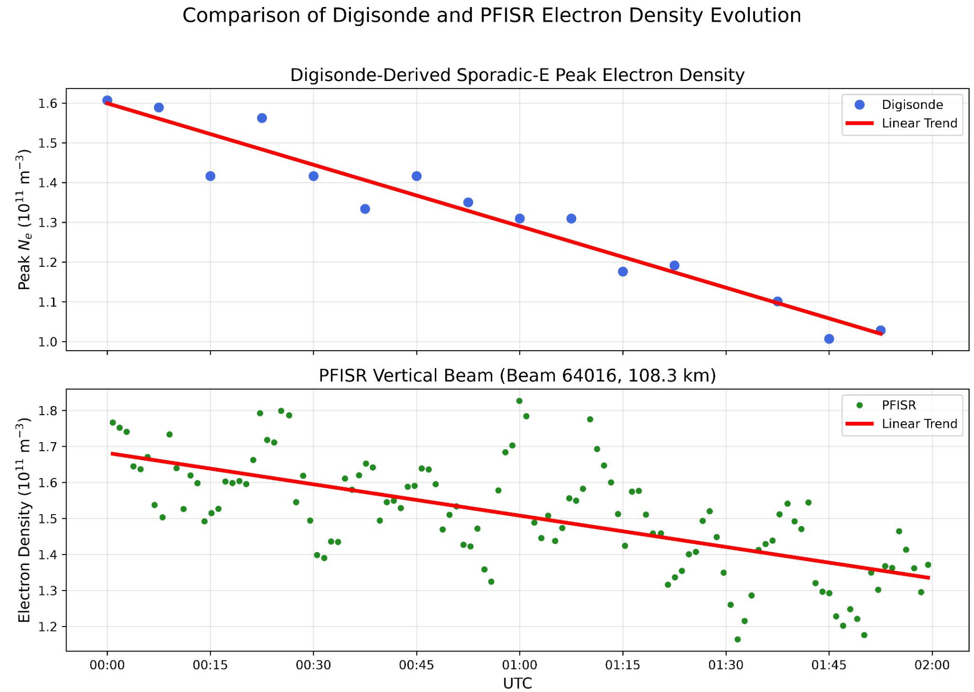
Outputs:

- Peak electron density
- h'Es

Maximum foEs : 3.60 MHz
Minimum foEs : 2.85 MHz
Maximum Peak Ne : 1.61e+11 m^-3
Minimum Peak Ne : 1.01e+11 m^-3

Temporal Evolution of E-region Electron Density





Category	Digisonde	PFISR
Selected Altitude	h'Es ≈ 102–112 km	108.27 km (Beam 64016, Vertical)
Maximum (Ne)	1.61×10^{11} m^{-3}	1.83×10^{11} m^{-3}
Minimum (Ne)	1.01×10^{11} m^{-3}	1.16×10^{11} m^{-3}
Linear Trend	-0.309×10^{11} m^{-3} hr^{-1}	-0.174×10^{11} m^{-3} hr^{-1}

- Digisonde Peak Ne **decreases** during the event.
- PFISR electron density at 108.3 km also **decreases**.
- PFISR measurements are consistent with the large-scale evolution of the E-region during the Digisonde-observed sporadic E event.
- Decreasing solar EUV production together with ongoing chemical loss and plasma transport can lead to a gradual reduction in E-region electron density.

Tracing the Sporadic E Layer Using PFISR

Objective

Investigate whether the PFISR alternating-code observations can directly identify the sporadic E (Es) layer observed by the Digisonde.

Midlatitude Sporadic *E* Layers 449

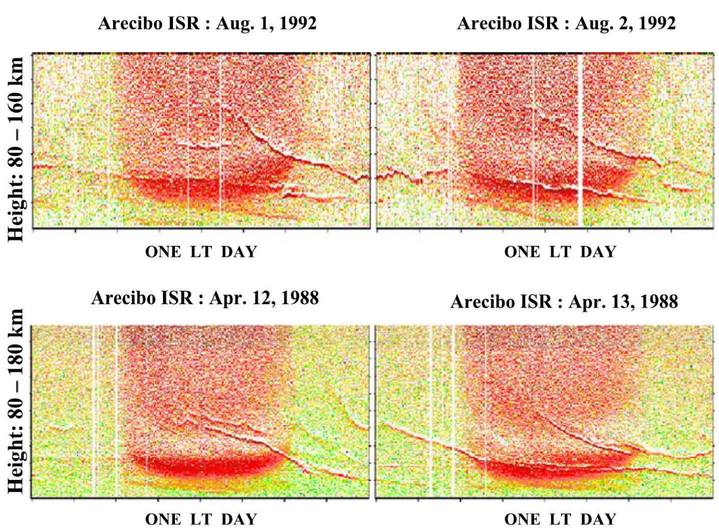
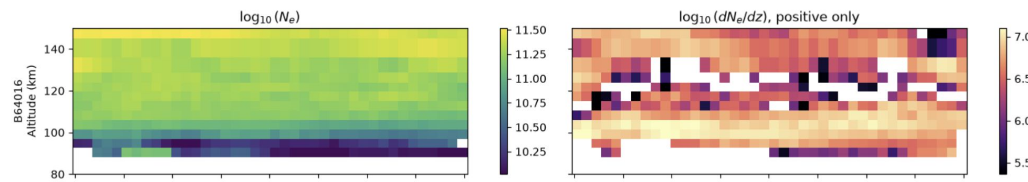


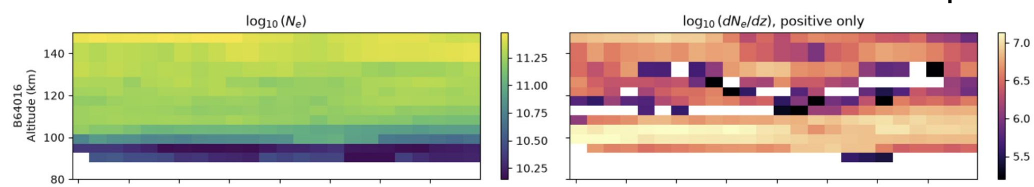
Fig. 4 Arecibo incoherent scatter radar HTI (height-local day time-log(dNe/dz) intensity) plots for 2 time intervals, each made of two consecutive day continuous radar runs. The local day E_s traces display a regular and repeating pattern in layer occurrence and altitude descent that follows diurnal and semidiurnal tidal-like periodicities

[Haldoupis, 2012]

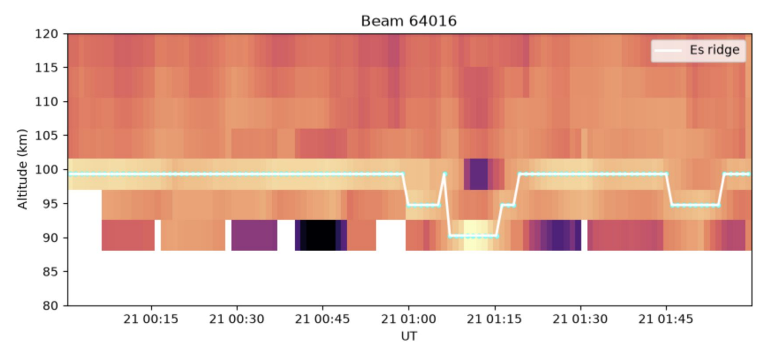
Time Resolution 3 min: AC data smoothed over 5 samples



Time Resolution 5 min: AC data smoothed over 5 samples



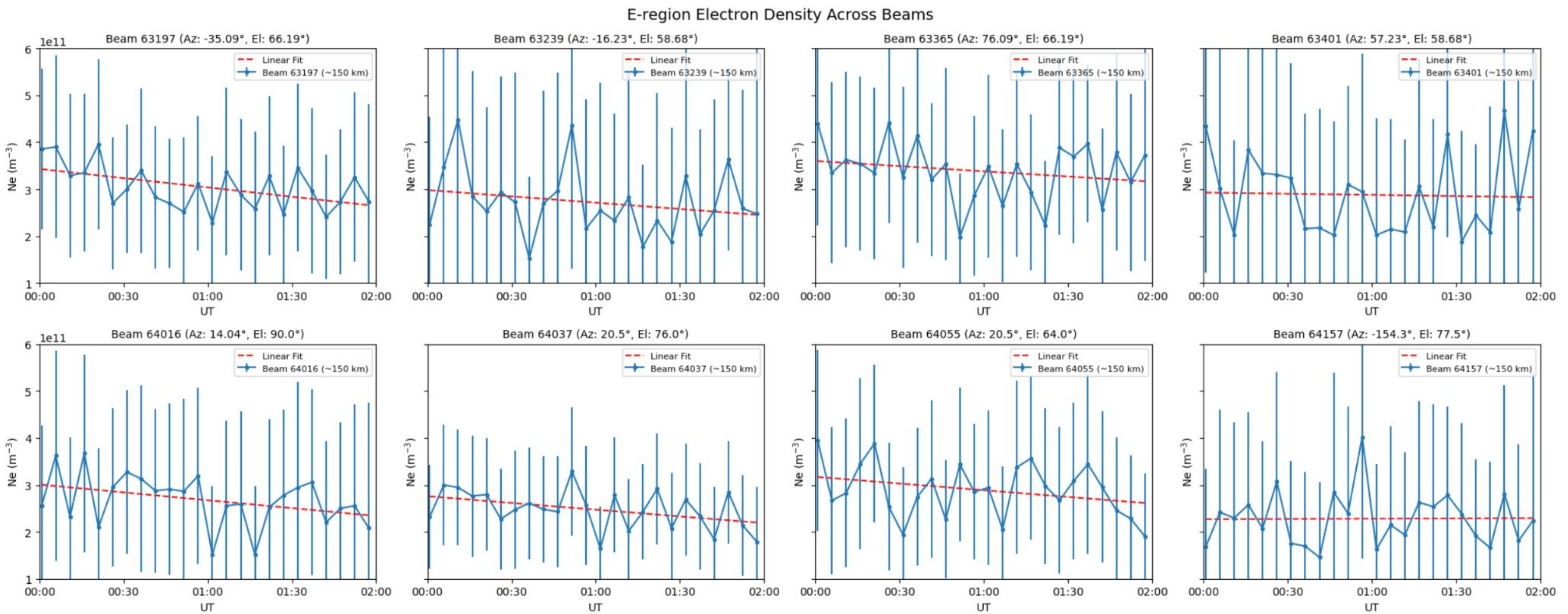
Es layer peak tracing results



PFISR did not directly resolve the thin Es layer,

- PFISR vertical resolution ≈ **4 km**
- Typical Es layer thickness ≈ **1–3 km**

Electron Density Evolution Across PFISR Beams at ~150 km



Observations

- Electron density at **~150 km** generally decreases during the 2-hour observation period.
- Negative linear trends are observed in **most beam directions**.
- Temporal variability differs among beams because they sample different regions of the ionosphere.

Scientific Interpretation

Although sporadic E is confined to ~90–120 km, the widespread decrease in electron density observed across all PFISR beams at ~150 km suggests that the ionosphere was undergoing regional evolution during the observation period. The concurrent decrease near the Es altitude is therefore consistent with a background reduction in ionospheric electron density.

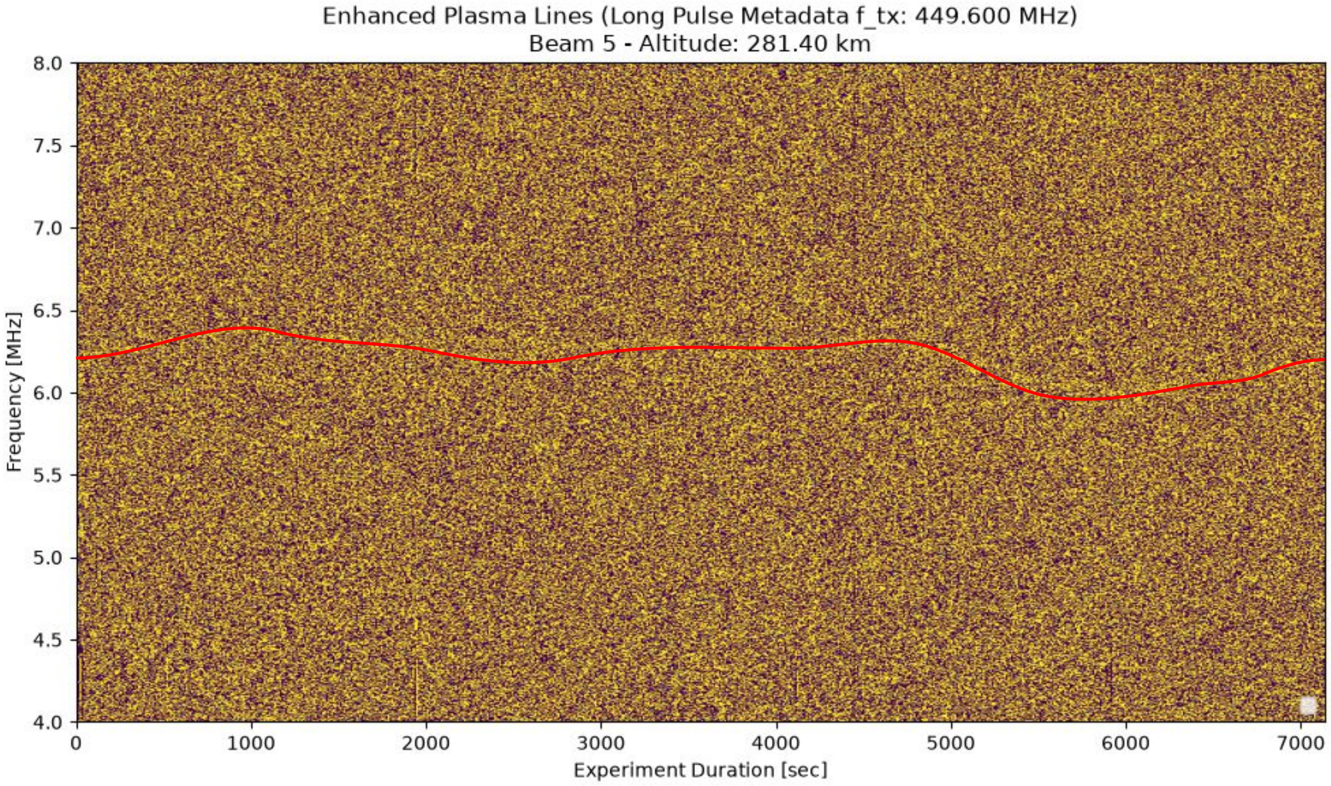
Observations: Plasma Line

Plasma line observed in frequency-time plot

A dip in plasma line frequency is observed in the last 30 minute window

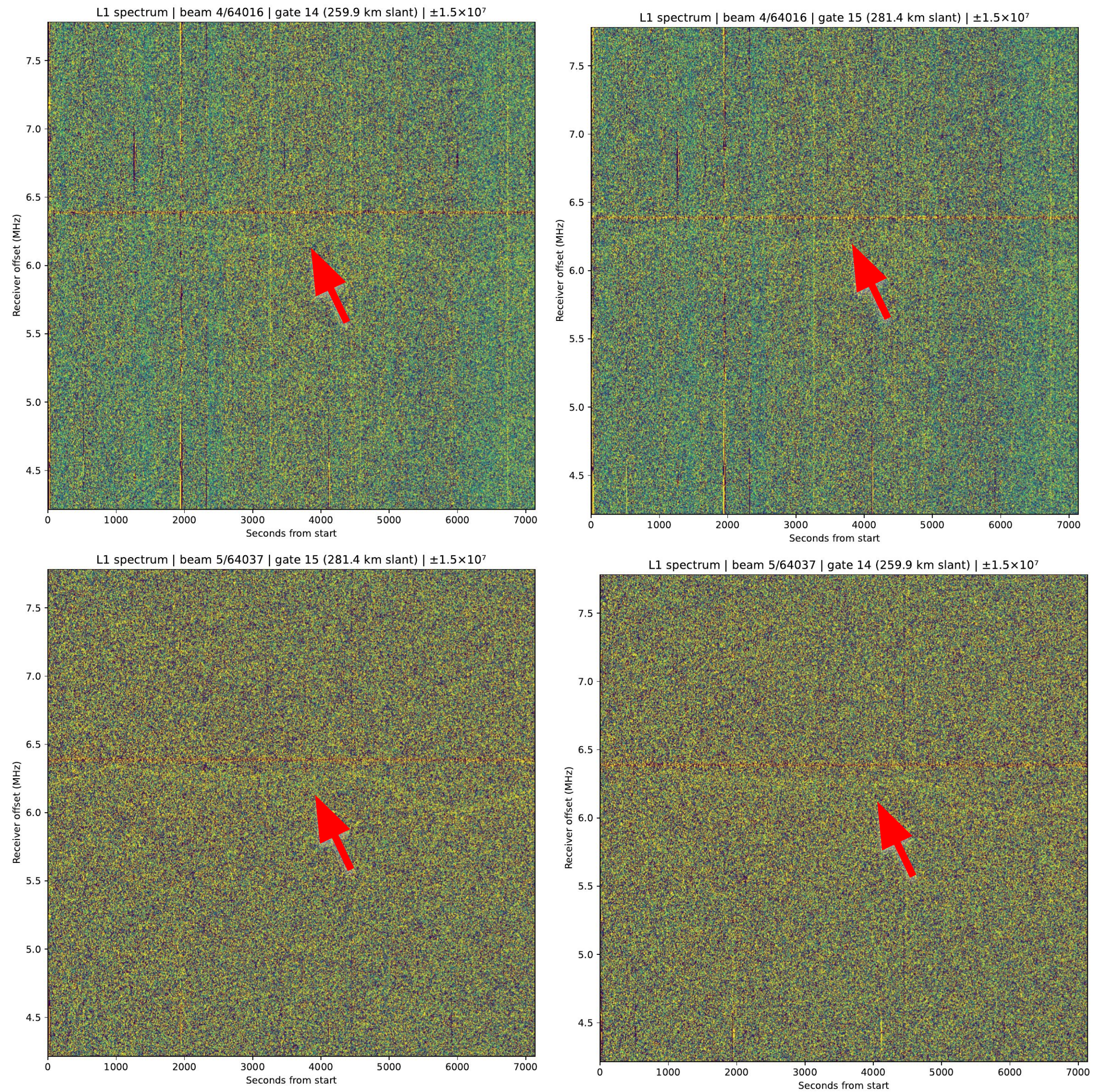
0.4MHz decrease represents a depletion of plasma density

Indicates a perturbation event such as a TID



A faint plasma-line appears in two look direction

Vertical beam 64016
High-elevation beam 64037, 76°
Selected altitudes: 260–295 km



Ion-line measurements predict the plasma-line frequency

$$f_{pe} = 8.98\sqrt{N_e}$$

$$k = \frac{4\pi f_{\mathrm{tx}}}{c}$$

$$f_{ce} = \frac{eB}{2\pi m_e}$$

$$f_L^2 = f_{pe}^2 + \underbrace{\frac{3k^2 k_B T_e}{(2\pi)^2 m_e}}_{\text{thermal correction}} + \underbrace{f_{ce}^2(1 - k_{\parallel}^2)}_{\text{magnetic/geometry correction}}$$

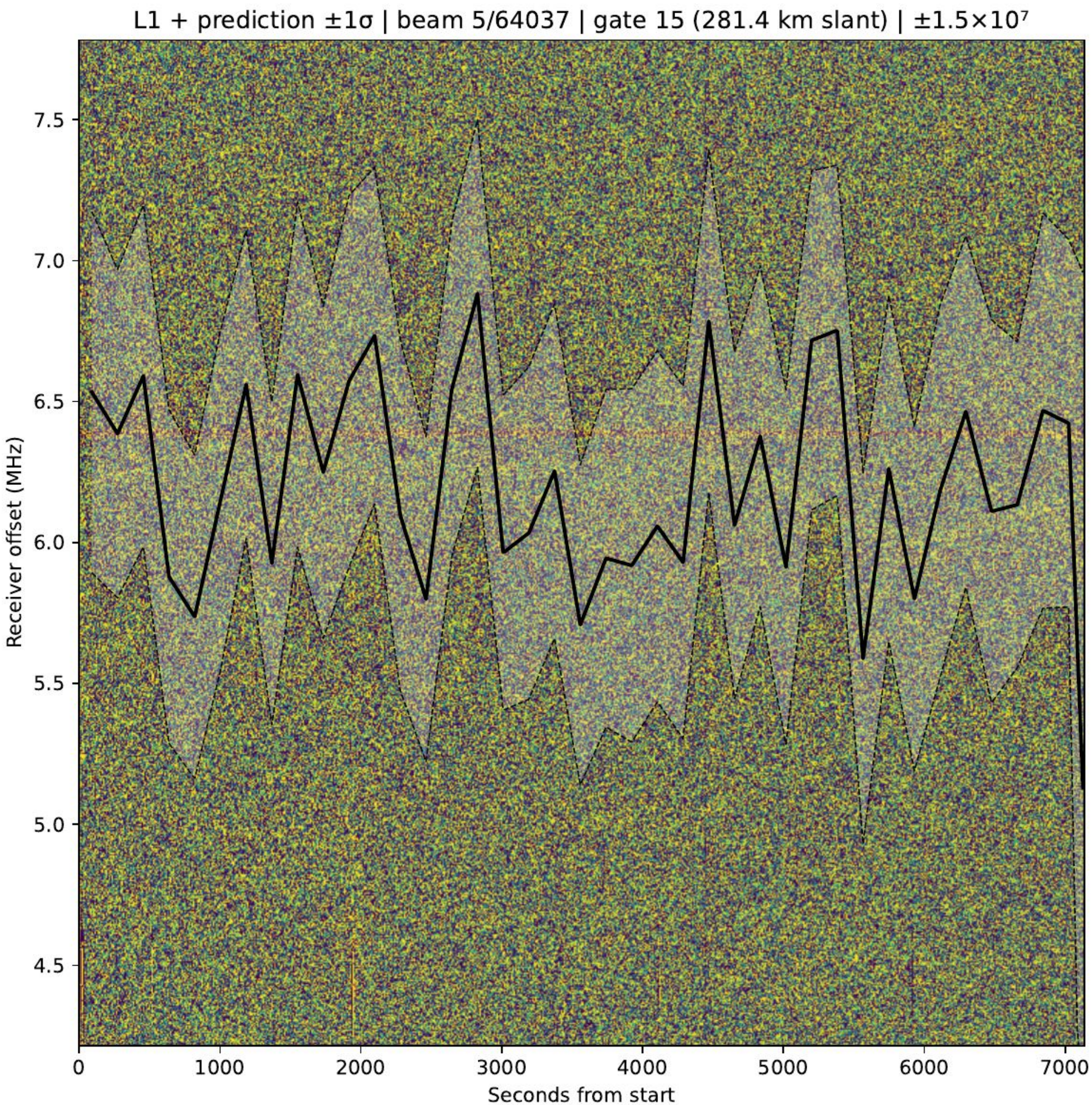
Cold density
f_pe²

Warm-electron
Bohm–Gross correction

Magnetic / geometry
f_ce²(1 − k_// ²)

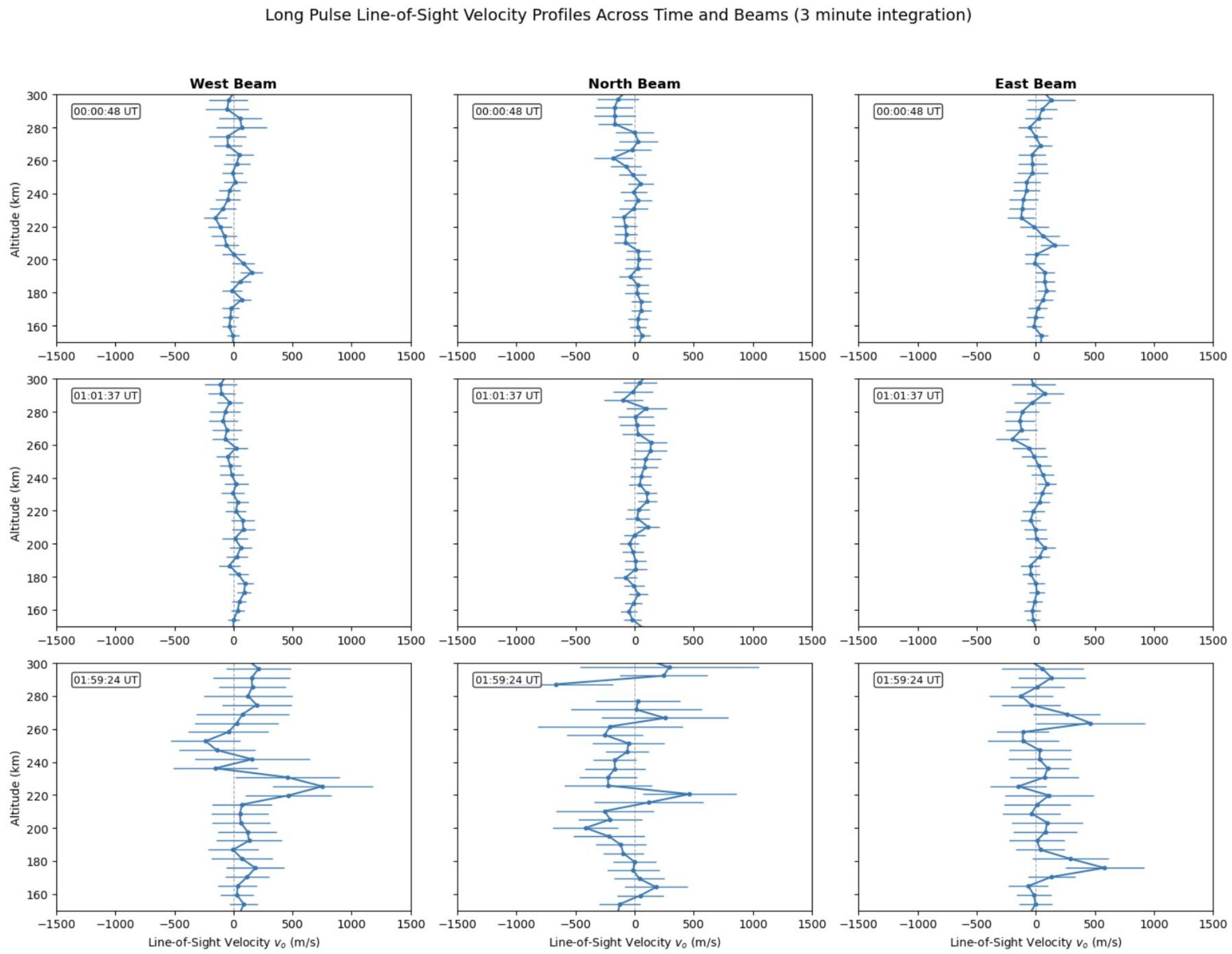
Formal ion-line errors explain the prediction offset

Black line: central prediction f_L
Gray band: $f_L \pm 1\sigma_{f_L}$
Propagated from dN_e and dN_e



Observations: Vector Velocity Evolution (Long Pulse)

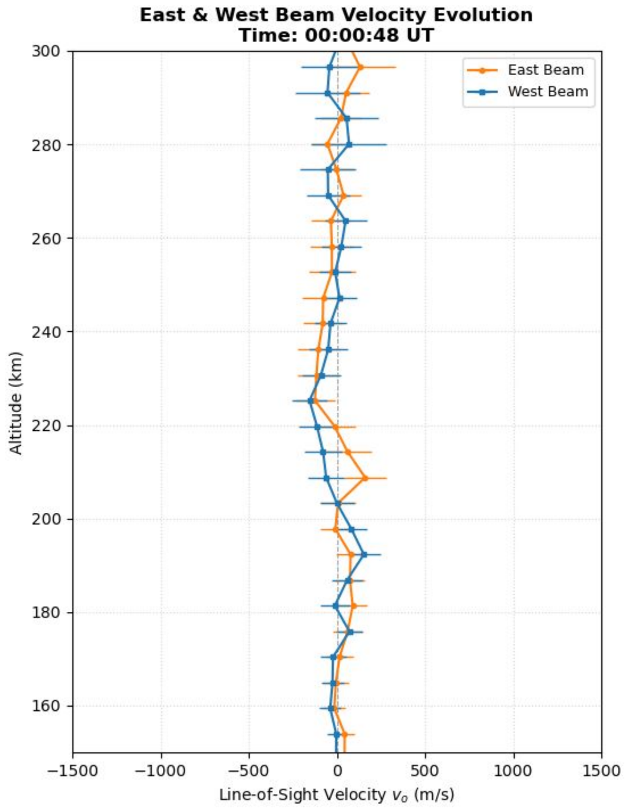
- 3 evenly spaced time periods
- West, North, and East beams with 3 minute integration - focussing on F-region ionosphere
- All 3 beam show minimal variation about zero until the final time step
- Velocity fields at final time step show a perturbation linking to the plasma line depletion

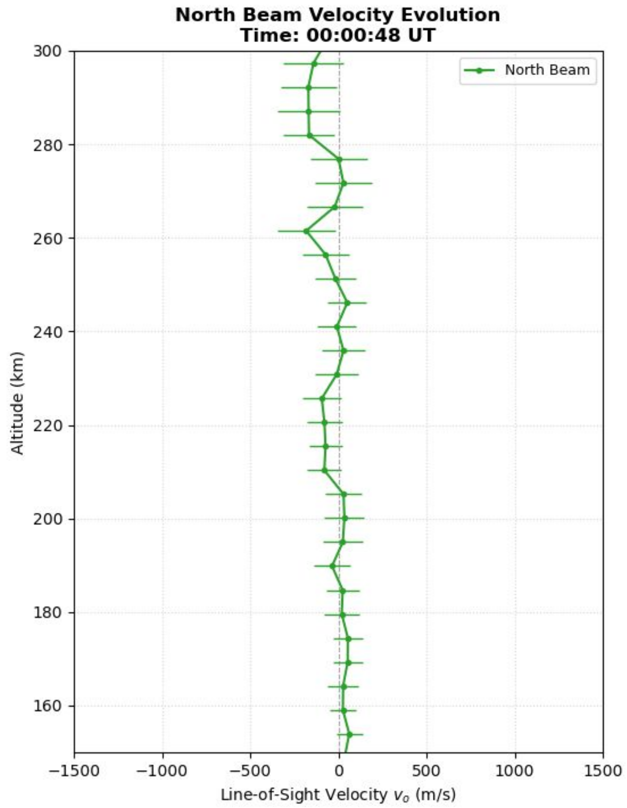


Observations: Vector Velocity Evolution (Long Pulse)

Time evolution of lon pulse vector velocity (3 minute integrated)

Steep gradient of activity towards end of simulation



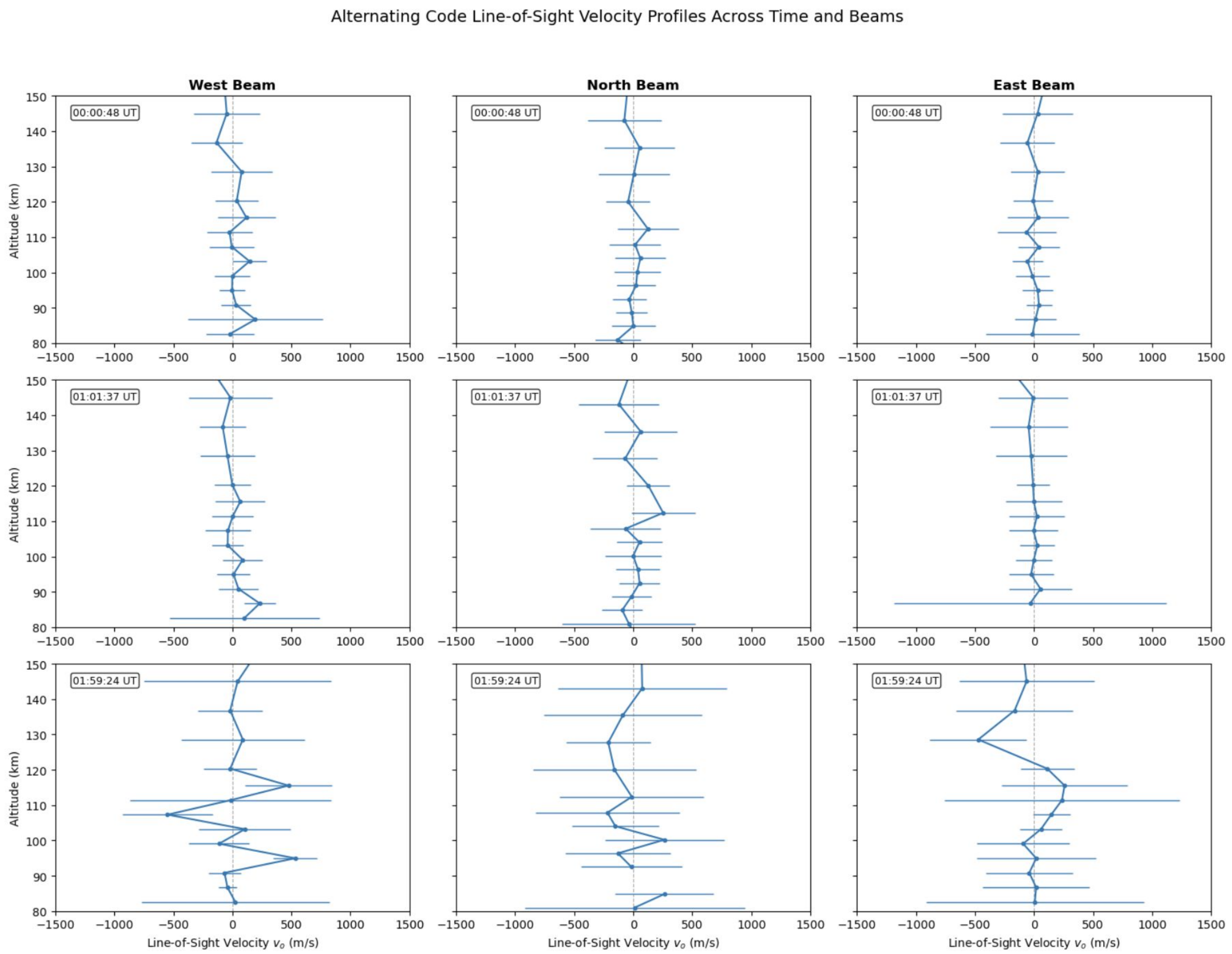


Observations: Vector Velocity Evolution (Alternating Code)

E-region velocity fields with alternating code

Again, low activity varying about 0m/s until final timestep, peaking over 500m/s

This could suggest a vertically propagating wave to the F-region ionosphere

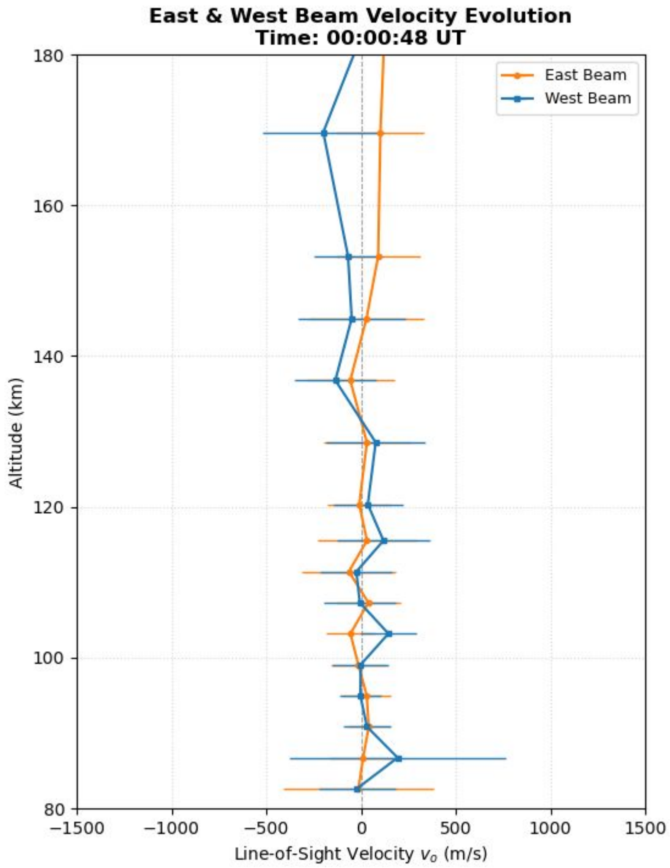


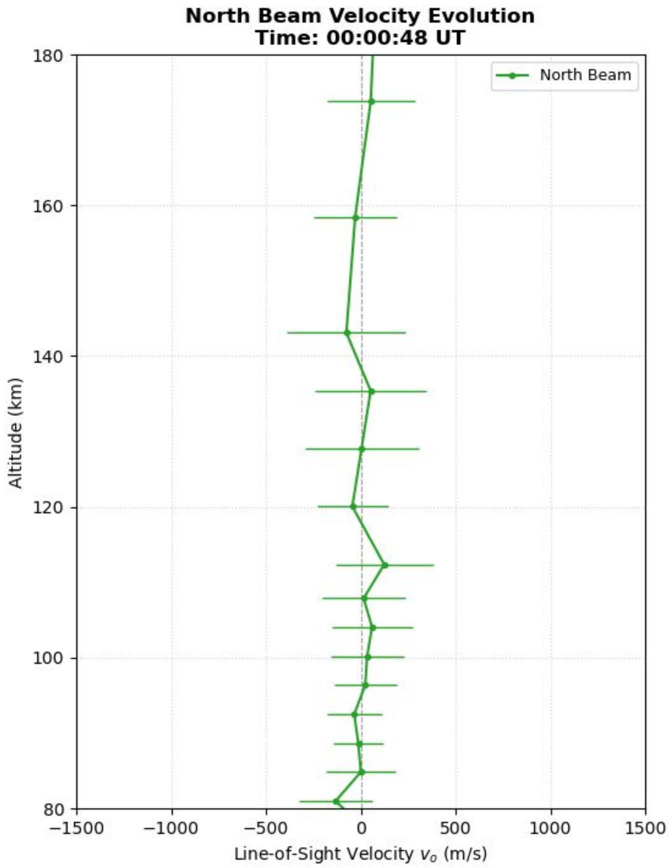
Observations: Vector Velocity Evolution (Alternating Code)

Time evolution of alternating code vector velocities (3 minute integration)

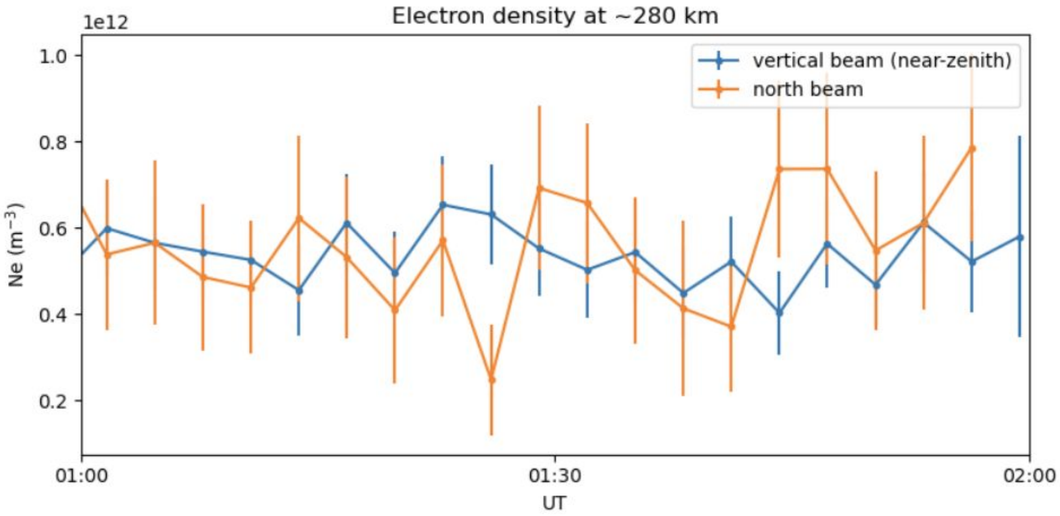
Larger uncertainty at lower altitudes

Increased variability seen on final timestamp





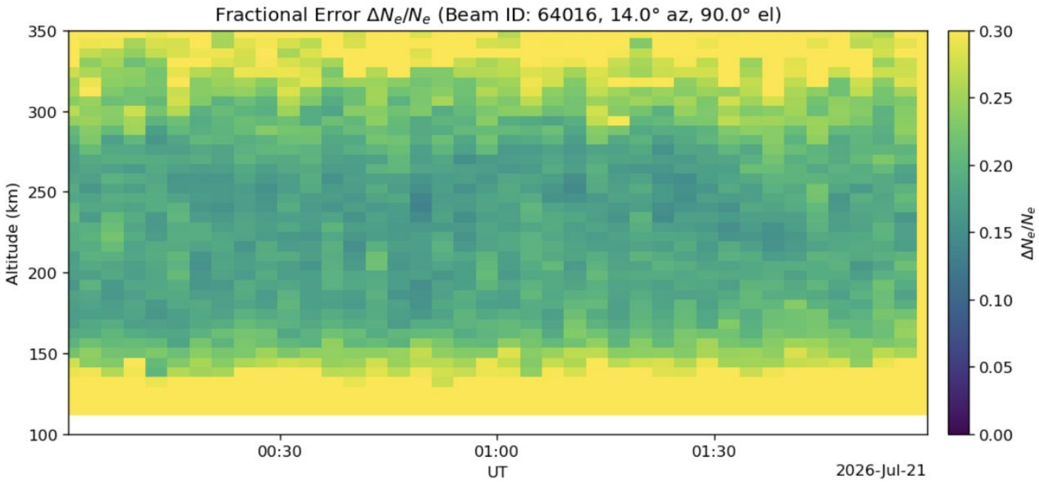
Observations: Ne Comparison North and Vertical Beams



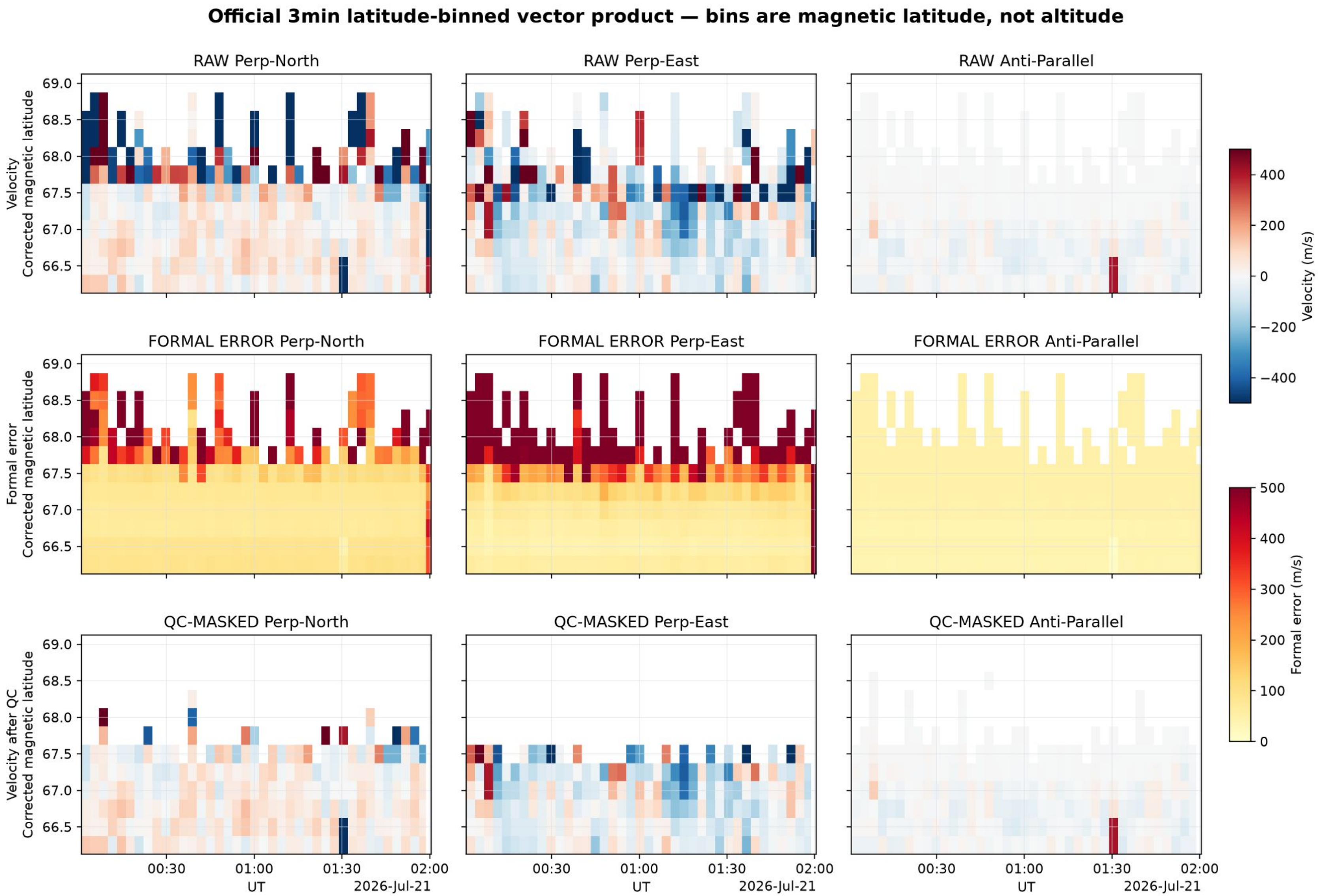
Looking at the last half hour of experiment, north and vertical beam electron density overlap suggests small perturbation in electron density

Although no noticeable artifacts in dNe/Ne plots

Further temporal analysis is required to verify if this is truly a TID



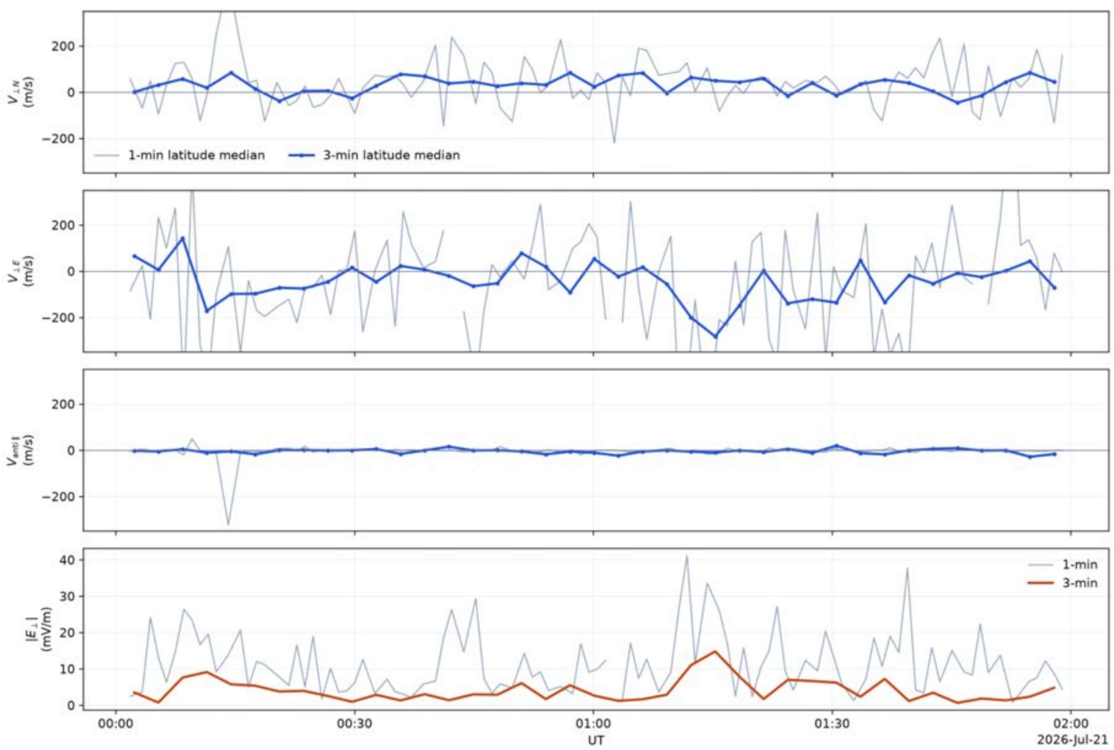
Resolved velocity



Electric field comes from the official all-look solution

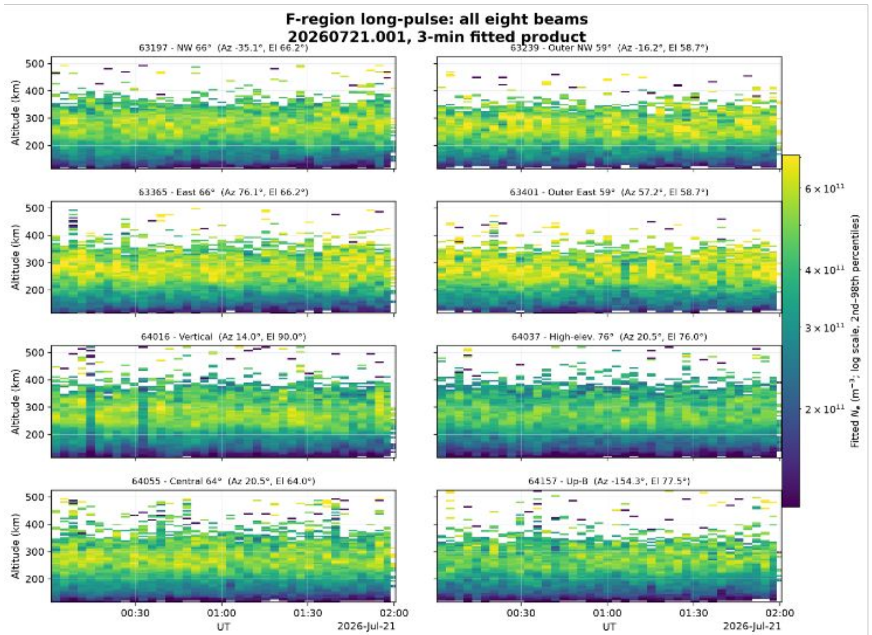
07 VECTOR VELOCITY AND ELECTRIC FIELD

One-minute timing versus three-minute precision in the official all-look solution

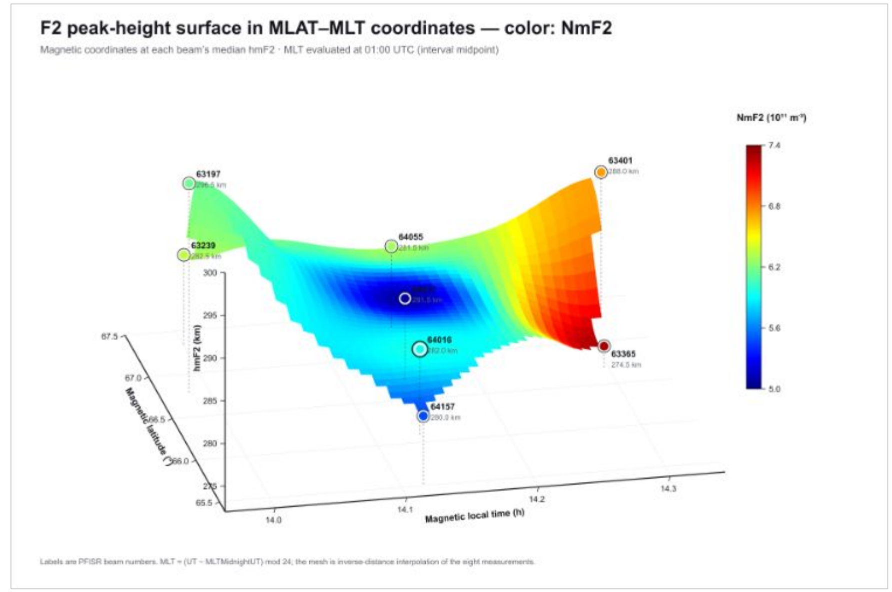


$$vE = E \times B / B^2$$
$$E\perp = -v\perp \times B$$

Observations: F-region Ne spatial distribution

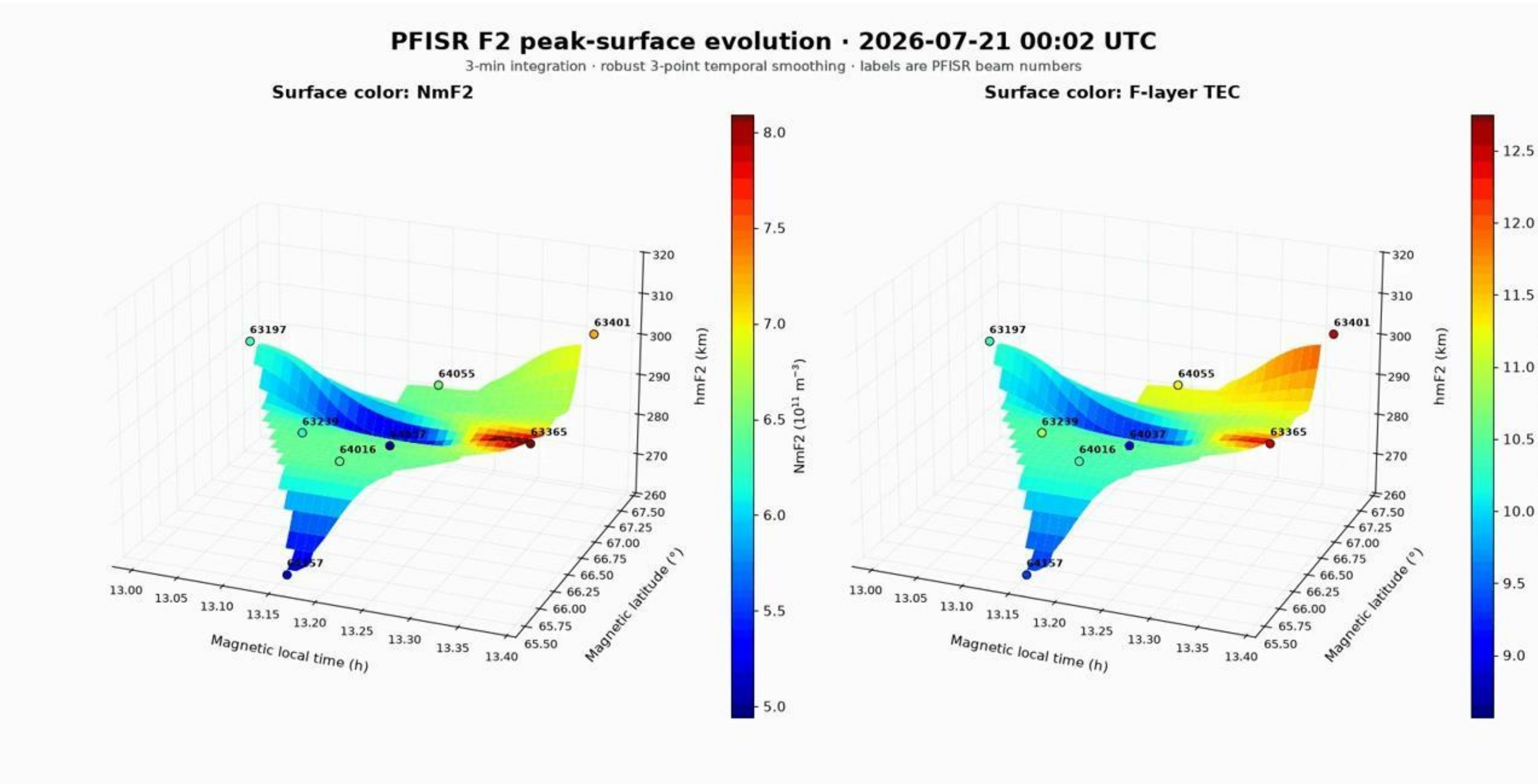


Ne exhibits regional variation.

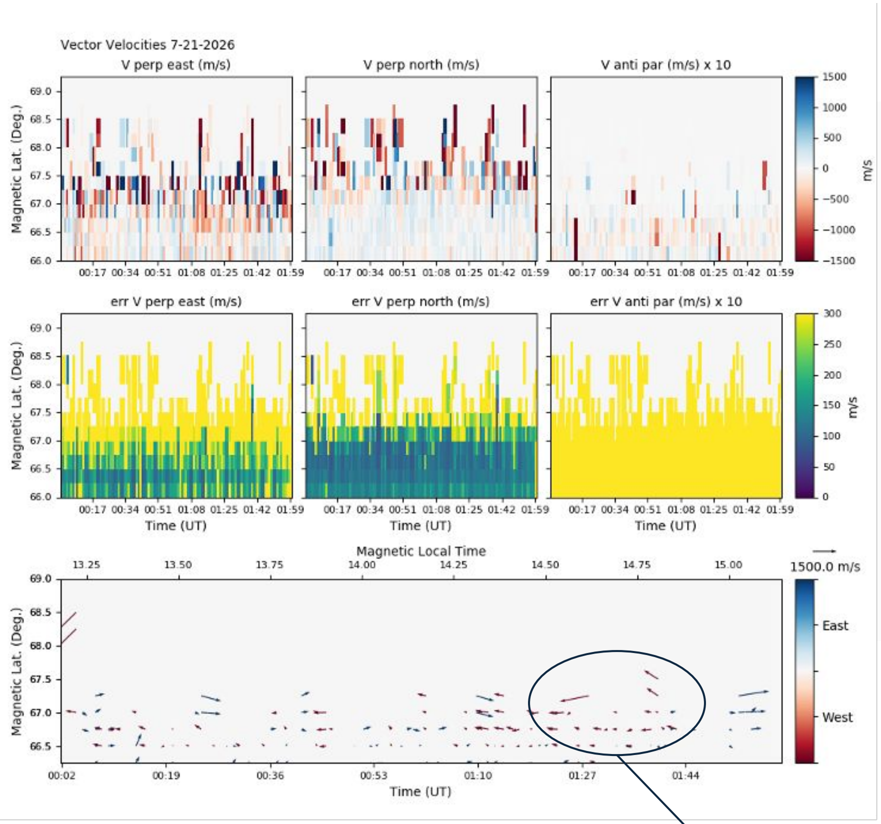


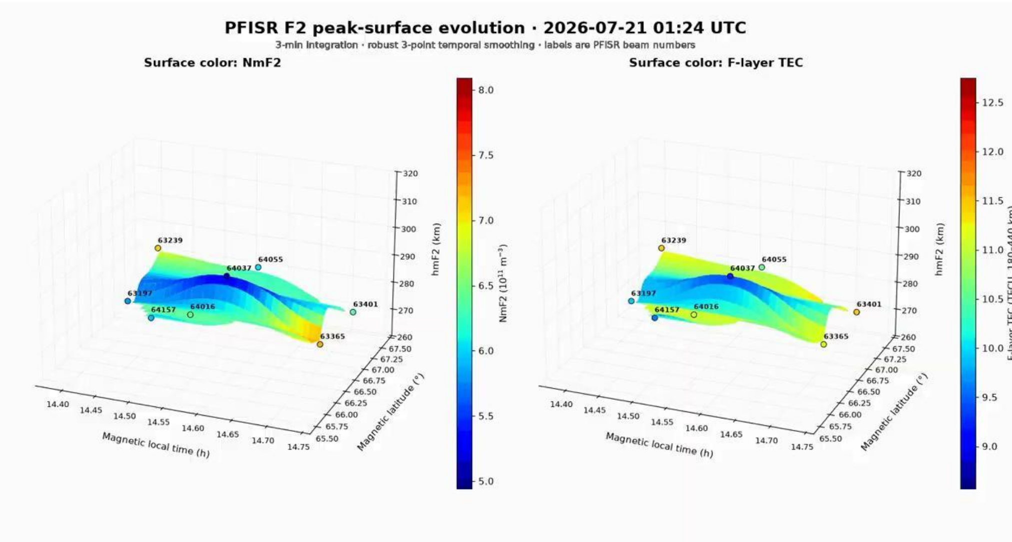
The eastern side exhibits higher N_e, possibly due to better illumination conditions resulting greater electron accumulation.

Observations: F-region Ne temporal and spatial evolution



Observations: F-region westward flow

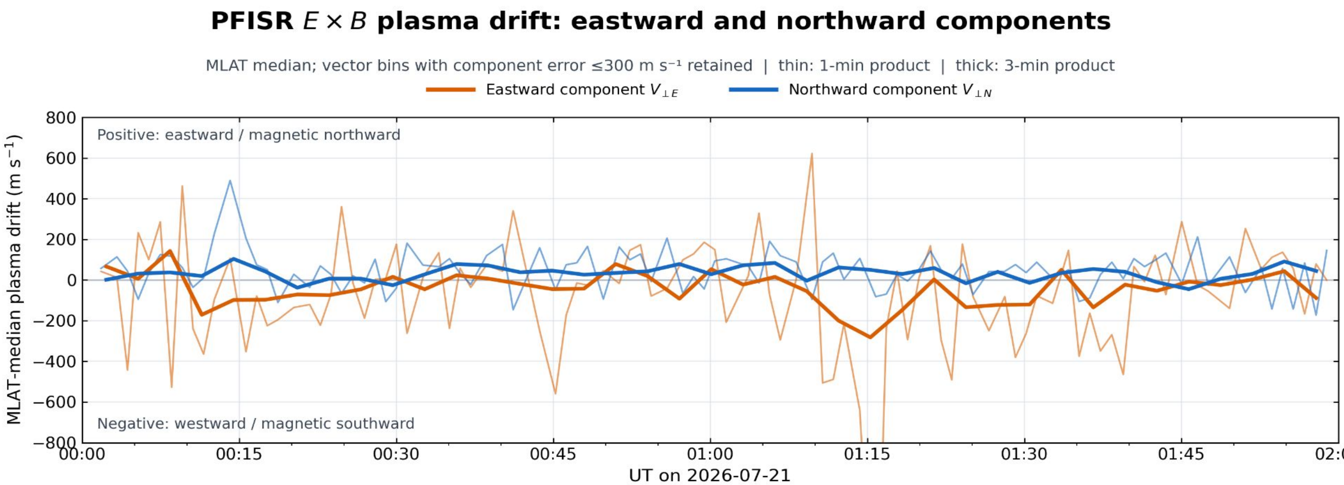




concentrated westward flow

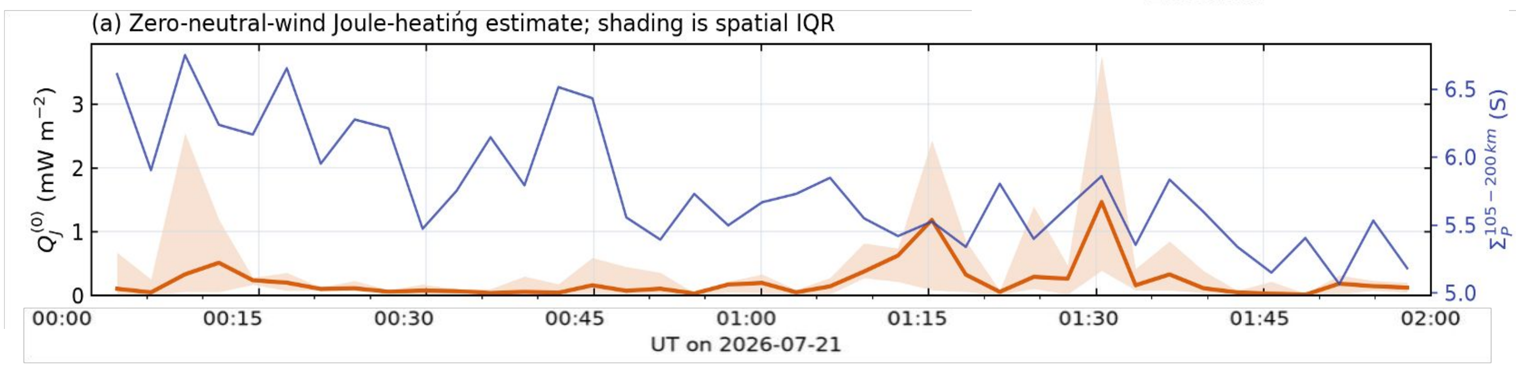
F-region uplift propagated westward

Observations: F-region E×B drift and Joule Heating



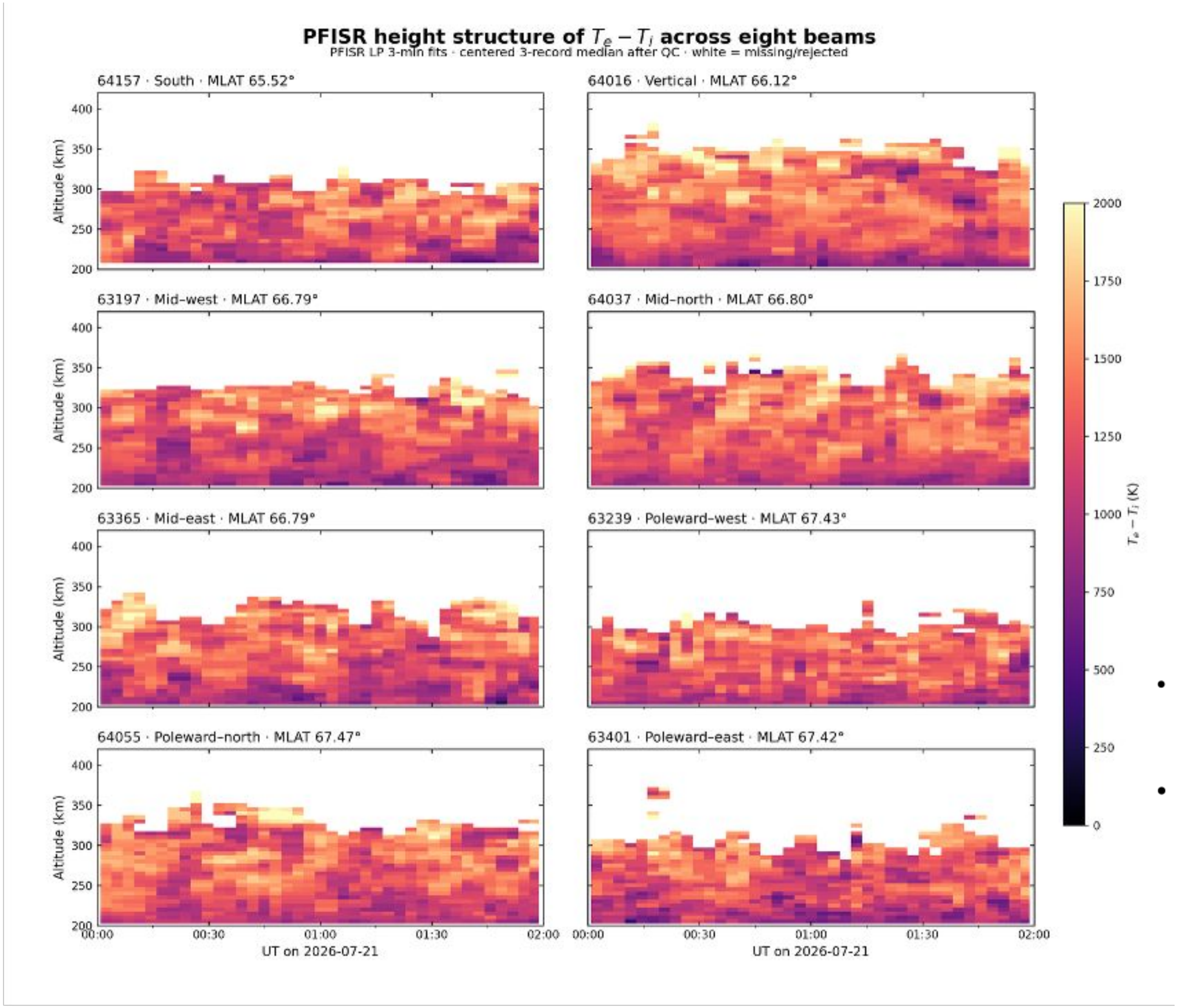
Joule Heating assuming neutral wind is zero $Q_J = \int \sigma_P \, |\mathbf{E} + \mathbf{U}_n \times \mathbf{B}|^2 dz$

Peterson Conductivity: $\sigma_{P,s} = \frac{n_s q_s^2}{m_s} \frac{\nu_s}{\nu_s^2 + \Omega_s^2}$ $\Sigma_P = \int_{105\,\mathrm{km}}^{200\,\mathrm{km}} \sigma_P(z)\, dz.$



The partial Pedersen conductance over 105–200 km decreased, indicating a F-region decay within 2 hours.

Observations: F-region T_i and T_e



Median separation

220–280 km
1,255 K
$T_e/T_i = 2.18$

280–340 km
1,438 K
$T_e/T_i = 2.28$

340–400 km
1,646 K
$T_e/T_i = 2.41$

- $T_e > T_i$ in every retained sample and increases with altitude.
- Persistent $T_e > T_i$ indicates that the electrons are likely being continuously heated.

Summary

The goal of this experiment was to gain a general understanding of how the E and F regions evolve by examining the temporal and spatial evolution of the E/F-region Ionosphere.

We did this by:

- Designing an experiment to balance spatial and temporal observations.
- Examining the E-region.
  - Sporadic-E
- Examining the plasma line.
- Examining the F-region.

Questions?