Group 1: Joule heating & Neutral Winds (JouNeuW)

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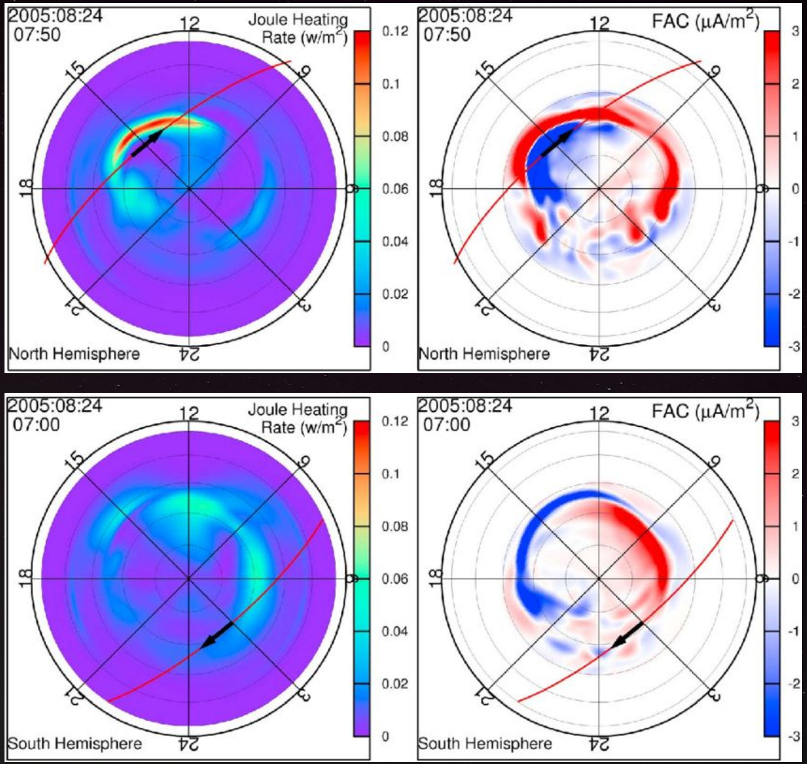
2025 ISR Summer School - Fairbanks, AK

Motivation & Goals

- Neutral winds play an important role in ionospheric conductivity and energy dissipation and are a critical component in the study of ionosphere-thermosphere coupling.
- Joule heating is the process by which electric-field-driven plasma motion leads to thermal energy deposition in the neutral atmosphere via collisions.
    - It is one of the dominant forms of energy dissipation in the ionosphere.



OpenGGCM Joule heating rate (left) and FAC (right)
Credit: Wenhui Li, 2010

Motivation & Goals

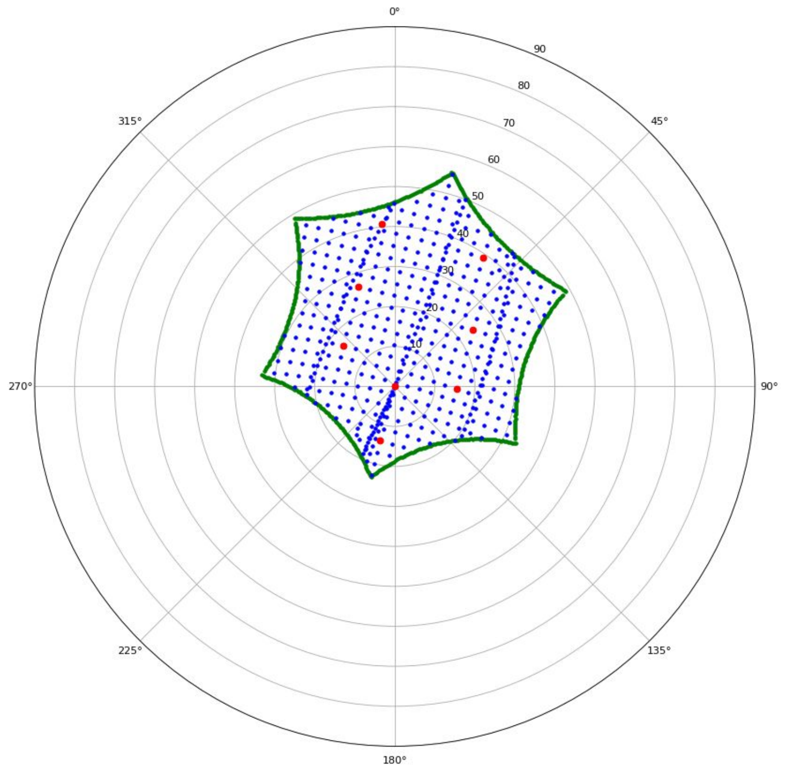
In this project, our group:

- Used PFISR to collect line-of-sight velocity data
- Estimated neutral winds in the E-region ionosphere
- Quantified Joule heating rate using two different methods
- Determined wave parameters for gravity waves

Credit: Craig Heinselman

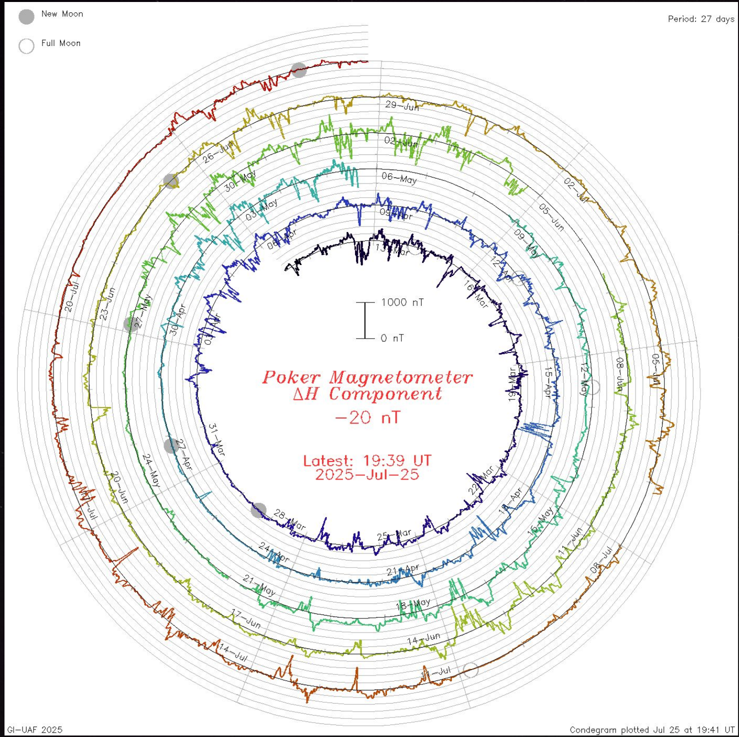
Experiment Methodology

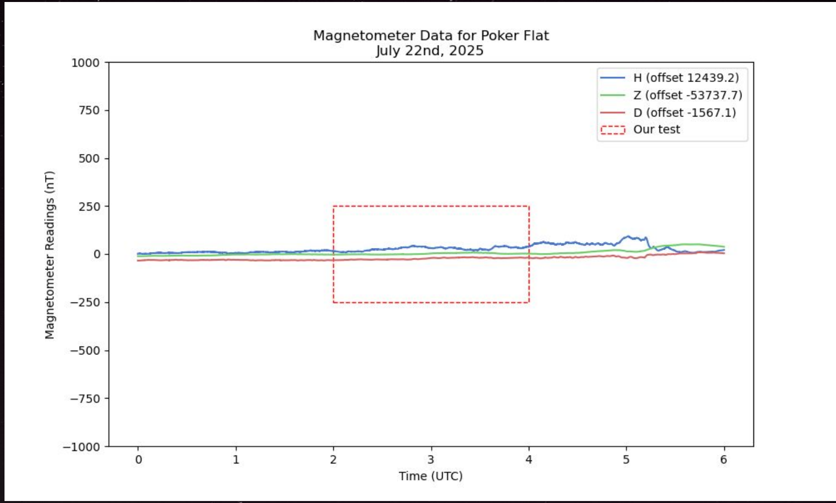
- Run PFISR in alternating code + long pulse
- Eight beams were used
  - Vertical, up-B, and three pairs oriented along the same magnetic latitude
  - Based on setup from Heinselman and Nicolls (2008)
- This orientation allows for the line-of-sight velocities to be well-resolved.

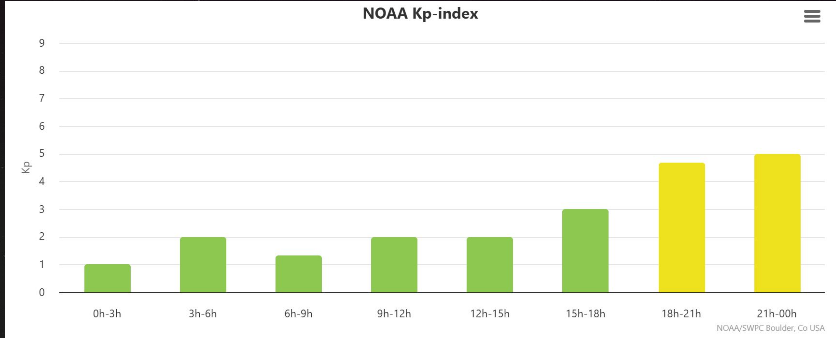


PFISR beam locations

Space Weather Conditions







00-03h	03-06h	06-09h	09-12h	12-15h	15-18h	18-21h	21-00h
1	2	1+	2	2	3	5-	5

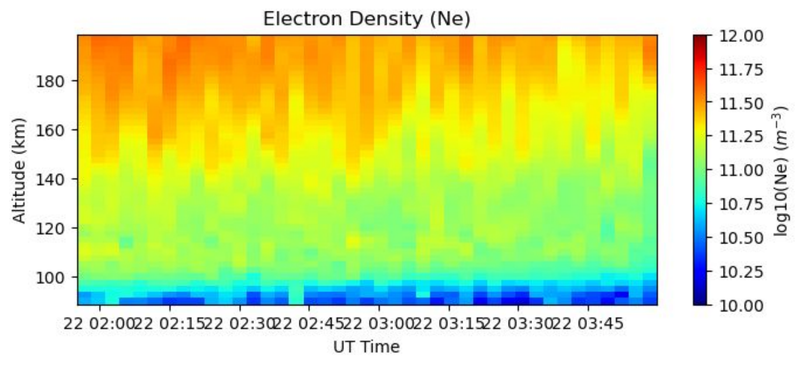
Experiment Results and Data Quality

The lack of precipitation during our experiment made the error for our calculation astronomical, therefore making our desired calculations unfeasible

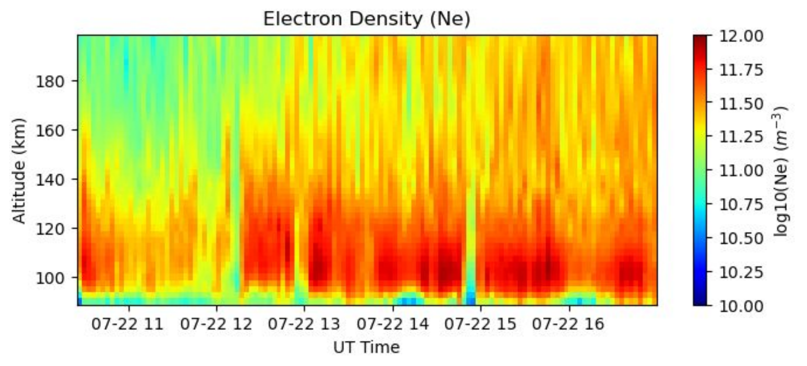
To demonstrate our ability to calculate neutral winds and joule heating, some data from previous experiments were used

Unless otherwise stated, assume data is from July 2016

Our data :(→



“Good” data →



Calculating Neutral Wind Velocity

Using the ion momentum equation, neglecting contributions from gravity and diffusion, we can derive the neutral wind velocity to be

$$\vec{u} = \vec{v}_i - \frac{e}{m_i \nu_{in}}(\vec{E} + \vec{v}_i \times \vec{B})$$

Here, we assume that all the ions are NO^+.

To solve this equation, we must first determine $\boldsymbol{v_i}$ from the line-of-sight (LOS) velocities.

Heinselman and Nicolls (2008)

Determining Ion Velocity Vector

A LOS velocity vector can be expressed in a geographic radar-centered coordinate system as

$$\vec{v}_{los} = k_e v_e + k_n v_n + k_z v_z$$

where $\hat{k} = \begin{bmatrix} k_e & k_n & k_z \end{bmatrix}^T$ is a unit vector.

At high elevation angles, **k** can be written as

$$\vec{k} = \begin{bmatrix} k_e \\ k_n \\ k_z \end{bmatrix} = \begin{bmatrix} cos\theta \ sin\phi \\ cos\theta \ cos\phi \\ sin\theta \end{bmatrix}$$

where θ is the elevation angle and ϕ is the azimuth angle.

Heinselman and Nicolls (2008)

Determining Ion Velocity Vector

To convert from this geographic radar-centric coordinate system to a local geomagnetic coordinate system, we make use of this rotation matrix

$$R_{geo \to gmag} = \begin{bmatrix} cos\delta & -sin\delta & 0 \\ sinI\ sin\delta & cos\delta\ sinI & cosI \\ -cosI\ sin\delta & -cosI\ cos\delta & sinI \end{bmatrix}$$

where I is the dip angle (~77.5° at PFISR) and δ is the declination (~14.5° at PFISR).

Applying this to **k**, we get

$$\vec{k} = \begin{bmatrix} k_{pe} \\ k_{pn} \\ k_{ap} \end{bmatrix} = \begin{bmatrix} k_e cos\delta - k_n sin\delta \\ k_z cosI + sinI(k_n cos\delta + k_e sin\delta) \\ k_z sinI - cosI(k_n cos\delta + k_e sin\delta) \end{bmatrix}$$

Heinselman and Nicolls (2008)

Determining Ion Velocity Vector

We can now convert our LOS velocities to velocity vectors.

Using the pairs of beams along the same magnetic latitude and up-B beam, we solve the following system of equations for v_{pe}, v_{pn}, and v_{ap}.

$$\begin{bmatrix} v_{los}^1 \\ v_{los}^2 \\ v_{los}^3 \\ v_{los}^4 \end{bmatrix} = \begin{bmatrix} k_{pe}^1 & k_{pn}^1 & k_{ap}^1 \\ k_{pe}^2 & k_{pn}^2 & k_{ap}^2 \\ k_{pe}^3 & k_{pn}^3 & k_{ap}^3 \\ k_{pe}^4 & k_{pn}^4 & k_{ap}^4 \end{bmatrix} \begin{bmatrix} v_{pe} \\ v_{pn} \\ v_{ap} \end{bmatrix}$$

We use a weighted least-squares method to solve the equation and calculate our error.

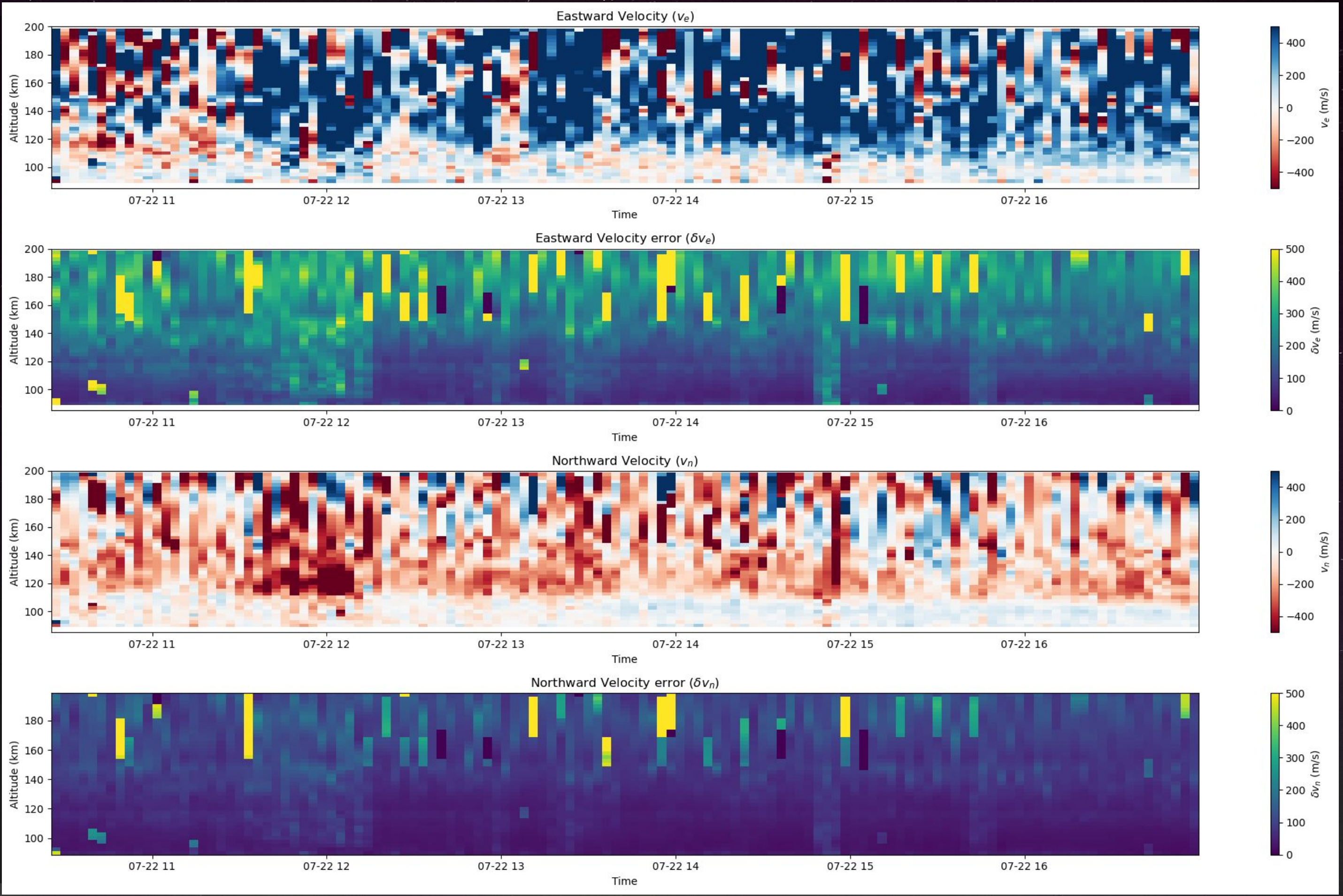
$$\arg\min_V \sum_{i=1}^{n} W_i \left(V_i^{los} - \sum_{j=1}^{m} k_{ij} V_j \right)^2 = \arg\min_V \left\| W^{1/2} \left(V^{los} - KV \right) \right\|^2.$$

$$\hat{V} = \left(K^T W K \right)^{-1} K^T W v^{los}.$$

Ion Velocity Vectors

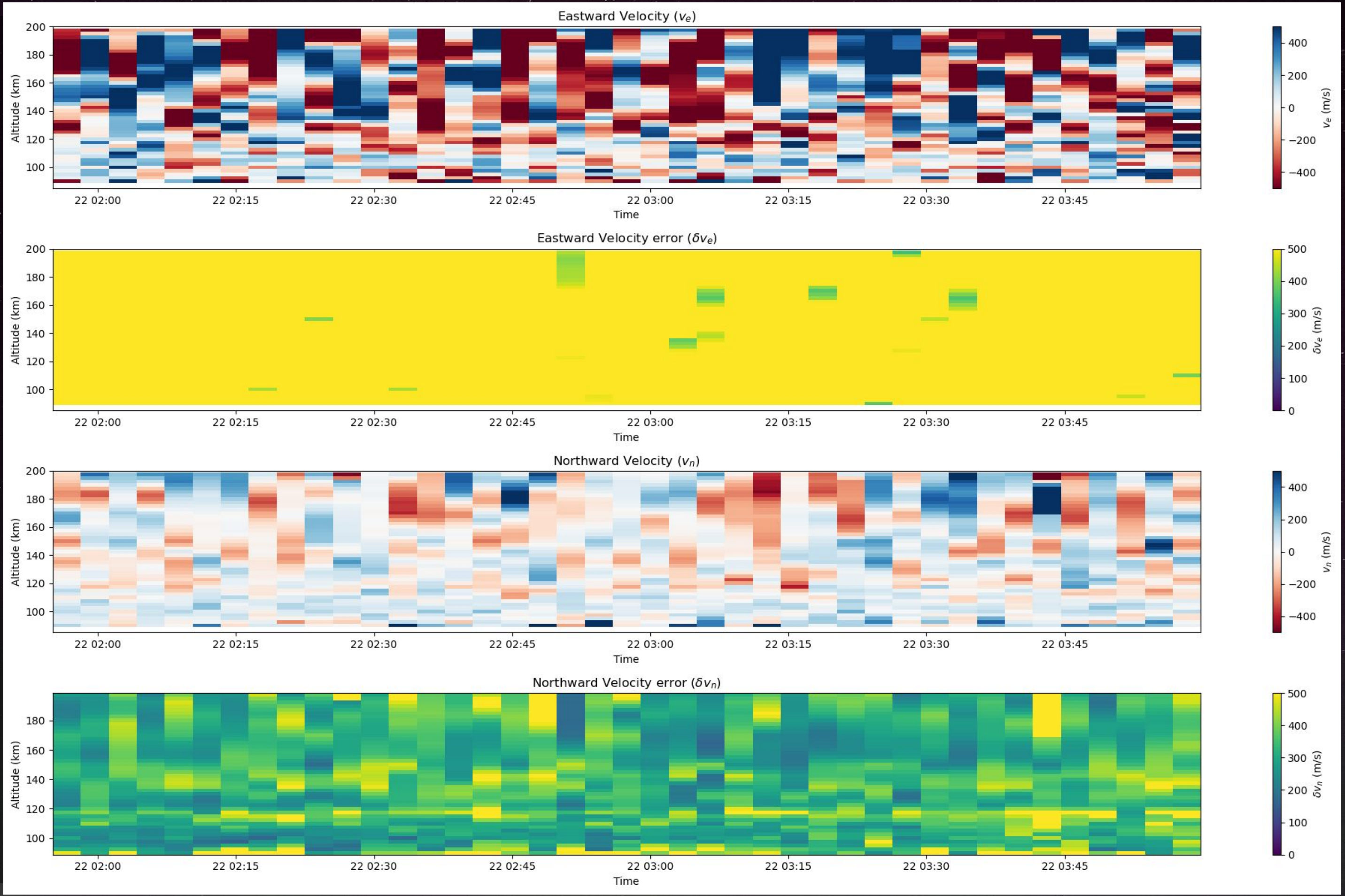
The ion velocity shows a strong eastward flow, as we would expect from two cell convection

Our errors are much more reasonable for this date compared to our experiment date...



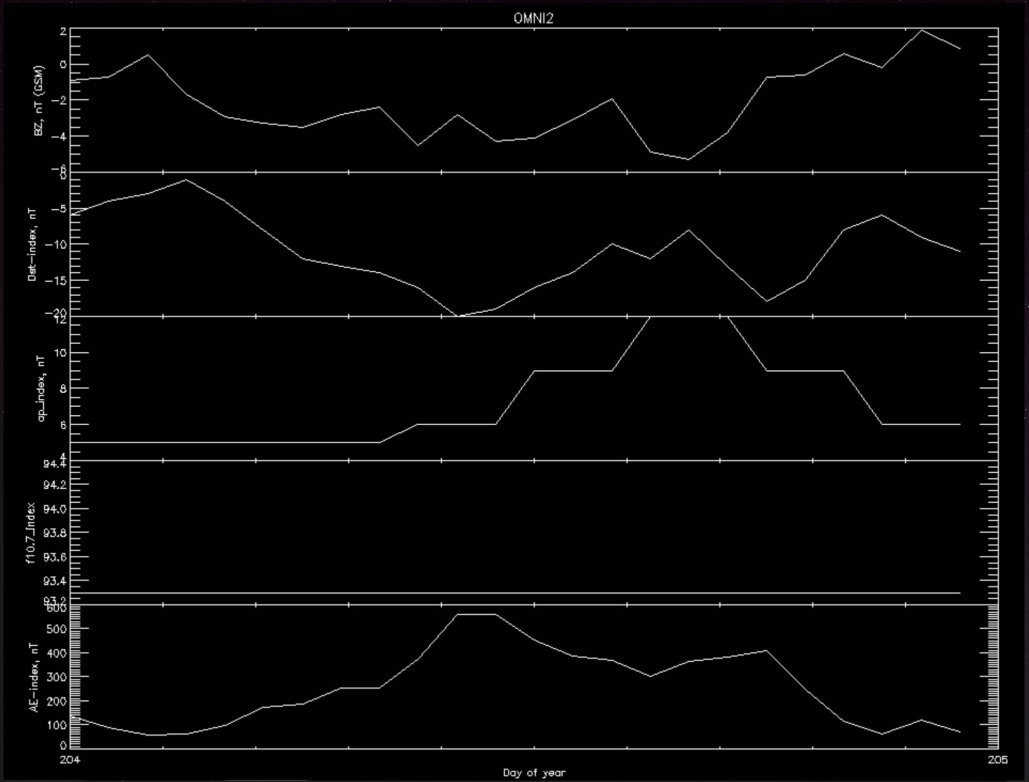
For Contrast...

Data from July 22nd, 2025



Yikes

Space weather conditions



Moderate F10.7, Ap, and Dst. (weak Geomagnetic storm)

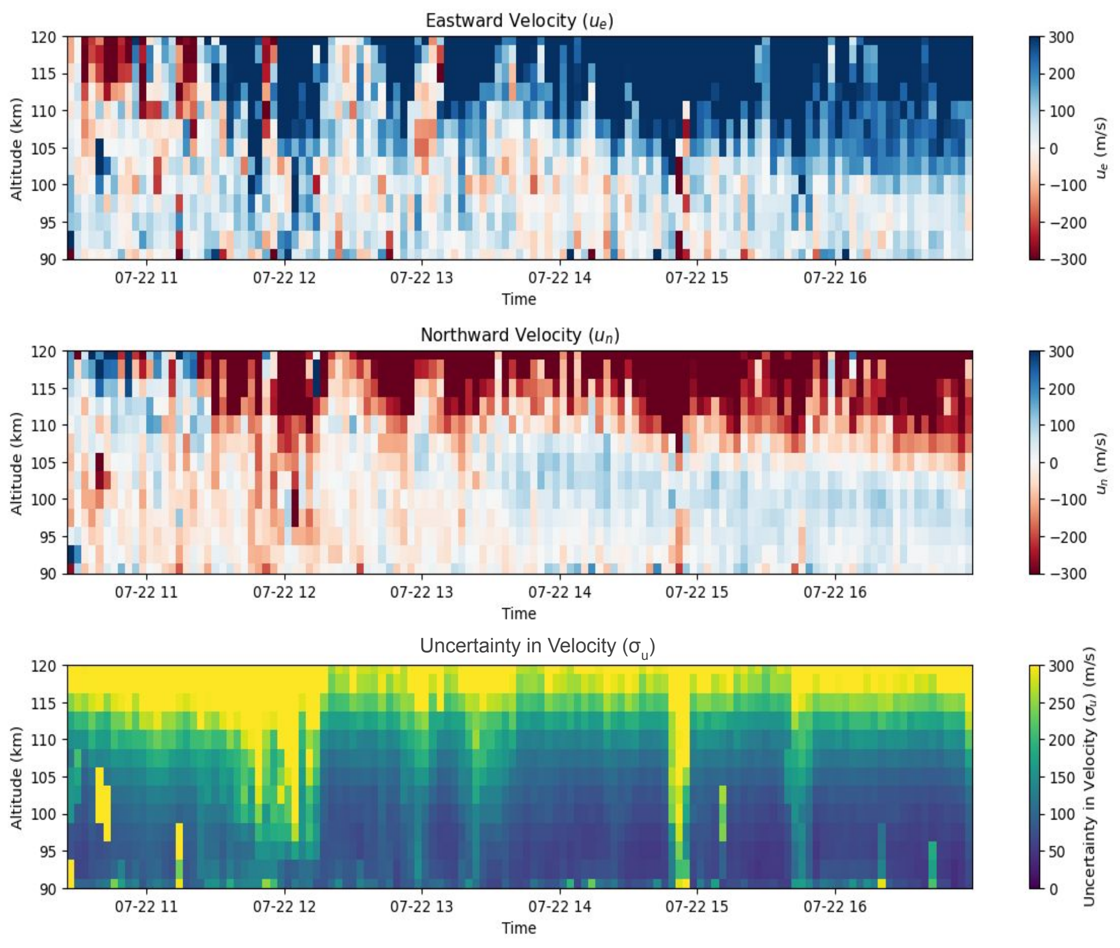
High AE index: relatively strong substorm, substorm current wedge, possibly discrete aurora.

Neutral Wind Velocity

Now, plug the following into our neutral wind equation:

- our **ion velocities**,
- the **electric field** estimates from PFISR
- the MSIS **ion-neutral collision rates**, and
- the **magnetic field** from GeoMag

$$\vec{u} = \vec{v}_i - \frac{e}{m_i \nu_{in}}(\vec{E} + \vec{v}_i \times \vec{B})$$



Joule Heating

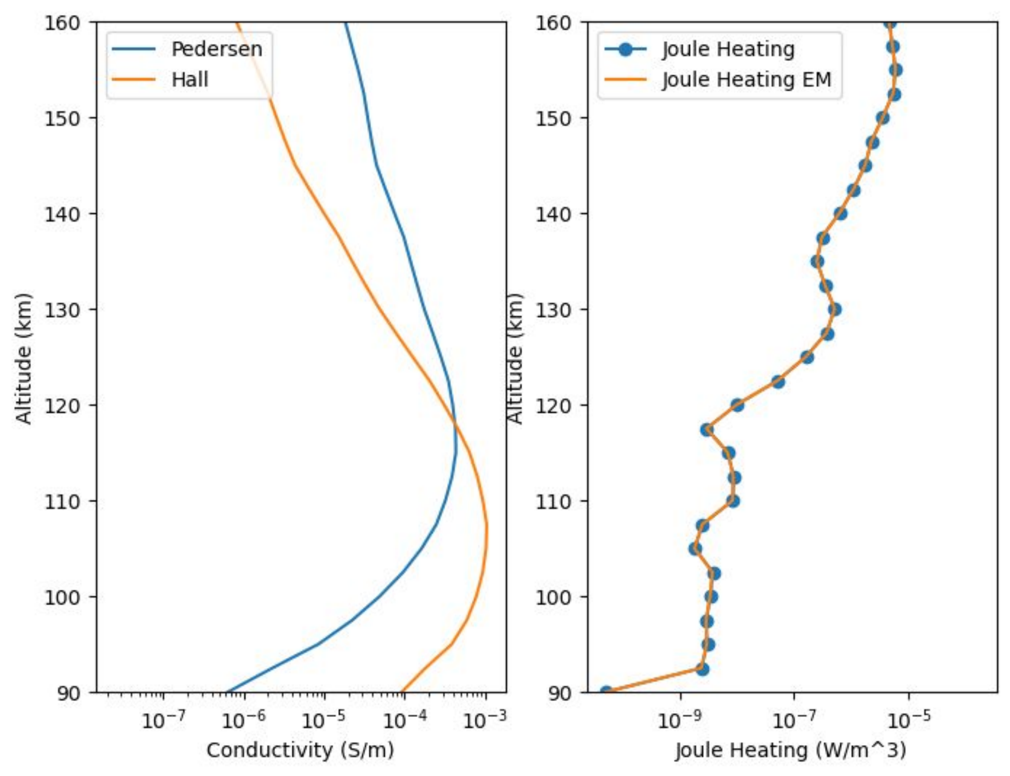
We calculate Joule heating in two different ways:

- Using the neutral wind velocity

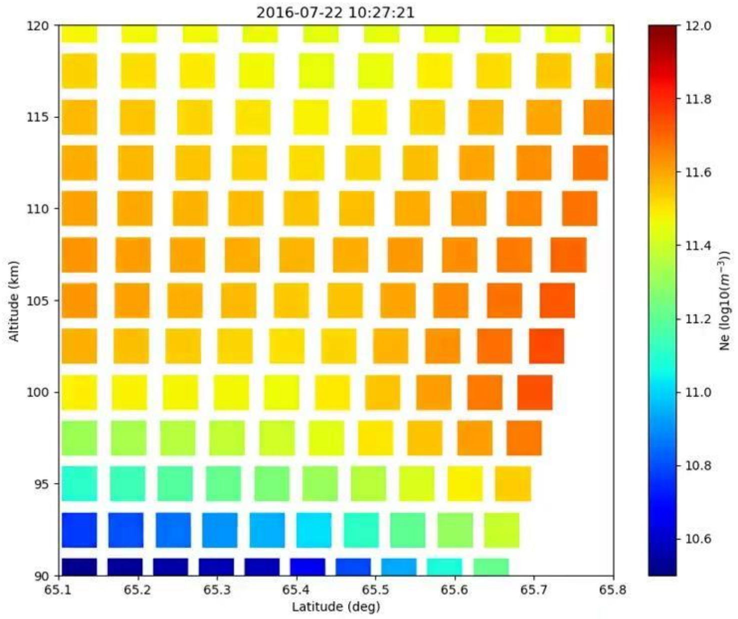
$$q_J^{NW} = n_i m_i \nu_{in} |\vec{v}_i - \vec{u}|^2$$

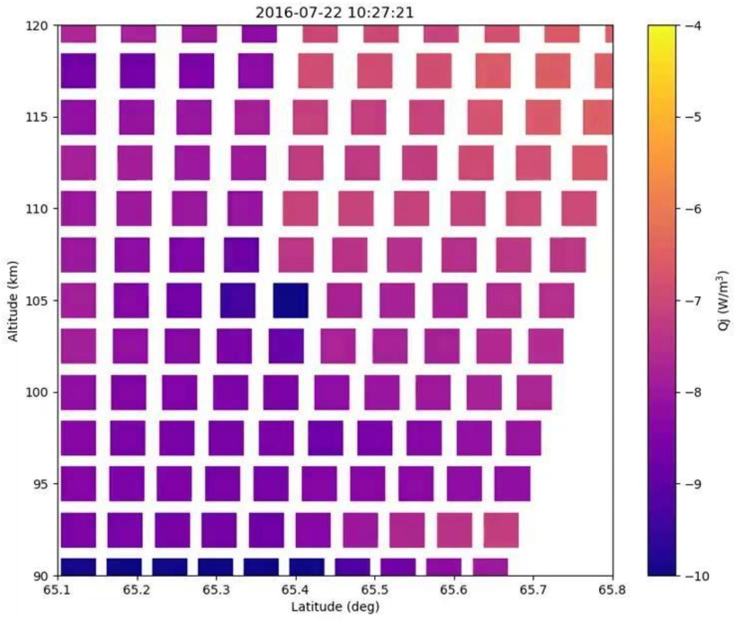
- Using the Pedersen conductivity

$$q_J^{EM} = \sigma_P |E|^2$$



Joule heating and precipitation.



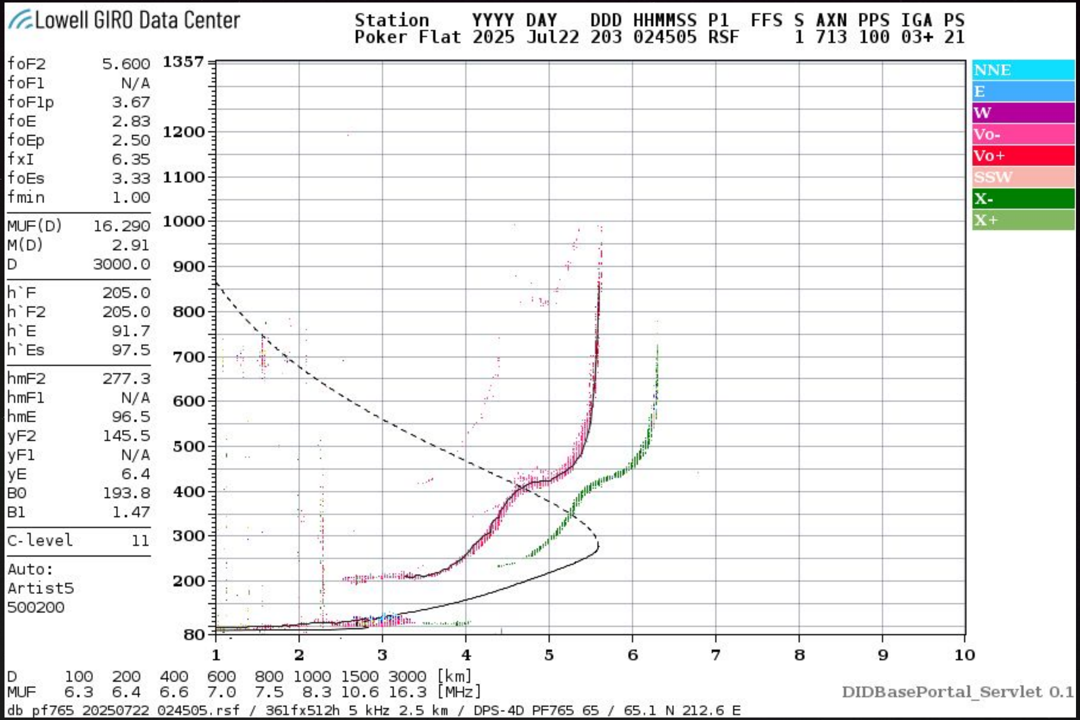


Ionosonde Data (From July 22nd, 2025)

foF2 around 5.6 MHz during our experiment

The black line is the Digisonde computed plasma frequency, which is a proxy for electron number density

This plot indicates a peak electron density between 250-300 km

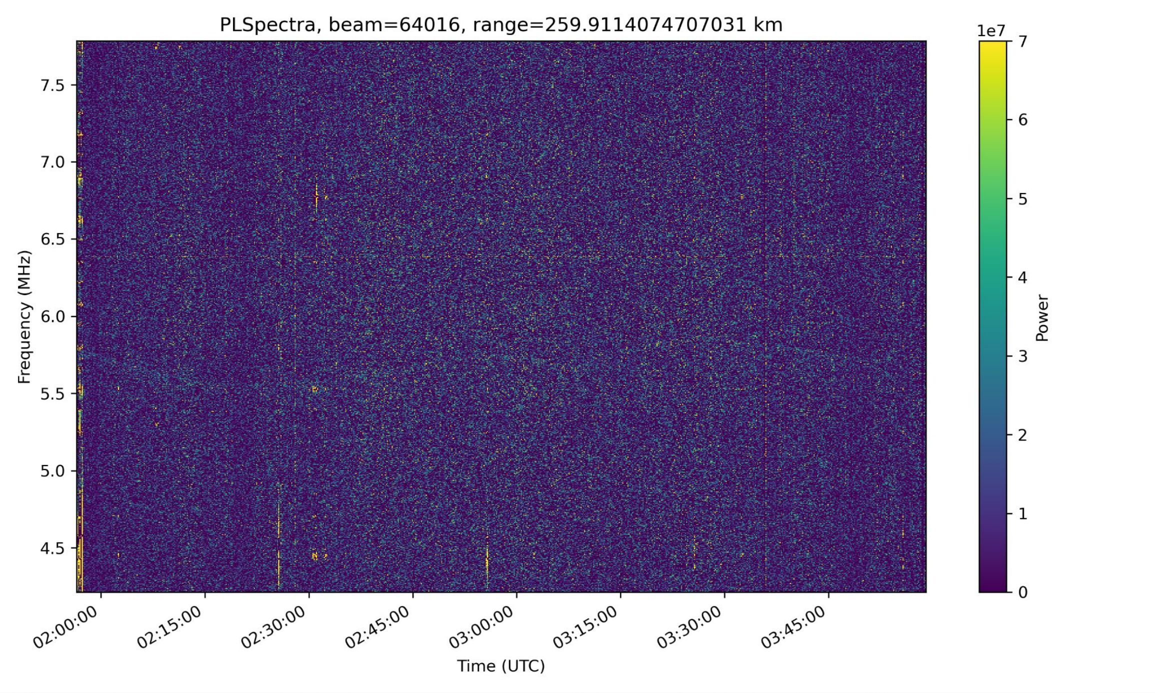


Plasma Line (From July 22nd, 2025)

Denoise the data and plot frequency vs time (for a fixed range and beam)

Plot at right shows the vertical beam at about 260 km

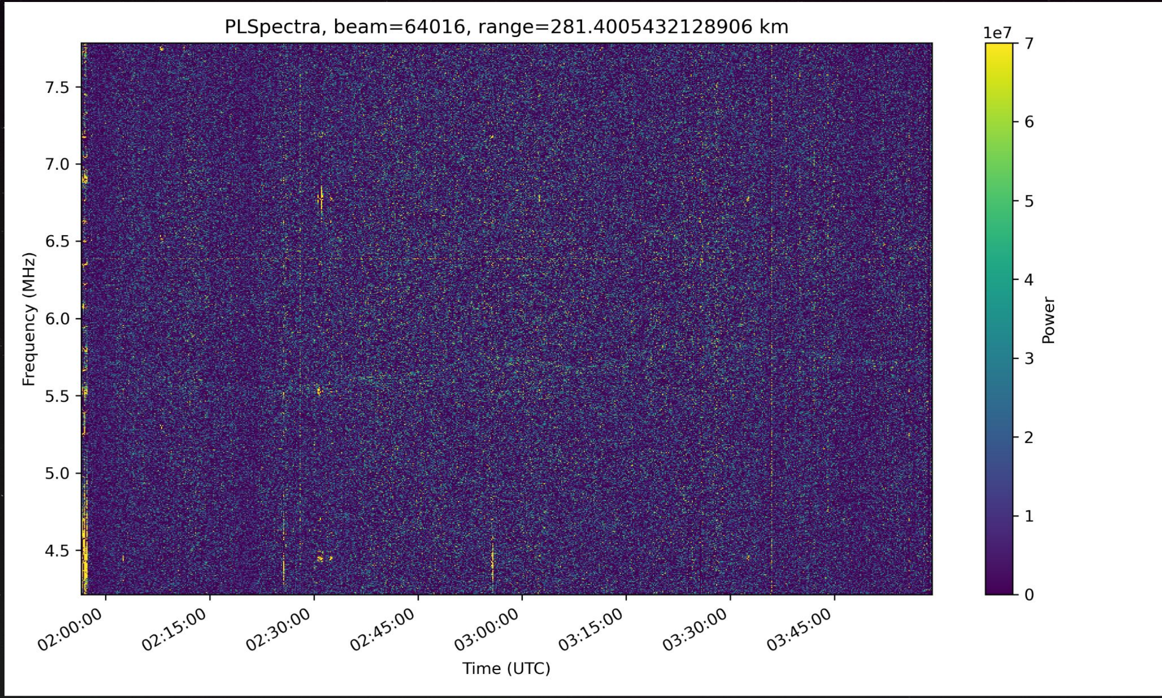
Plasma line is (faintly) visible, ranging between 5.5 and 5.8 MHz from 0200-0400 UTC



Plasma Line (From July 22nd, 2025)

Here we plot the same frequency vs time on the same vertical beam, but this time at ~281 km.

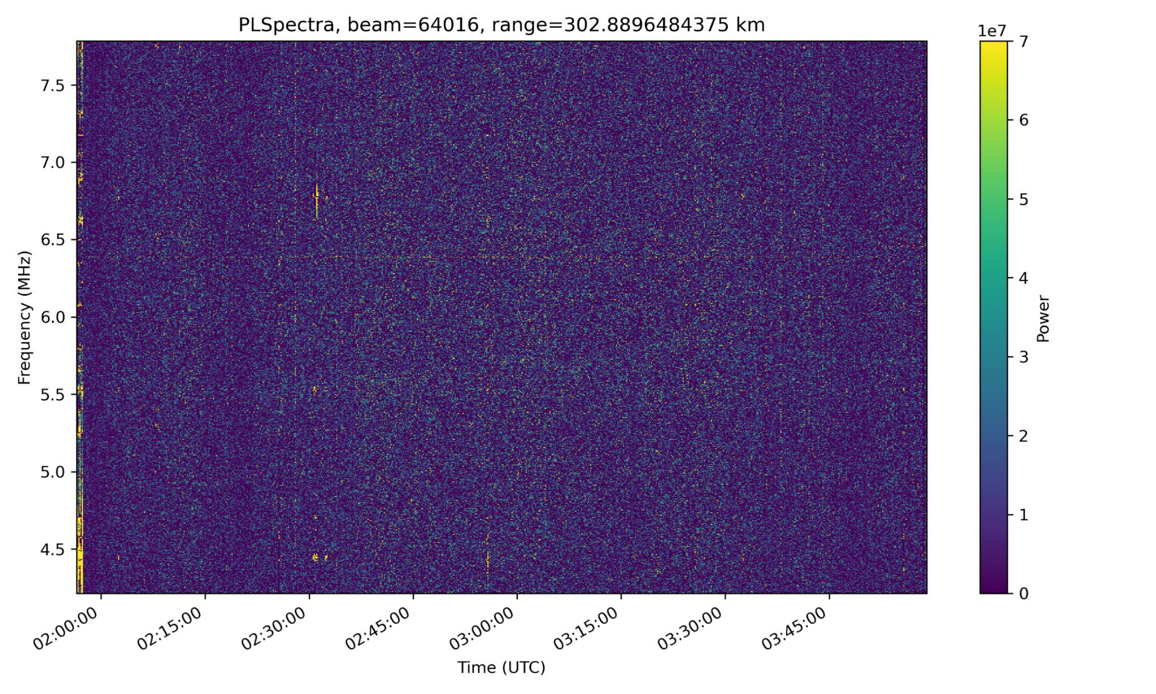
Note we can see the same plasma line feature here. At 0245 UTC, we're seeing a plasma frequency around 5.6 MHz, corresponding well to the Digisonde data.



Plasma Line (From July 22nd, 2025)

Finally we look at ~302 km; this is the highest altitude we were able to distinguish the plasma line from the background, however it is already noticeably weaker than at lower altitudes.

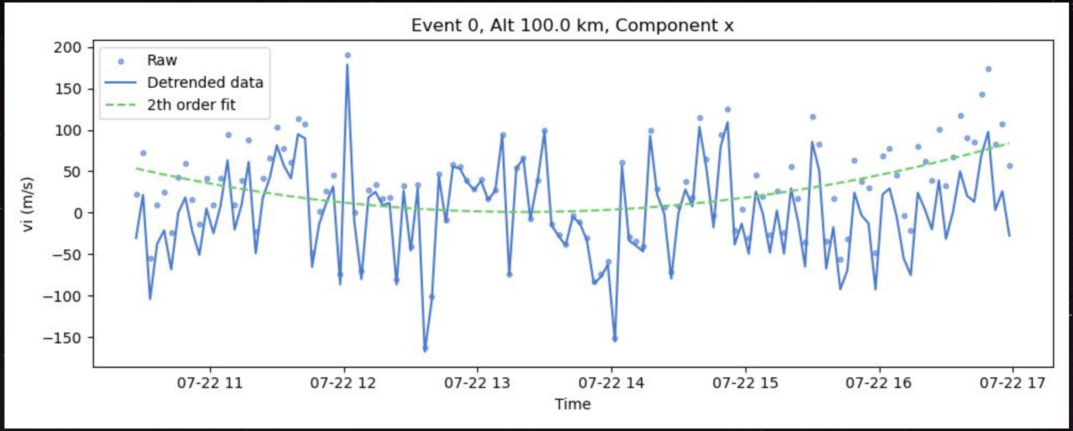
This again corresponds well to the ionosonde data, which showed increased electron density in this altitude range.



Normalizing Data

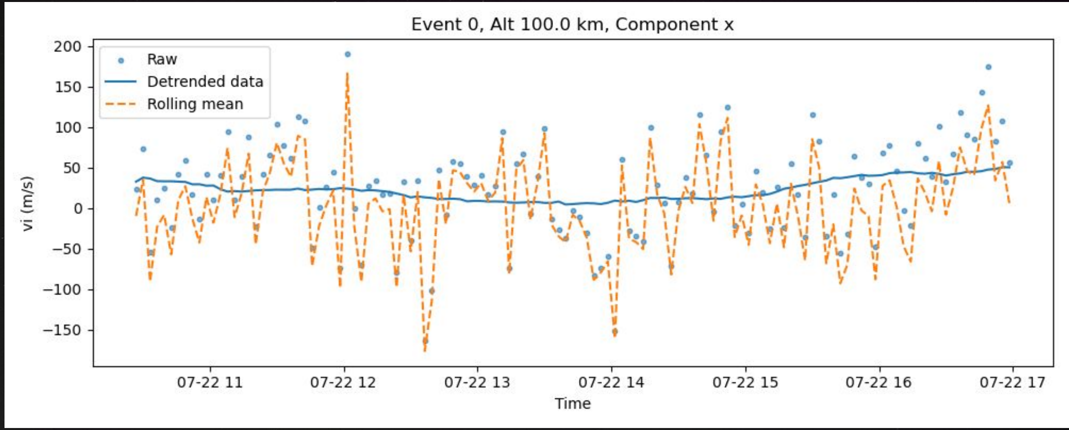
Two different methods used to detrend data to determine best fit: FFT and Rolling Average

Fast-Fourier Transform →

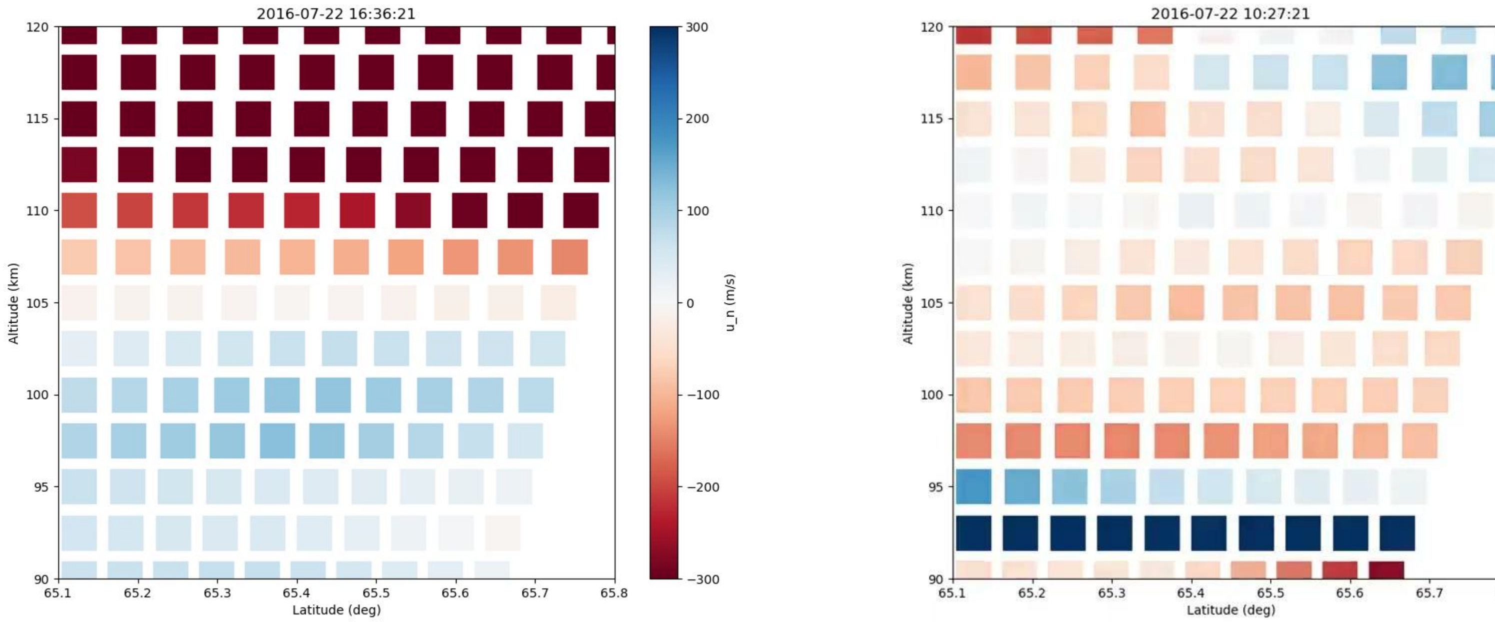


Normalized data used for further analysis

Rolling Mean →



Wind Shear and Wave Structure



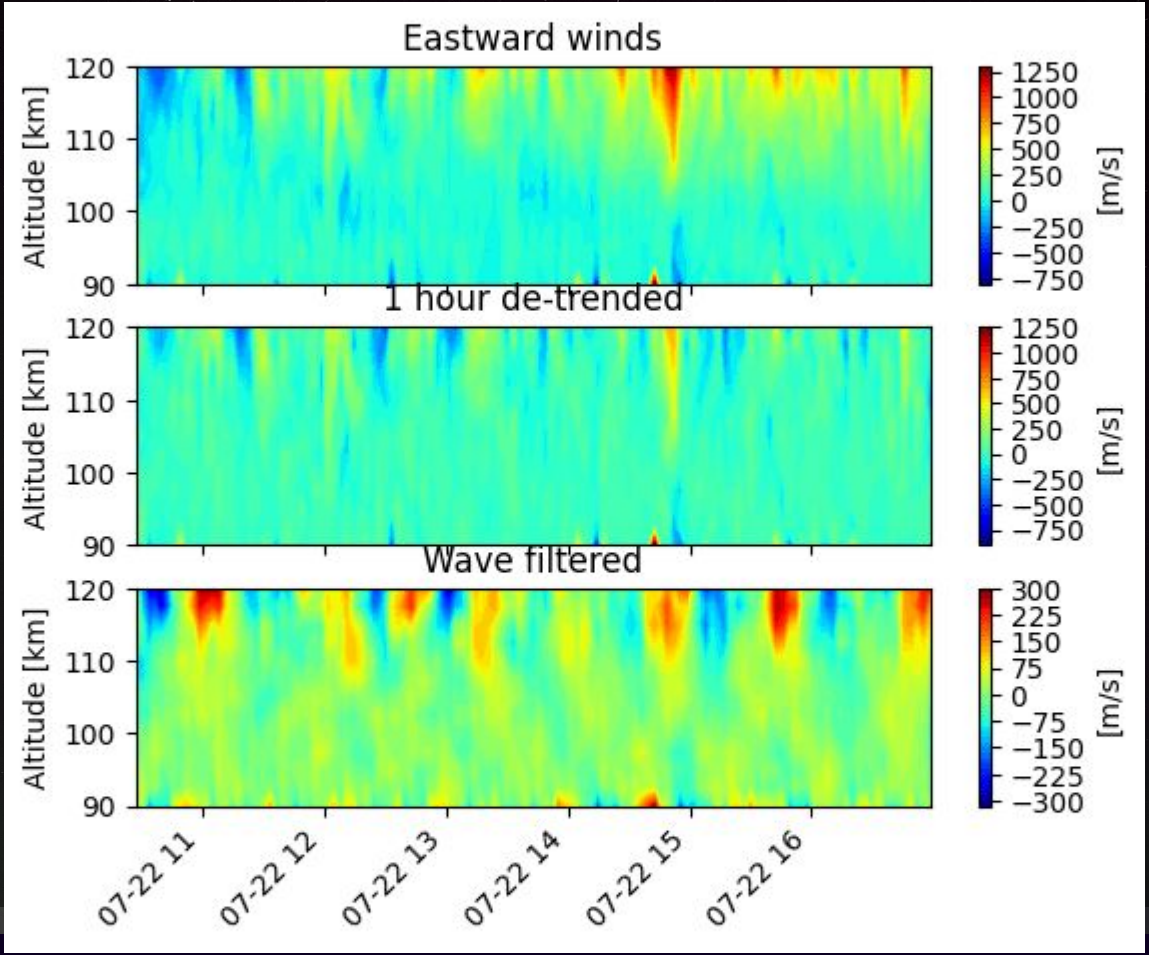
Wave Analysis

Subtract 1 hour rolling window mean to isolate < 1 hr waves

Waves are filtered by fitting 5 minute harmonics up to 1 hour

Filtered wave field shows upward and downward propagating waves

Consistent with gravity waves



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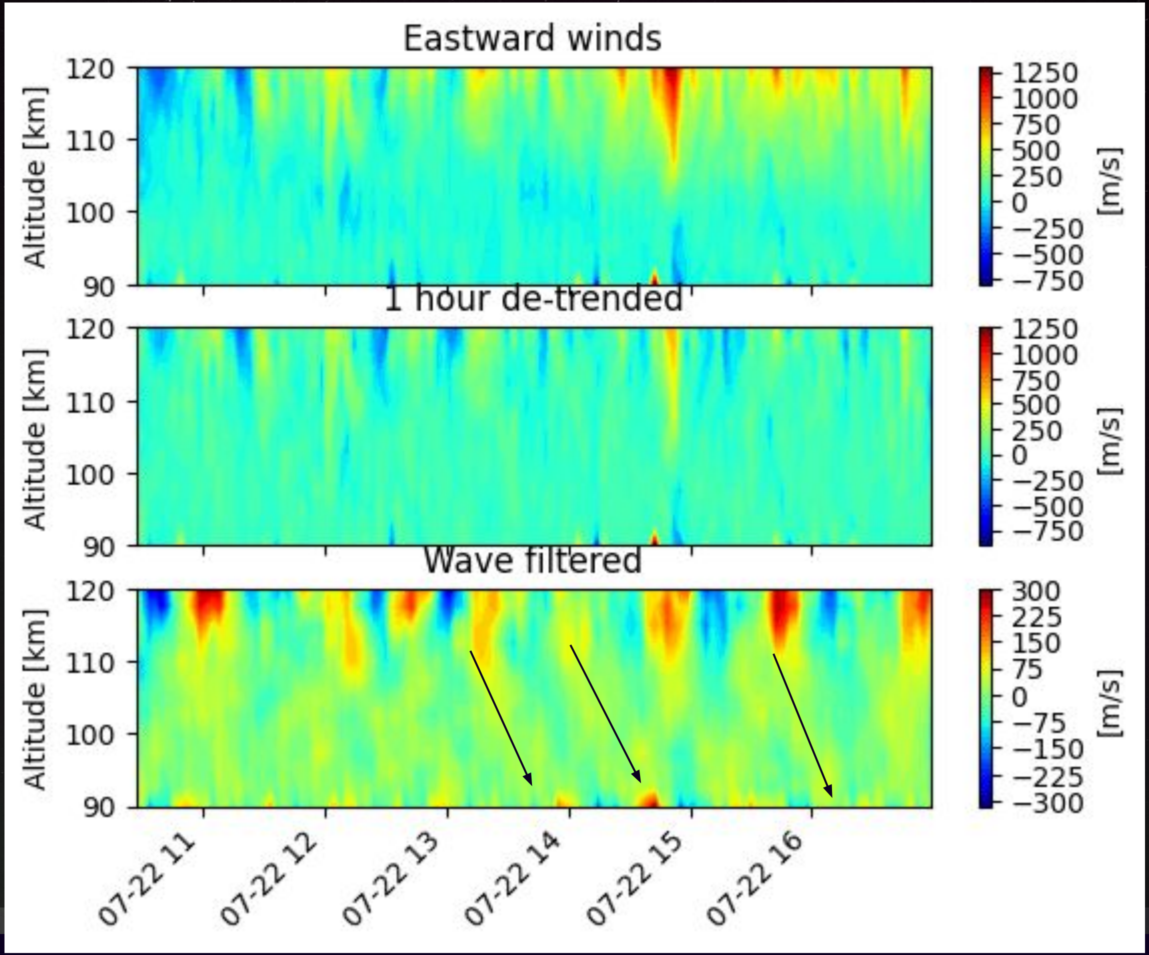
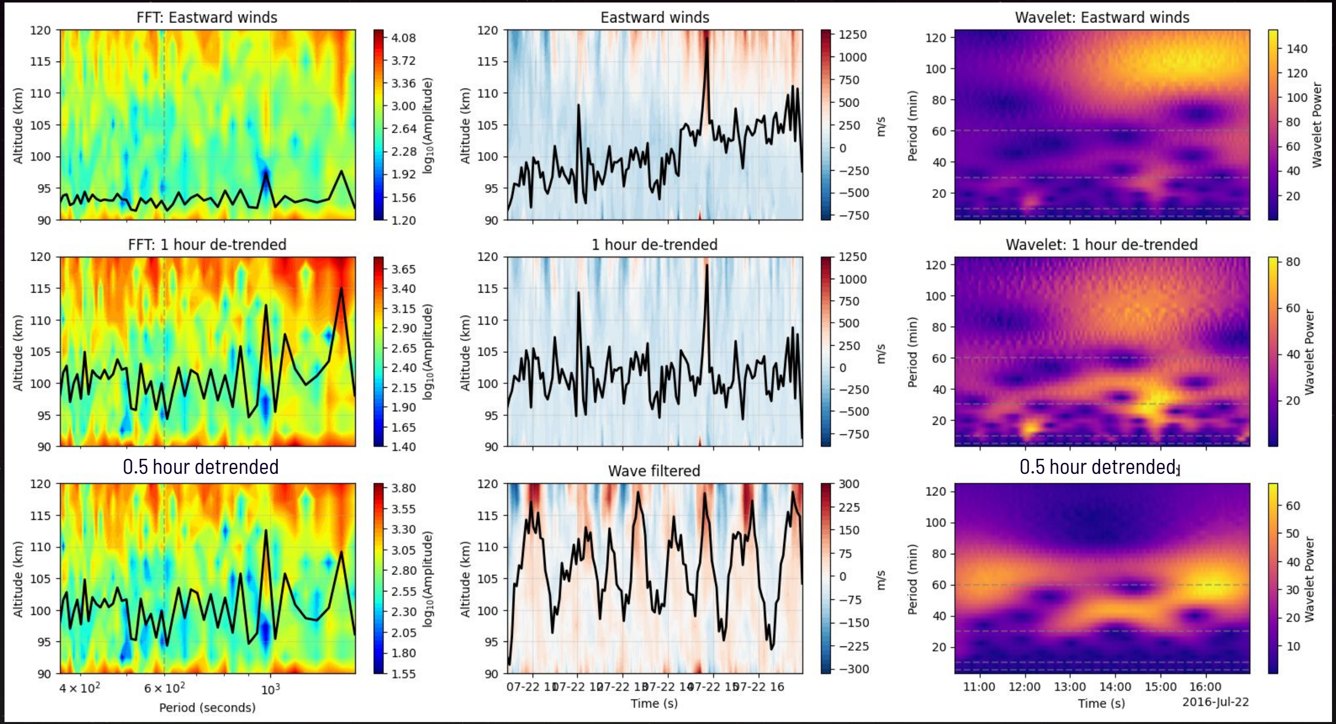


Wave Analysis

FFT and wavelets shows strong ~15 minute waves in 1 hour detrended winds

~1 hour signal dominates the filtered wave field

Consistent with gravity waves



Conclusions

Using PFISR, we were able to calculate neutral wind velocities from the line-of-sight ion velocities.

We used these neutral wind velocities to calculate the Joule heating rate and compared it to the Joule heating rate calculated from the Pedersen conductivity and electric field.

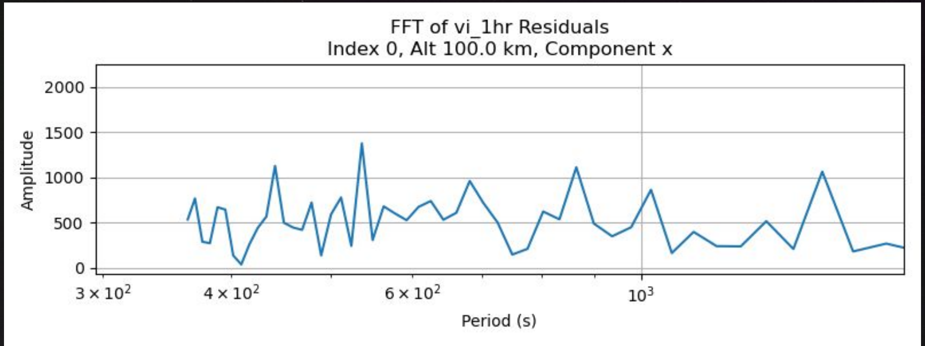
Using the plasma line data, we were able to extract a plasma frequency that corresponds to the foF2 line from the Poker Flat ionosonde graphs.

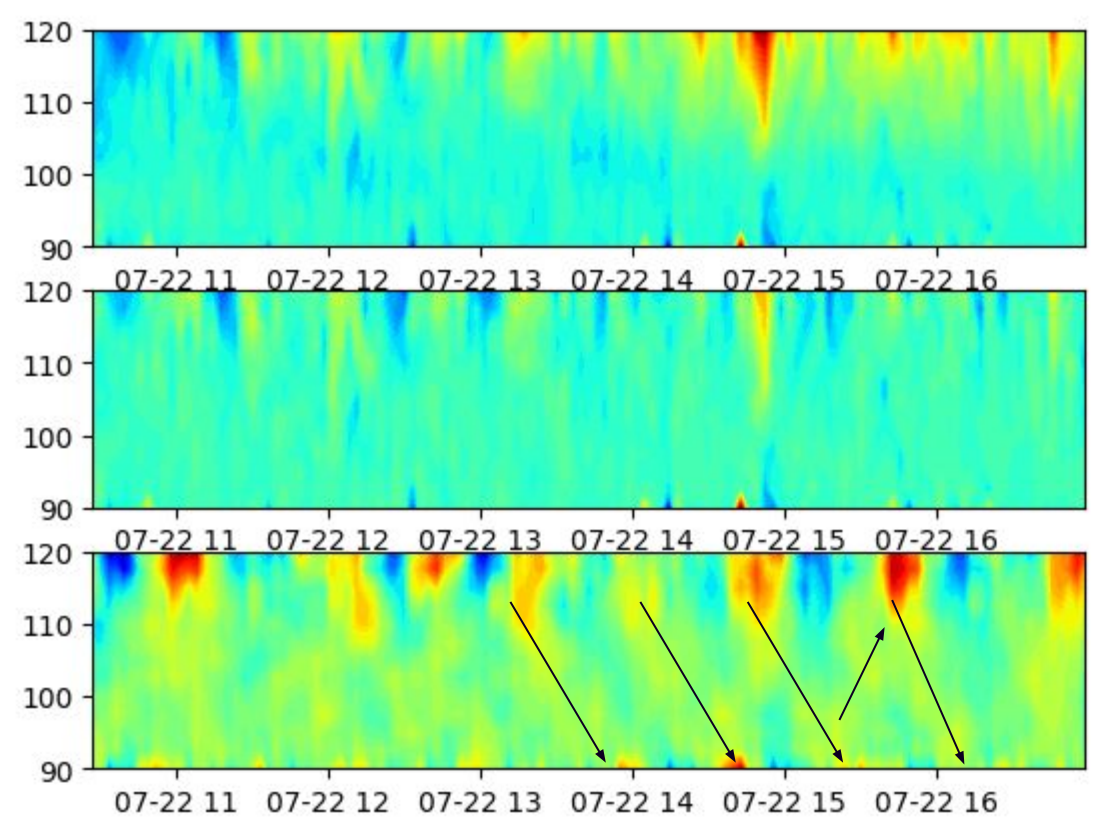
We were also able to extract wave parameters for gravity waves visible during the event.

Thank you!

Questions?

Unhoused Images

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