Improvements to the plasma line fitting for Millstone Hill ISR

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ISR Basics

- Incoherent scatter radar (ISR) has proved to be one of the most powerful and flexible ground-based instrument for probing the dynamics of thermal plasma in the Earth's ionosphere.

- ISR sends out a high energy beam and receivers obtain very low transmitted energy back (nearly 10^{-11} power back).

- From signal processing and spectra fitting, we can obtain full altitude profiles of the ionospheric plasma parameter state (temperature, density, composition, and velocity).

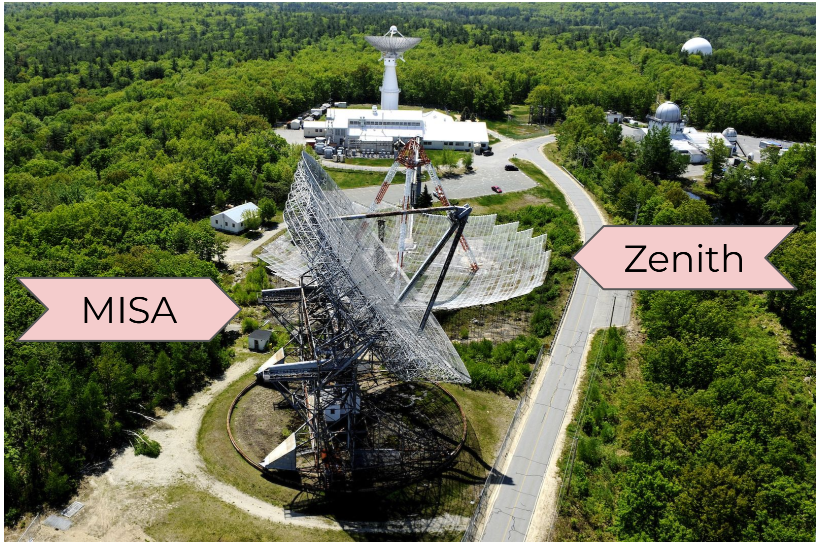

Image: Millstone Hill ISR @ Haystack

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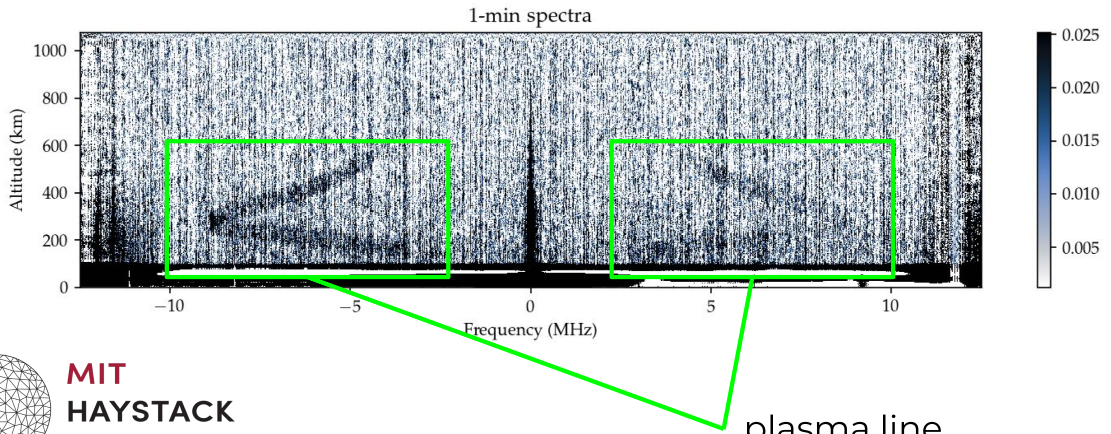
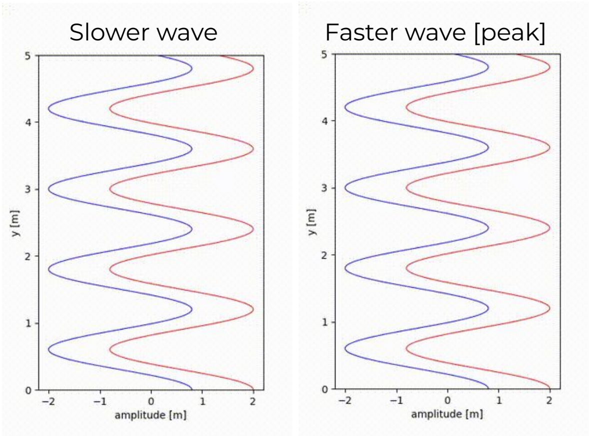
Goal

- Millstone Hill ISR is capable of observing the ion acoustic and Langmuir wave (plasma line)
- Ion lines can give us information about the electron and ion fluctuations in the ionosphere. But the plasma line may be an even better indicator of electron density and temperature.
- Previous work: Obtained the location of the peak of the plasma frequency
- Project goal: Obtain **electron density and uncertainties** ($n_e \pm \delta n_e$) from plasma line





Fittings [Pipeline]

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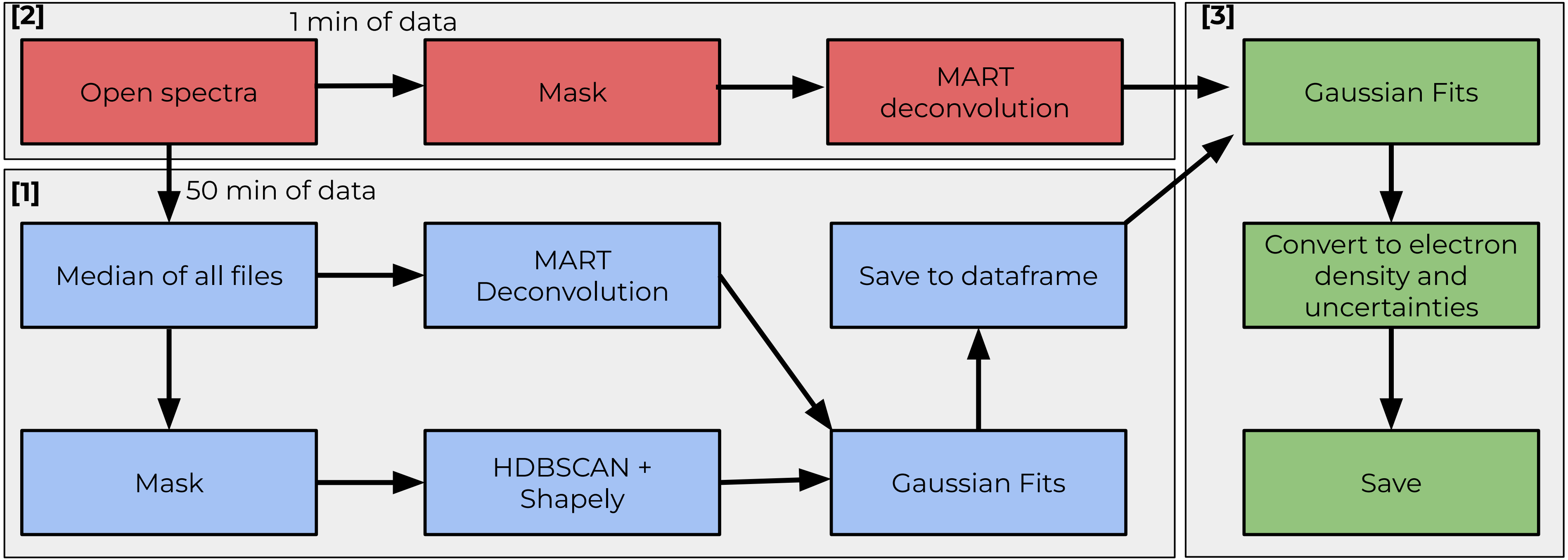


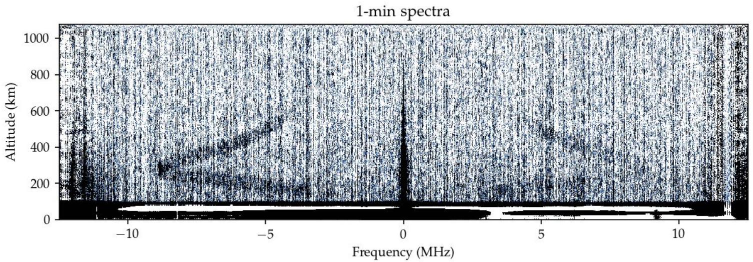
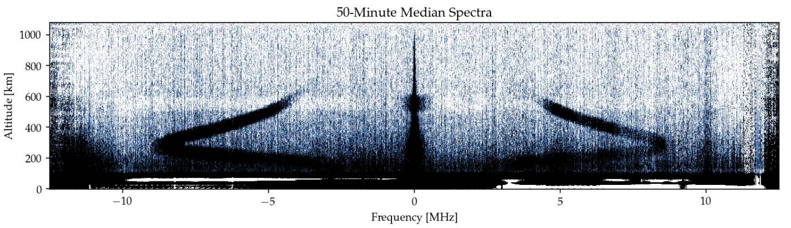


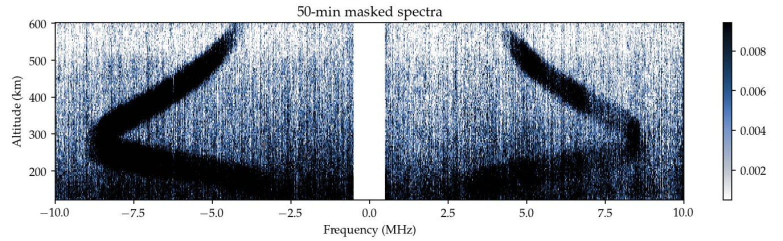
Image → analytical spectra

Pre-processing & constraint finding

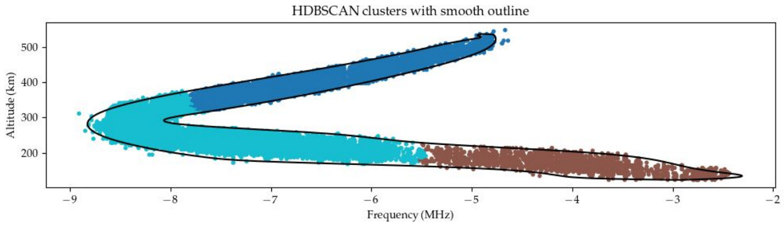
Estimation

Pre-Processing





Open spectra → Median of all files → Mask + Combine → HDBSCAN + Shapely



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Deconvolution

- To minimize instrument effects [radar byproducts], we need to deconvolve the spectra. Think that:
    - A → Instrument matrix, **x** → theoretical spectra **[WANT THIS!]**, **b** → actual spectra (when newly obtained from ISR)

$$A\vec{x} = \vec{b}$$

- **Plain text:** To go backwards from the real spectra, we need to obtain a less noisy version of the spectra. This can be achieved with deconvolution. We use MART in this study.

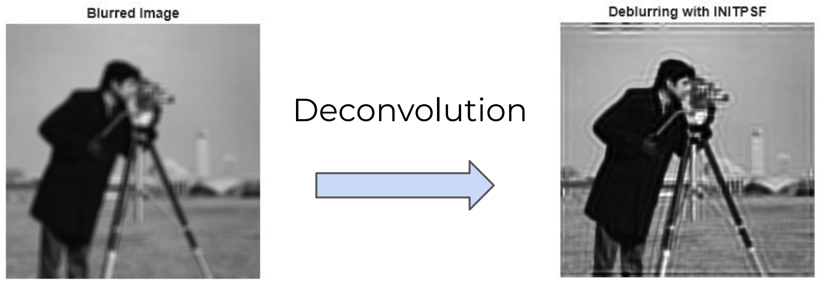
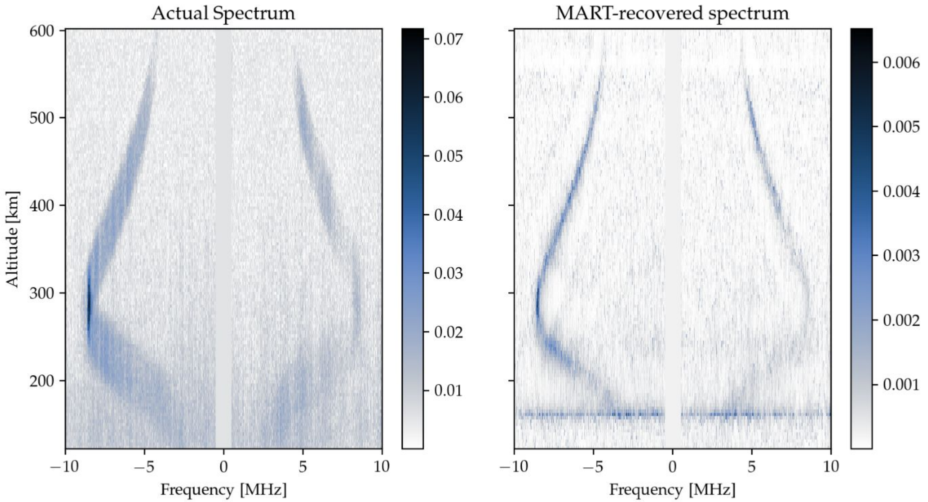


Image: Deblurring Images Using the Blind Deconvolution Algorithm from MATLAB



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Fittings

- We use the Levenberg-Marquardt Fitting algorithm [lmfit library]
  - Gaussians

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

$$\boxed{\mu \simeq \omega_p}$$

  - Plasma frequency resonance equation [influences from **Ne, Te, and B**]

$$\omega^2 = \frac{e^2 n_e}{\varepsilon_0 m_e} + \frac{3k_B T_e}{m_e} k^2 + \left(\frac{eB}{m_e}\right)^2 \sin^2\phi,$$

- 50 min → 1 min iteratively

$$\boxed{\omega_p}$$

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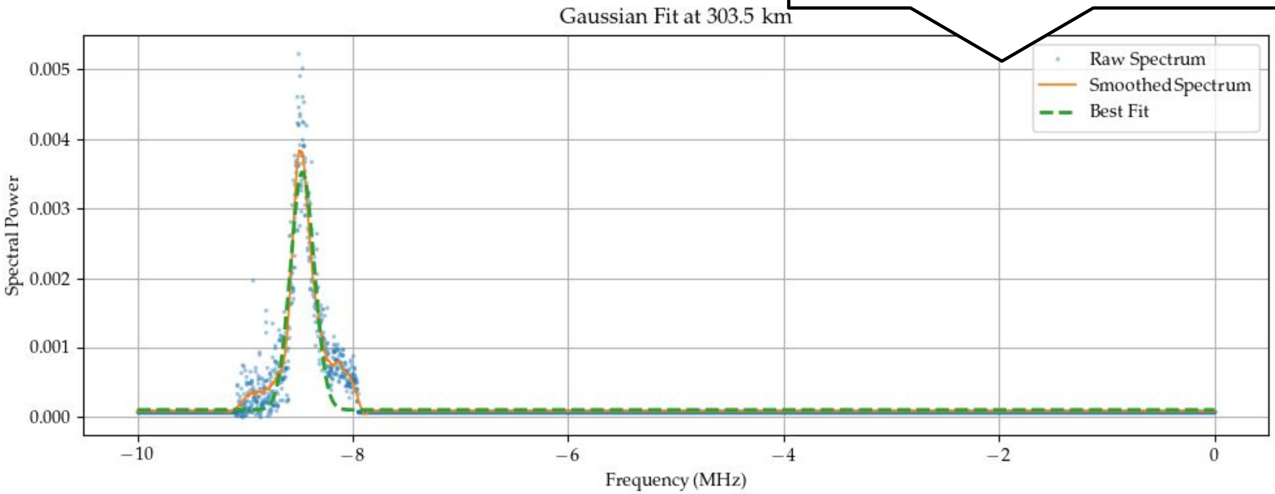
Fittings [Gaussian]

- We fit the combined median of every available spectra in the current hour using initial guesses from a model of the ionosphere [IRI2016]

- We use the larger fittings to fit the spectra in the smaller fittings.

[[Fit Statistics]]
fitting method = leastsq
chi-square = 2242.73062
reduced chi-square = 0.46762523

[[Variables]]
g_center: -8.46757791 +/- 5.3312e-04
g_sigma: 0.10984809 +/- 5.3861e-04



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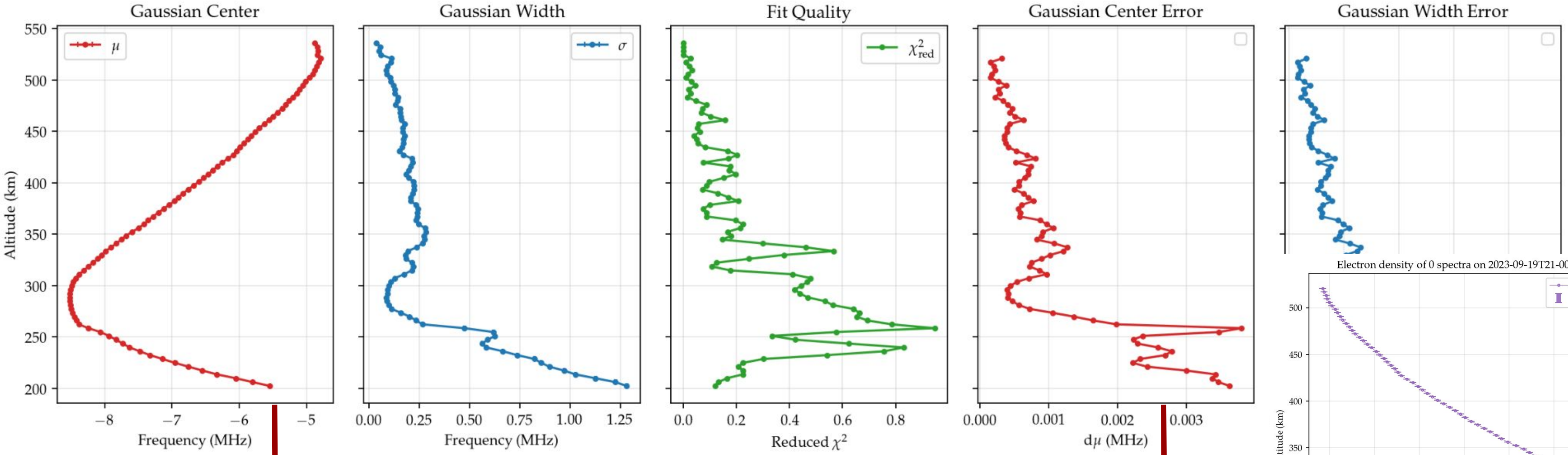
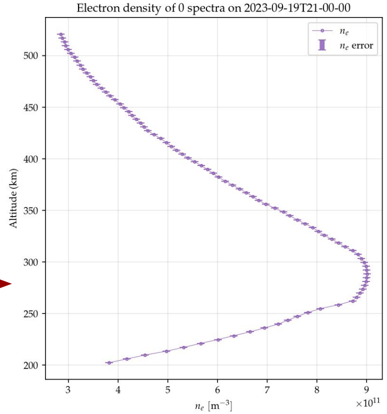
Fittings [Gaussian]

- You can obtain a full altitude profile fitting using Gaussians like this





$$\omega_p^2 \simeq \frac{e^2 n_e}{\varepsilon_0 m_e}$$

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Fittings [Pipeline]

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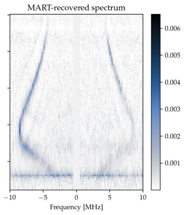
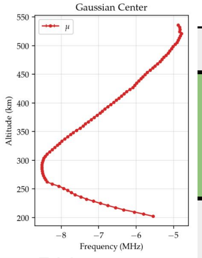
[2]

1 min of data

Open spectra → Mask → MART deconvolution → Gaussian Fits → Convert to electron density and uncertainties → Save

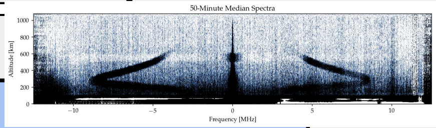


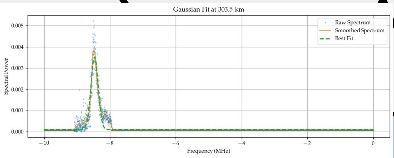


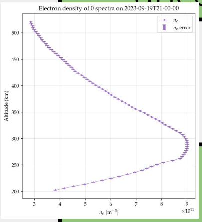
[1]

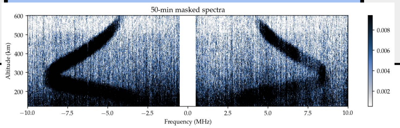
Median of all files → MART Deconvolution

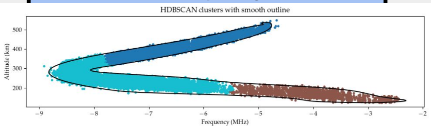
Median of all files → Mask → HDBSCAN + Shapely → Gaussian Fits → Save to dataframe





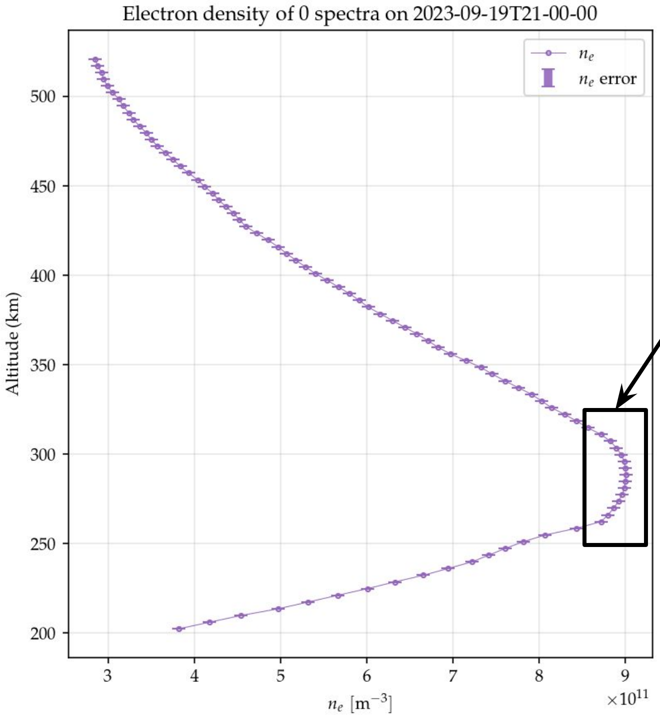


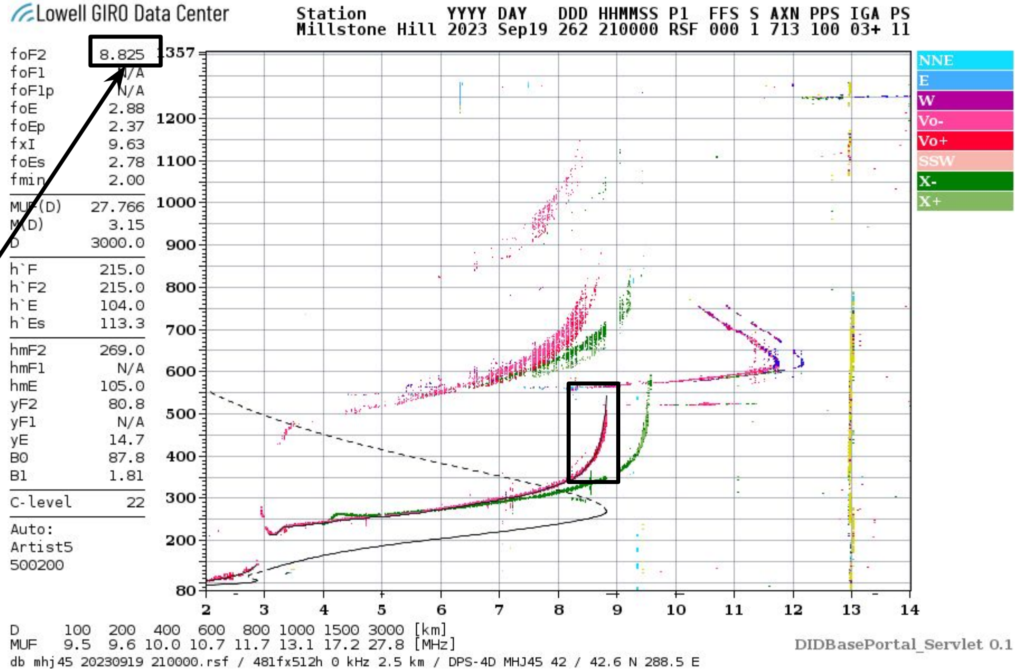




SUCCESS!!!

Fittings [Results]





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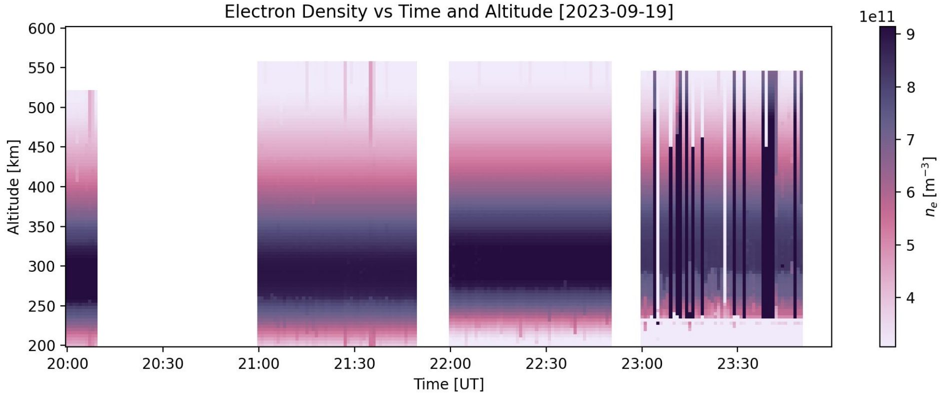
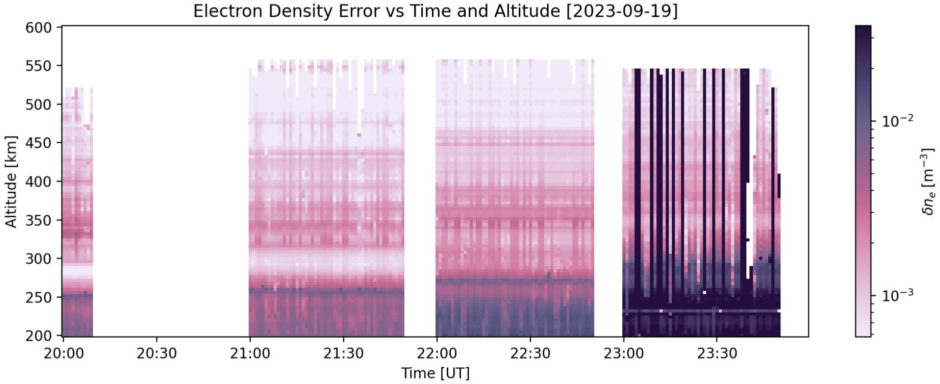
Electron density profiles

- I iteratively fit the spectra at every single altitude for multiple hours of data [Zenith] to obtain a electron density profile.
- I use multi parallel processing [mpi4py] to reduce computing time from 15 mins for 1 hour of data to 30 seconds.
- Gaps in altitude indicate lack of spectra from HDBSCAN
- Gaps in time range indicate no available measurements from ISR





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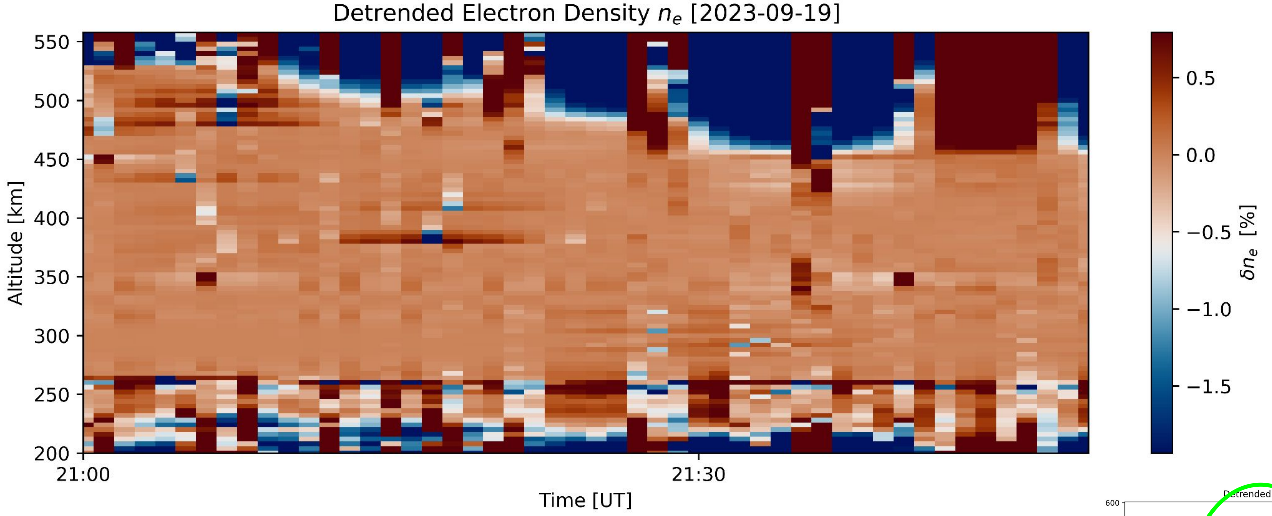
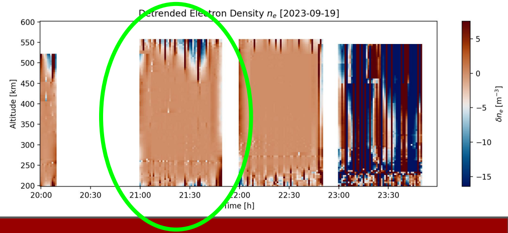
Electron density profiles

- We present a detrended electron density profile [in %] from 21:00 to 21:49 UT: this shows the short-term variations.

- **$\delta n_e = (n_e - \langle n_e \rangle / n_e) * 100$**





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Conclusion + Future Works

- **Takeaway:** We have created an algorithm that is capable of isolating plasma line traces and identifying confidence intervals for their fittings. This allows us to create near full-altitude profiles of electron density.

- Workflow:
  - Pre-processing → Deconvolution → Gaussian Fitting → Electron density and uncertainty profiles

- **Future works:**
  - Creating electron density profiles for multiple days of data

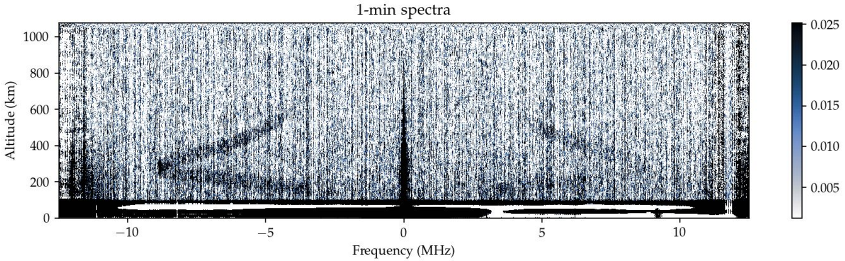
  - Fitting with collisional plasma frequency equation

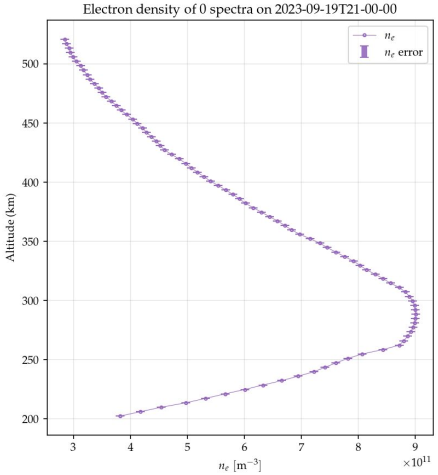
Acknowledgements

Thank you to everyone at Haystack for a great informative summer experience, specifically thank you to:

Kike, **Bill**, **Katherine**, **Bob**, **Nestor**, my fellow REU **students**, and Haystack **staff**!

Questions?





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