

PyRayHF: An Open Source Ray-Tracer for Ionospheric Data Assimilation



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CEDAR 2026 Presenting Author: Henry Valentine

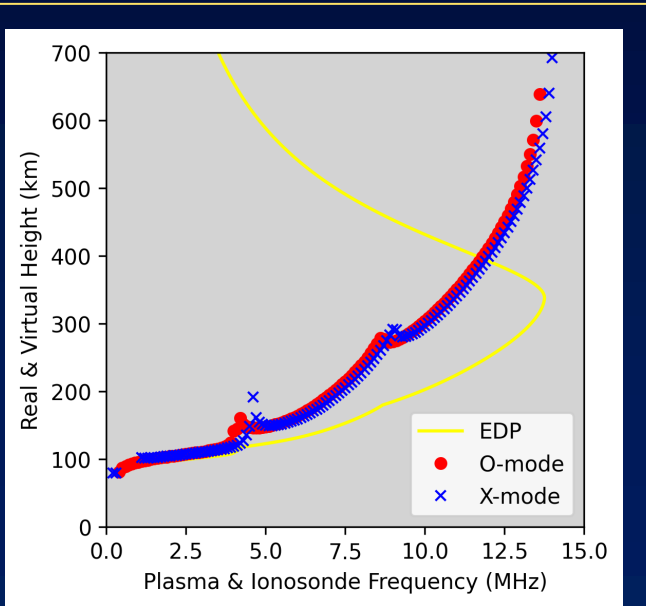
Co-Authors:

Douglas Drob, Joseph Hughes, Dustin Hickey, Angeline Burrell, Katherine Zawdie, Dev Joshi, William Bristow, Evan Thomas

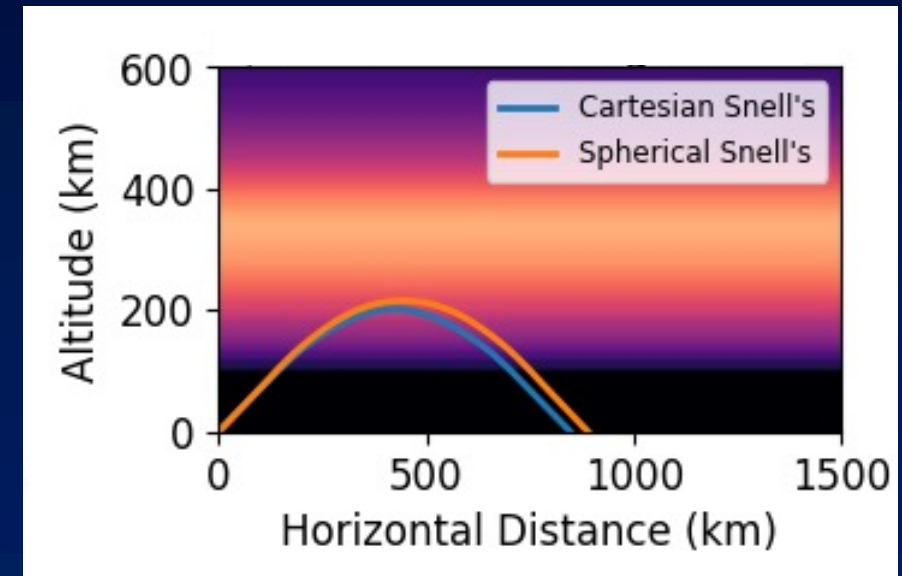
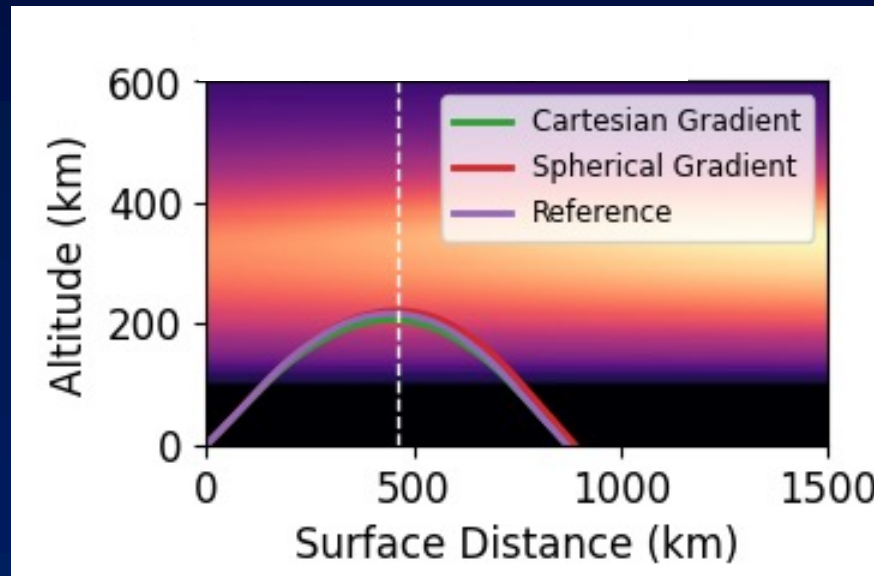
Overview: What is PyRayHF?

PyRayHF is an open-source Python framework for ionospheric ray tracing, with a particular emphasis on efficient forward operators for data assimilation applications.

Vertical Forward Operator

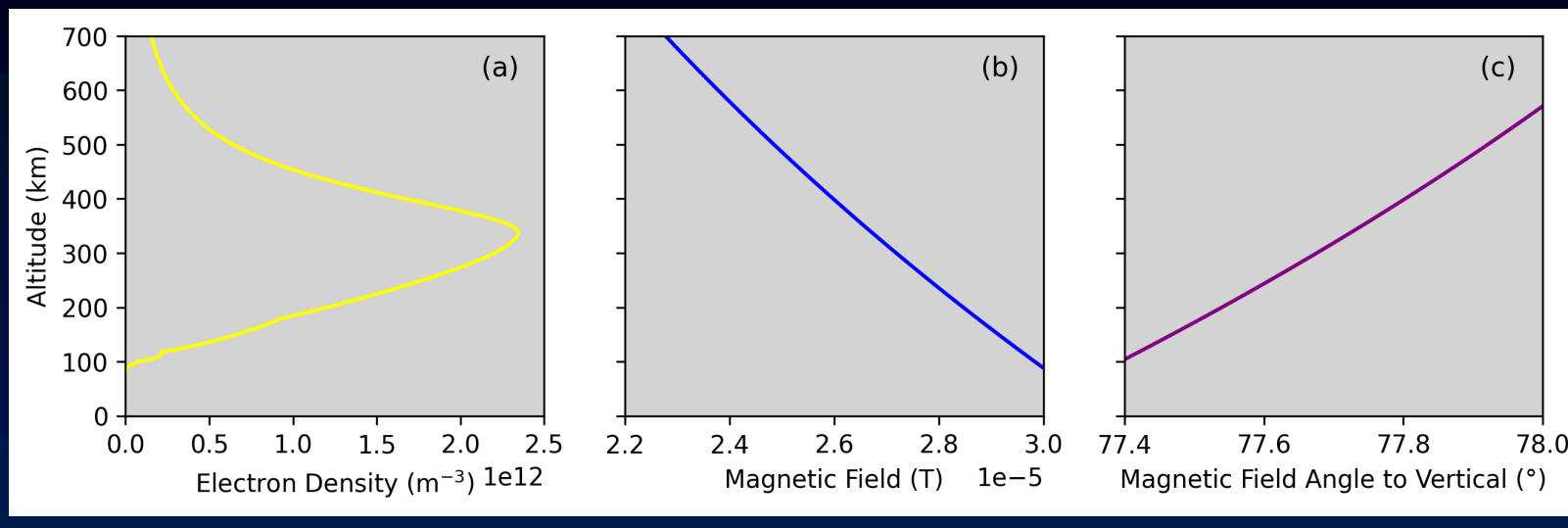


4× 2D Forward Operators

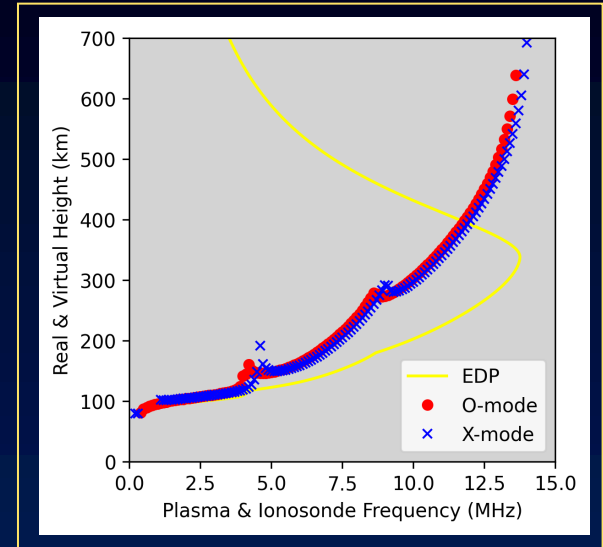


Vertical Forward Operator

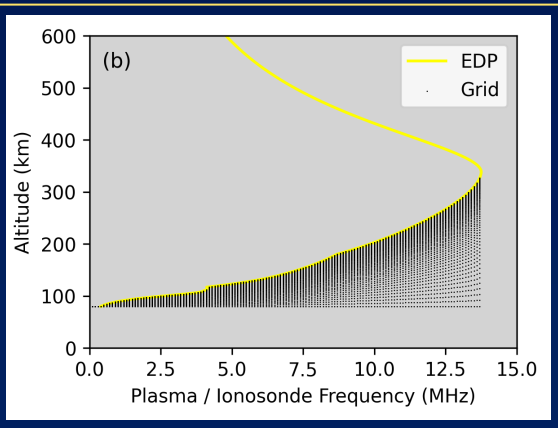
Inputs



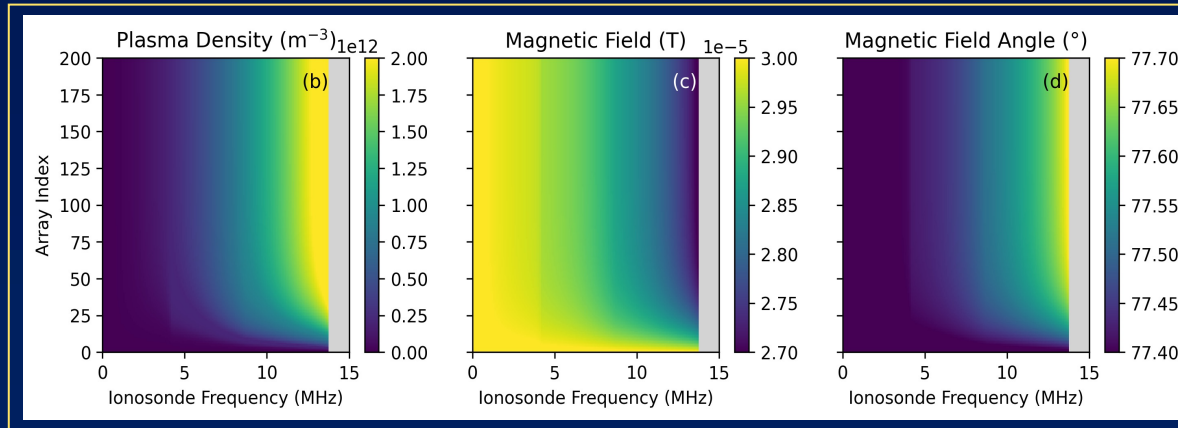
Output



Step 1: Adaptive gridding



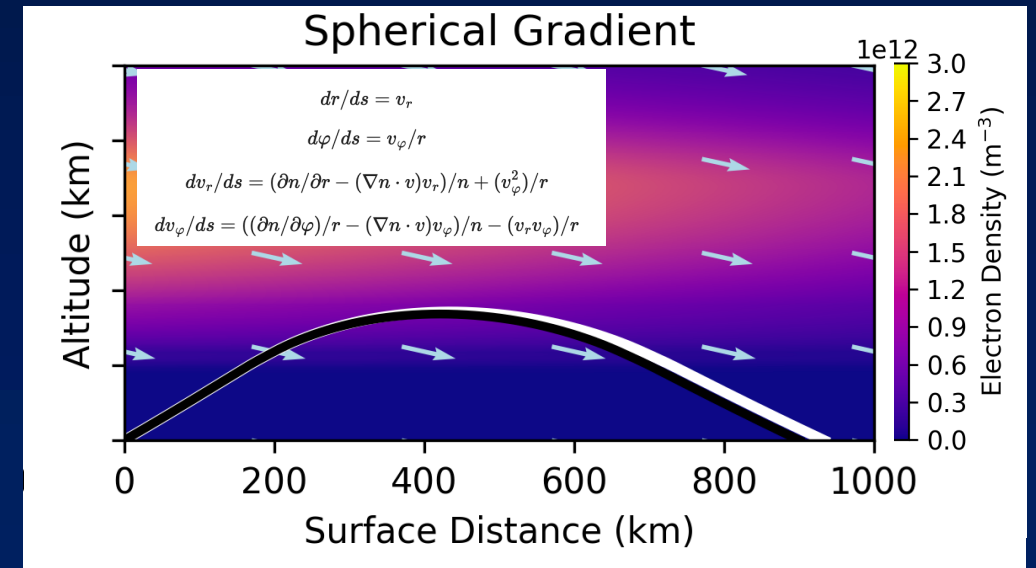
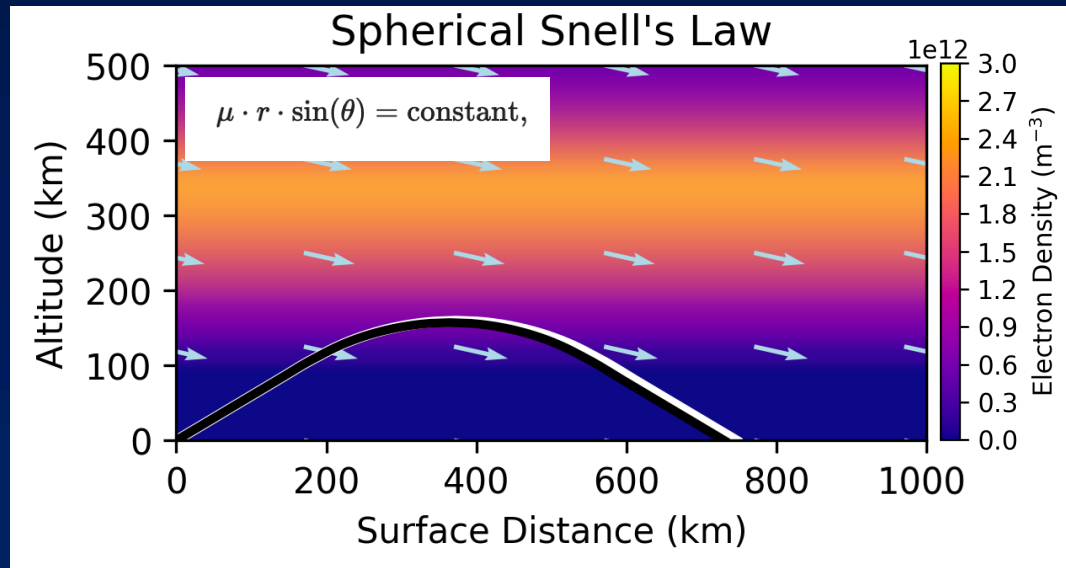
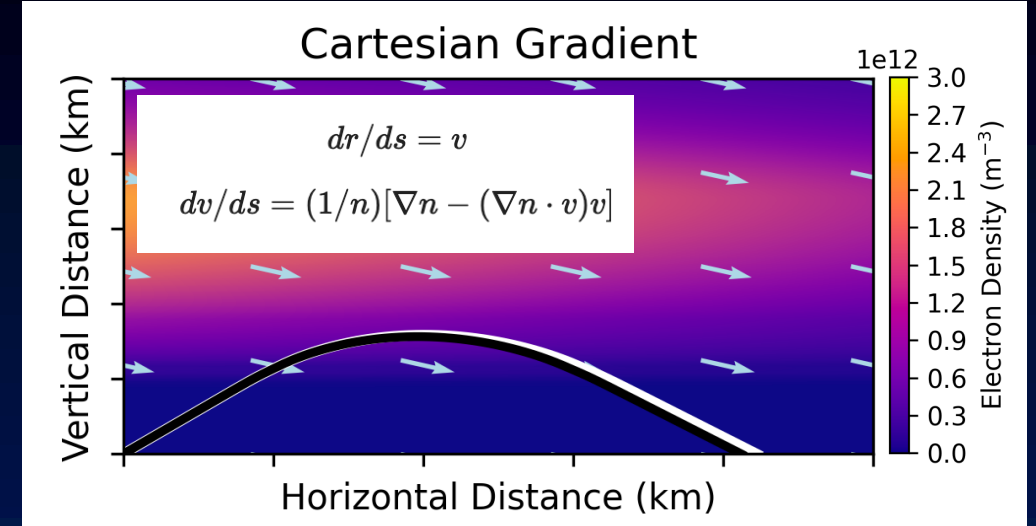
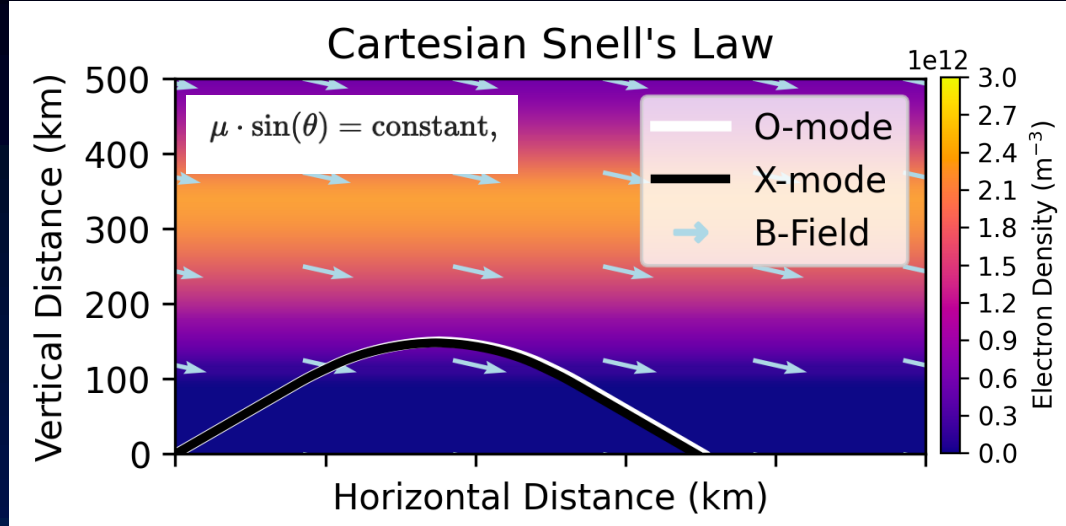
Step 2: Form 2D input matrices



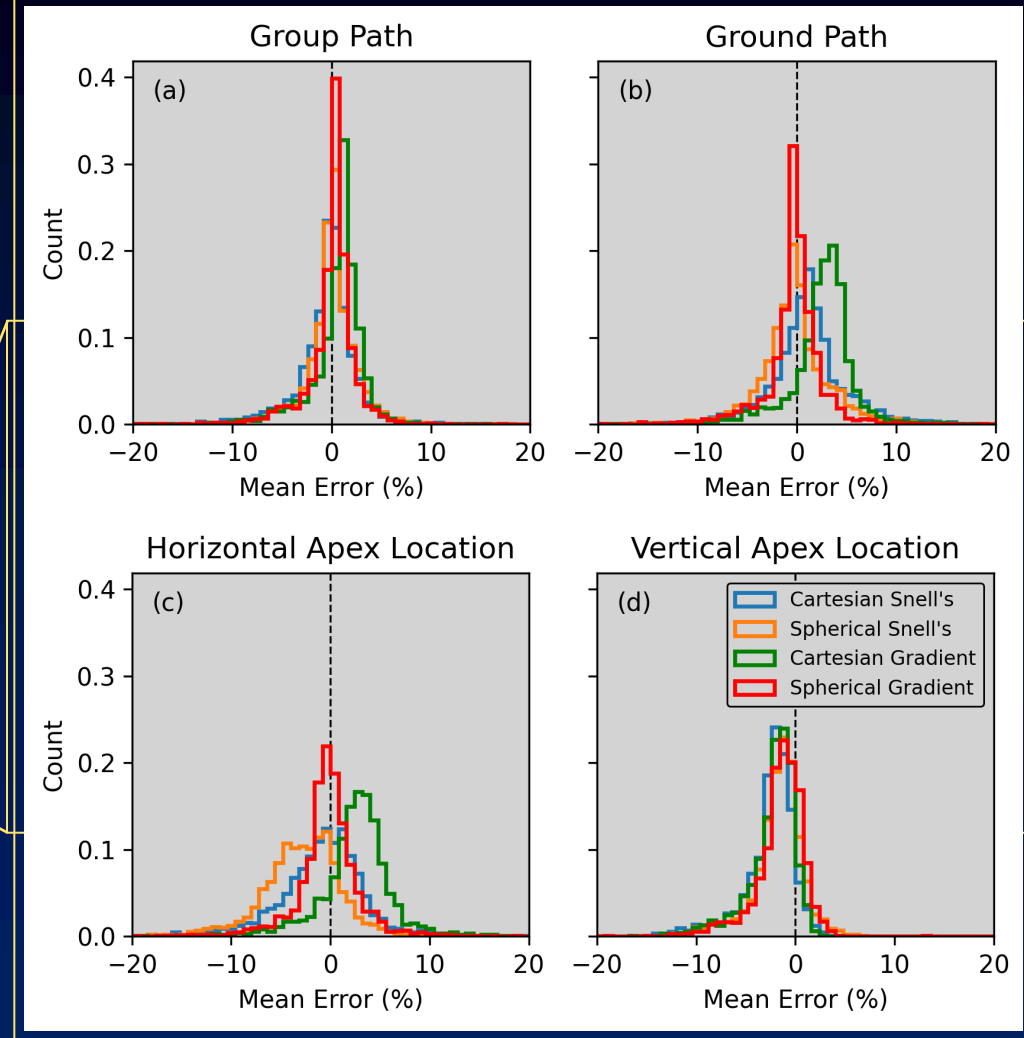
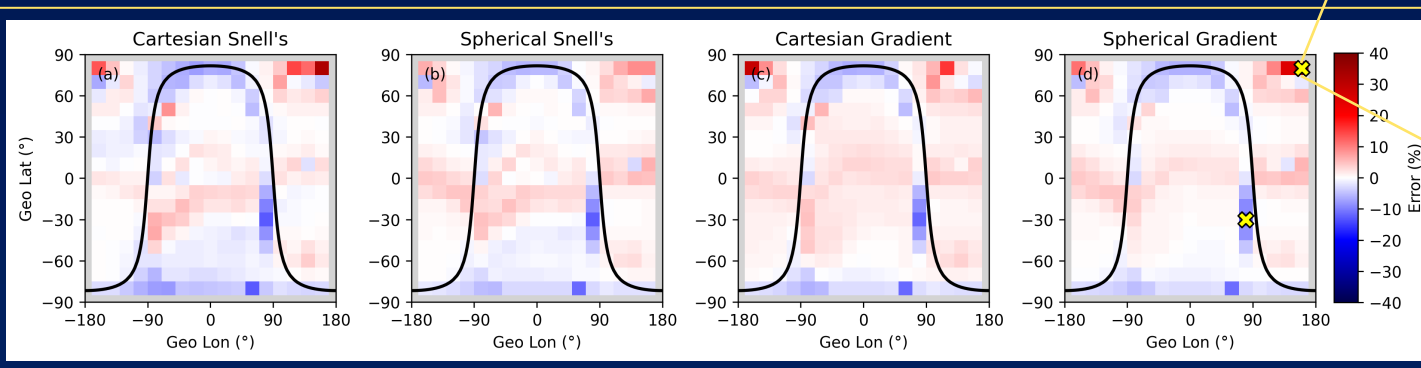
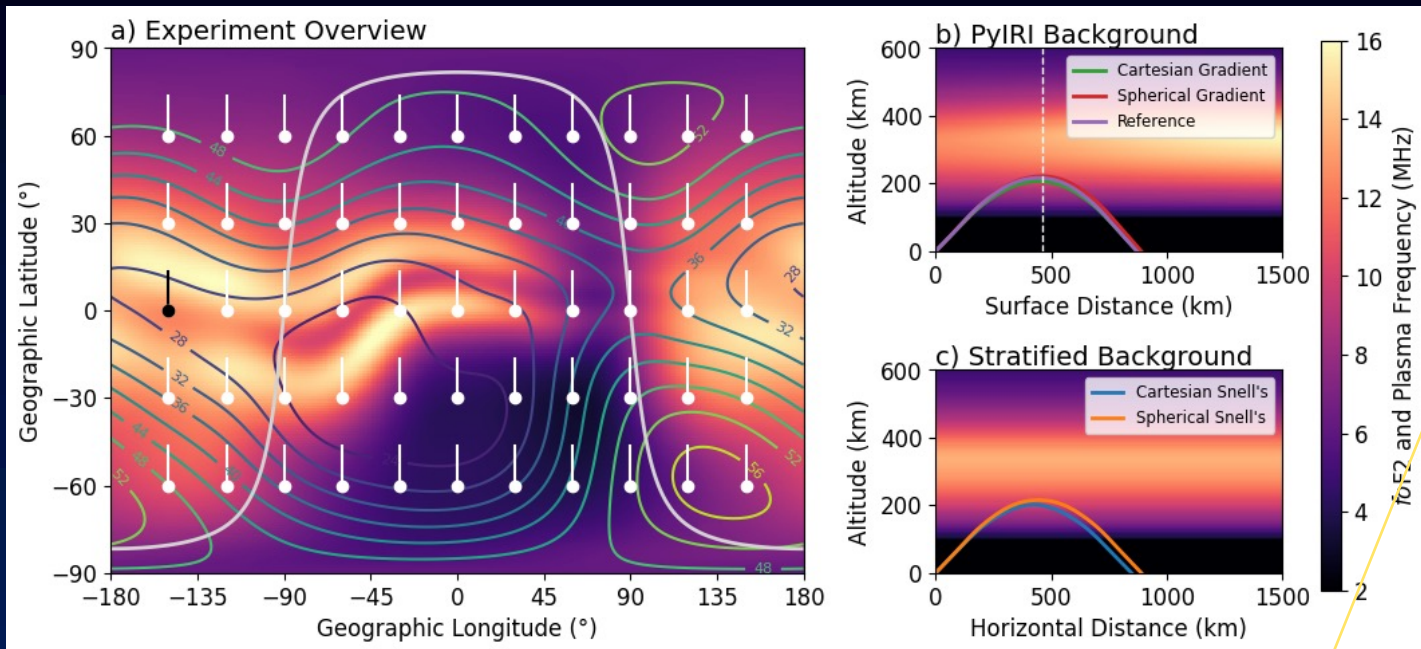
Step 3: Integration

$$h_v(f) = \int_0^{h_t} \mu'(h', f) dh',$$

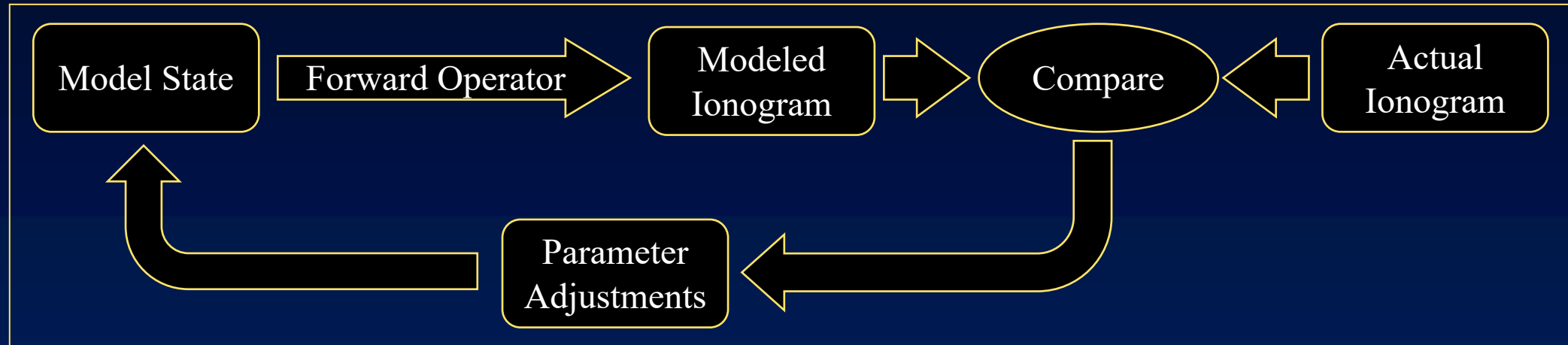
2D Ray-Tracing Forward Operators



Validation of 2D Ray Forward Operators



Goal: Extract ionosphere parameters (foF2, hmF2, etc.) from oblique ionograms using PyRayHF forward operators.



2D Forward Operators

$$N_{\text{tot}} = N_{\text{elev}} \times N_{\text{iter}} \times N_f.$$

$\sim 2 \times 10^4$ rays per
background state update

Forward Operator	t_{ray} (s)	T_{tot} (s)	T_{tot} (min)
Cartesian Snell's Law	1.78×10^{-3}	35.6	0.59
Spherical Snell's Law	2.41×10^{-3}	48.2	0.80
Cartesian Gradient	3.6×10^{-1}	3.6×10^4	600.0
Spherical Gradient	2.45	2.45×10^5	4083.0

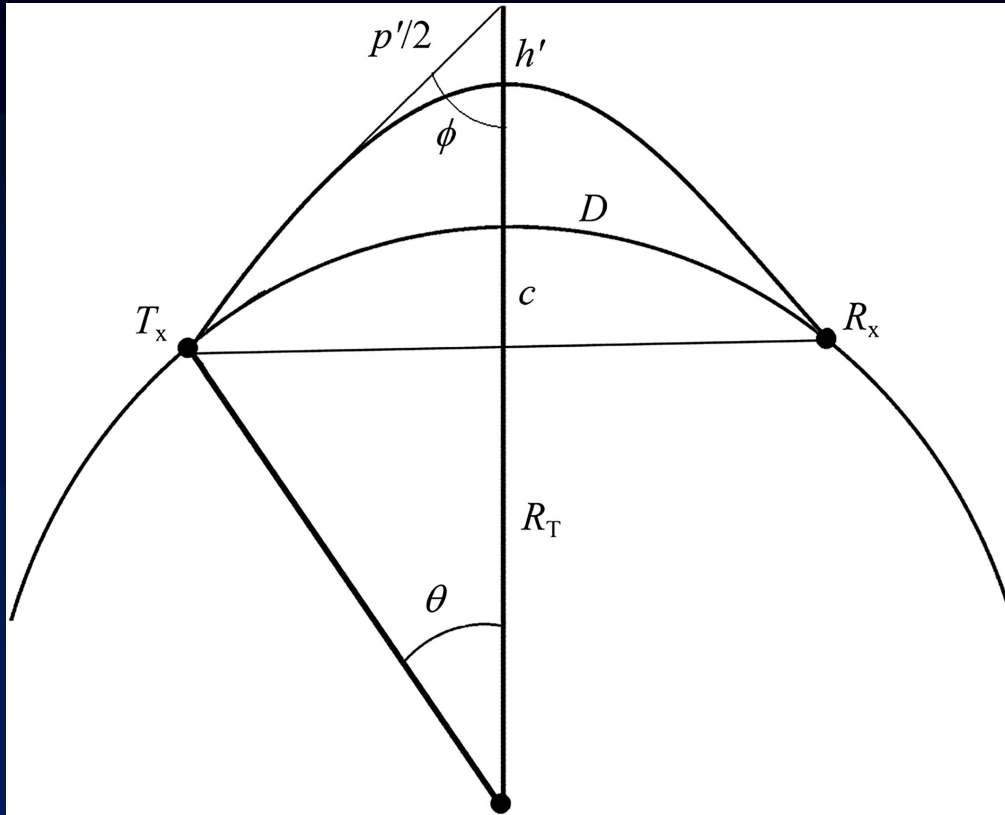
Vertical Forward Operator

$$N_{\text{tot}} = N_{\text{iter}} \times N_f.$$

$\sim 1 \times 10^3$ rays per
background state update

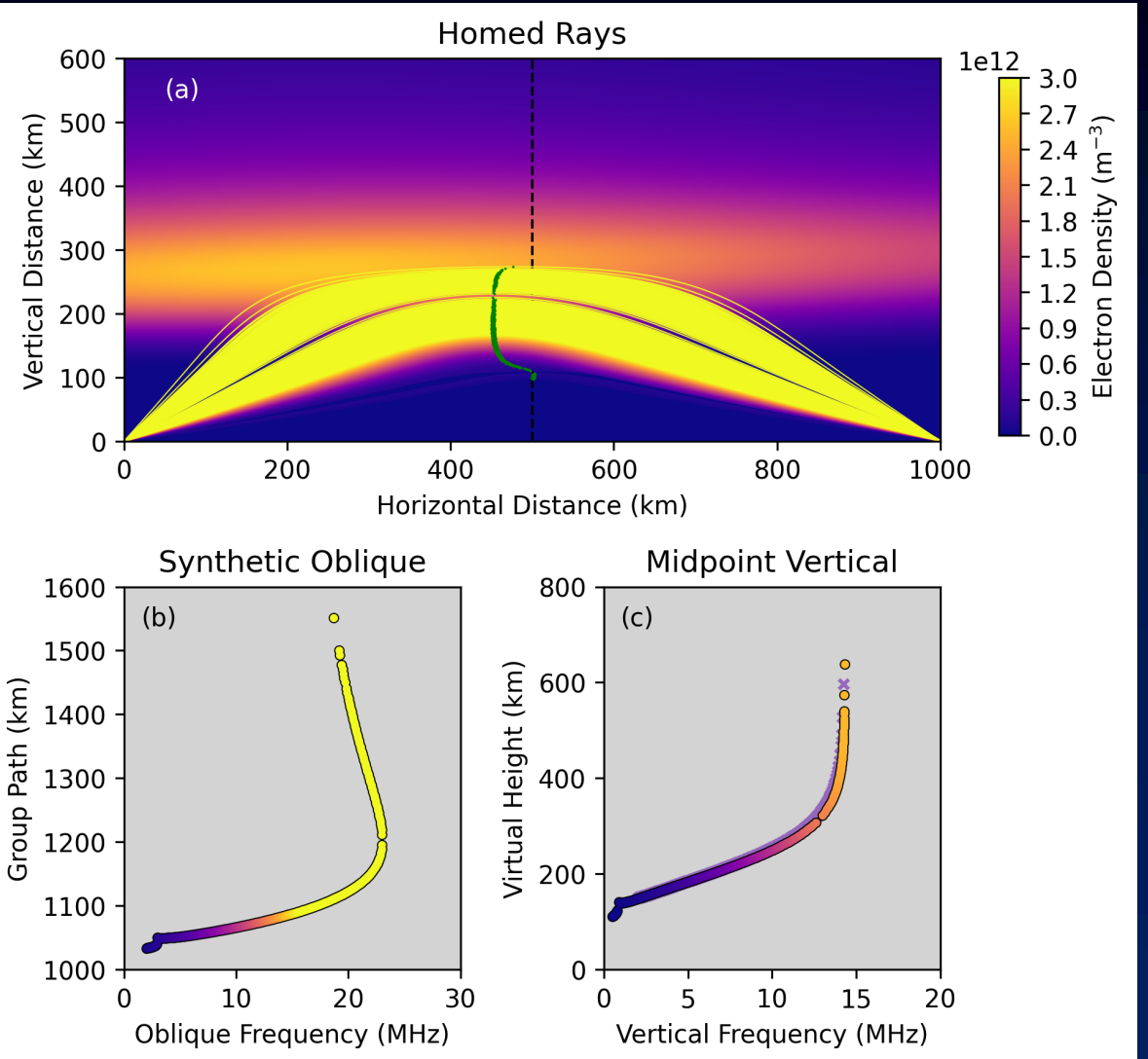
$$T_{\text{tot}} \sim 3.5 \text{ s}$$

Midpoint Approximation

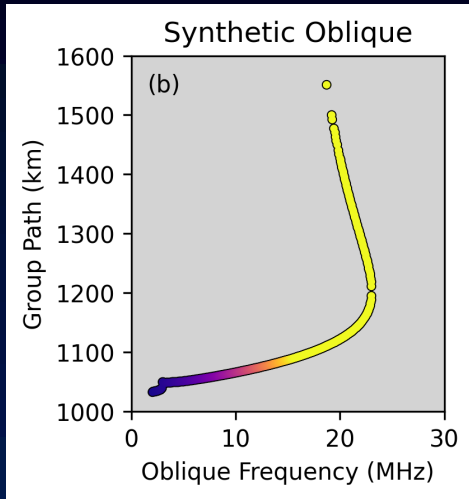


$$h_v = \frac{1}{2} p \cos \phi - \Delta h_{\text{curv}},$$

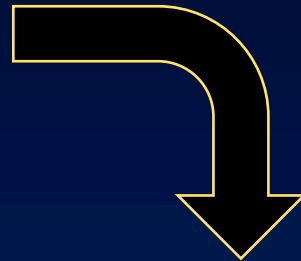
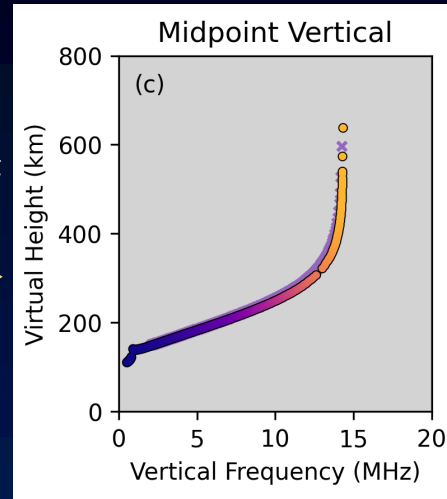
$$f_v = f \cos \phi.$$



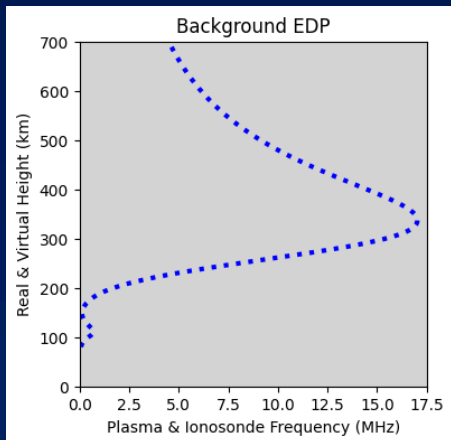
Input Oblique



Midpoint
Approx



Model Ionosphere

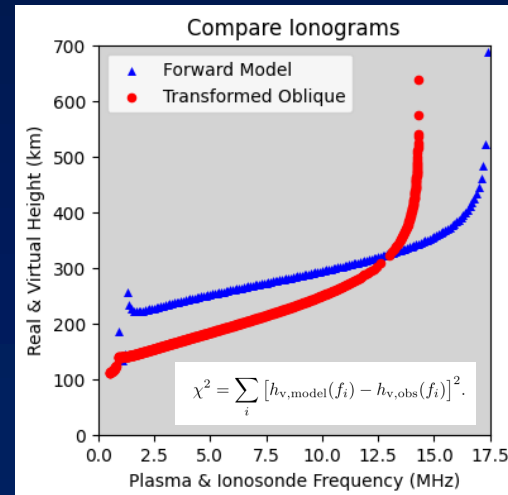


(Iterate)

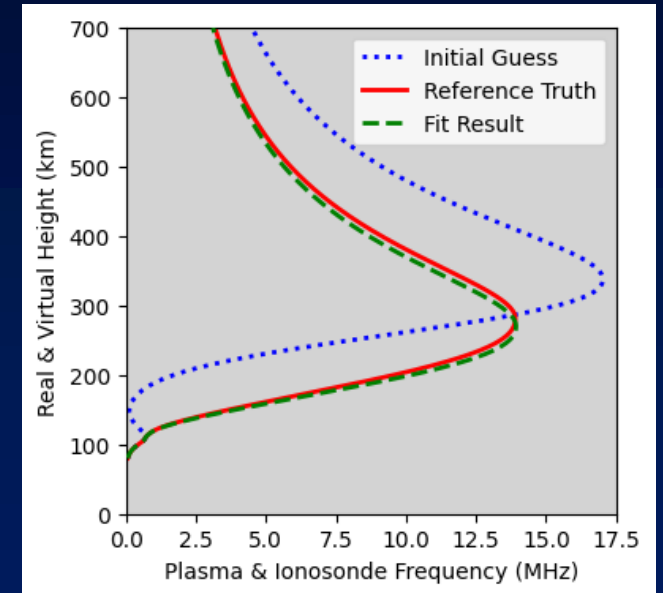
Forward Operator



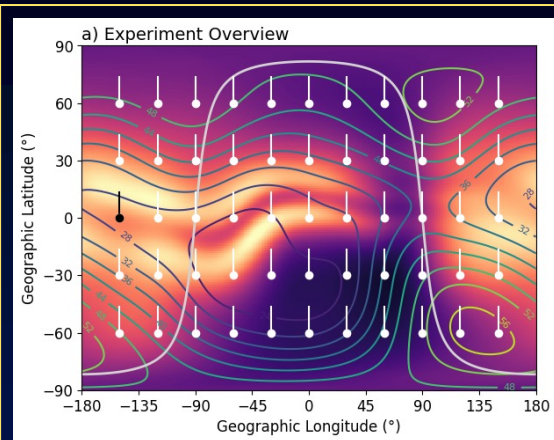
Update Ionosphere



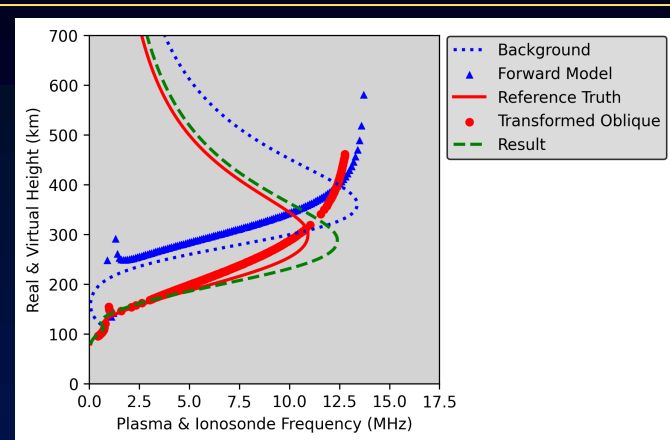
Final Output Ionosphere



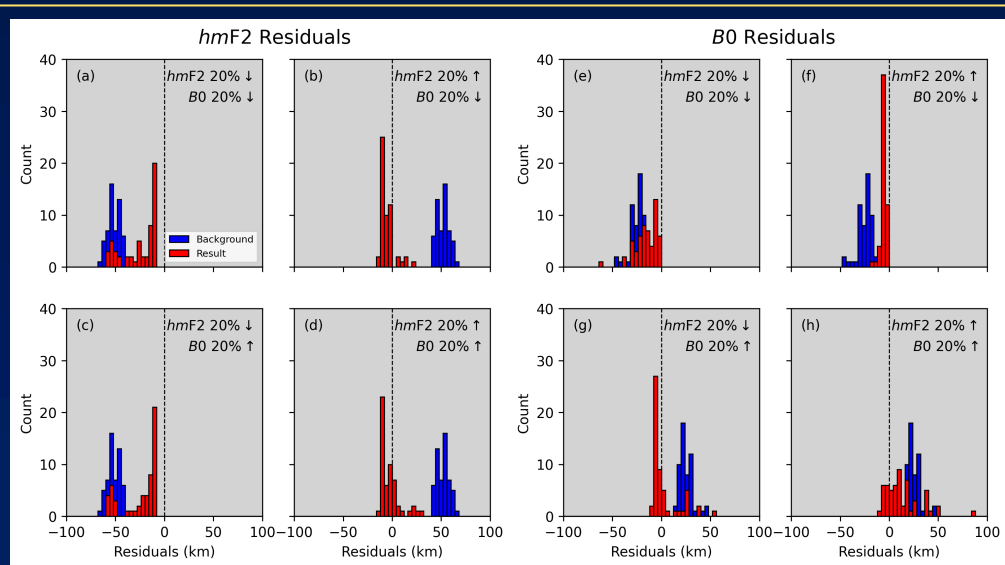
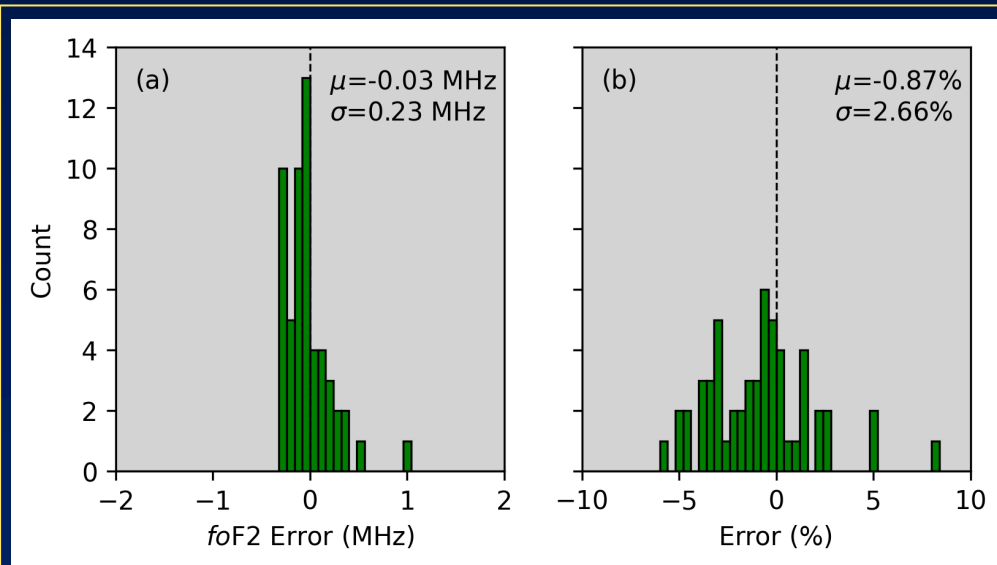
Global Simulated Obliques



Midpoint approximation
and parameter estimation



Resulting Error



```
pip install PyRayHF
```



<https://github.com/victoriyaforsthe/PyRayHF>

Forsythe, V. V., Valentine, H. C., Drob, D. P., Hughes, J., Hickey, D., Burrell, A. G., Zawdie, K. A., Joshi, D. R., Bristow, W., & Thomas, E. G. (2026). *Assimilating oblique ionograms in ANCHOR using PyRayHF: A fully open source forward operator for data assimilation*. Submitted to *Radio Science*, May 2026.