Topside Ionospheric Reconstruction from LEO Slant TEC Using Smooth Profile Parameterizations

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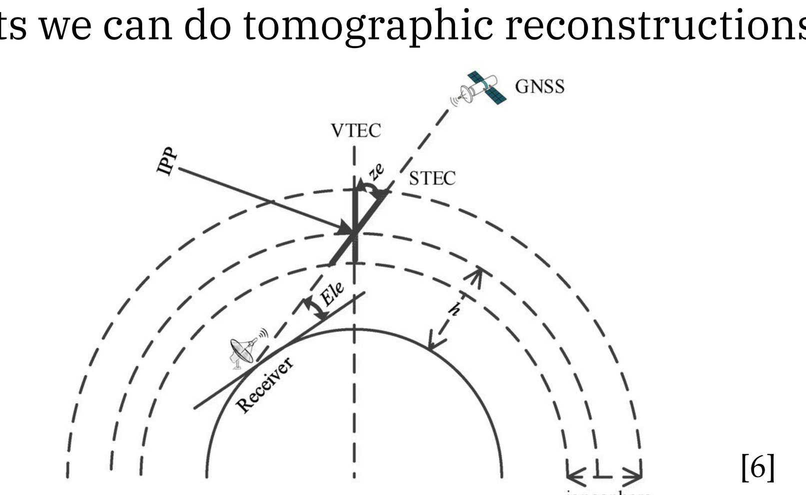
Abstract

Many ionospheric electron density reconstructions rely on spherical symmetry, which suppresses horizontal structure, and voxel-based inversions can introduce too many unknowns to constrain reliably. This work extends earlier studies of **profile parameterizations and slant TEC reconstruction to topside ionospheric tomography** using low-Earth-orbit satellite TEC data. Electron density is modeled with physically interpretable vertical profile families whose parameters vary smoothly along the satellite orbit. Over short orbital windows, the track is treated as a disk-like domain, allowing the parameter fields to be described with periodic angular and smooth radial structure. This approach reduces the number of unknowns while relaxing spherical symmetry. We compare several profile families motivated by prior midlatitude and topside studies and evaluate the method during quiet and disturbed conditions using independent measurements when available.

Introduction

TEC is often measured using a ground-based GNSS receivers and LEO satellites relationship, in which the slant TEC can be measured by integrating along the LOS between a specific receiver and satellite. These measurements describe the variation in the plasma within the ionosphere over a span of time. Using these measurements we can do tomographic reconstructions.

$$\mathrm{TEC} = \int_P n_e \, d\boldsymbol{l}$$



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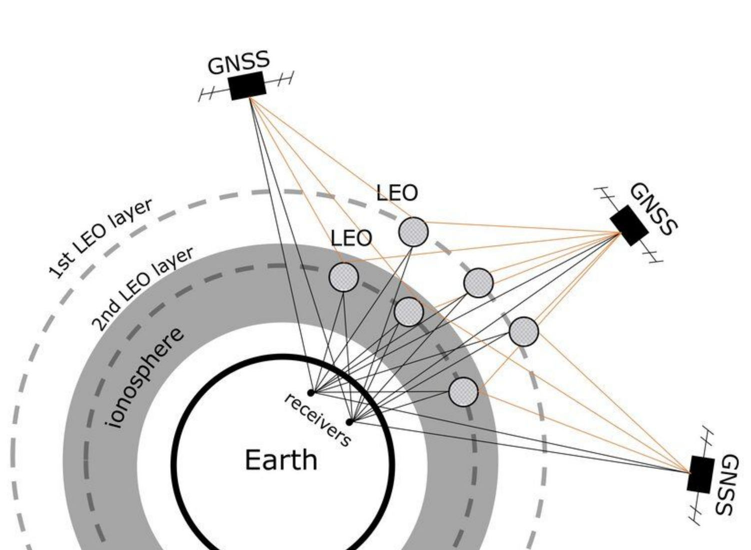
This work uses a parameterized tomographic approach to reconstruct topside ionospheric electron density using data from the Spire constellation of LEO satellites, which collects LEO-to-GNSS s-TEC observations. Topside ionospheric reconstructions are done by fitting physically meaningful profile parameters over multiple orbital windows.



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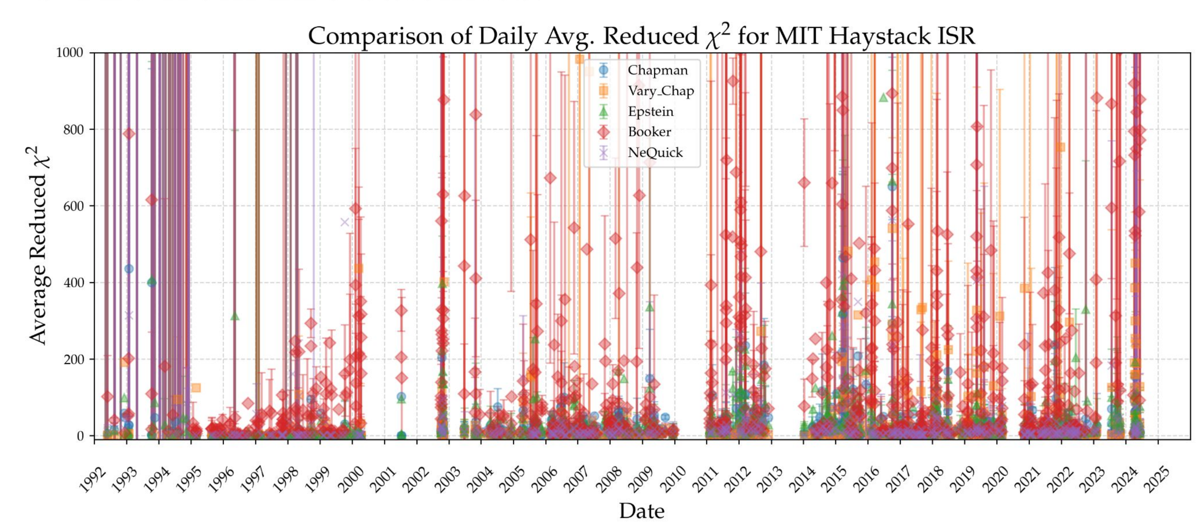
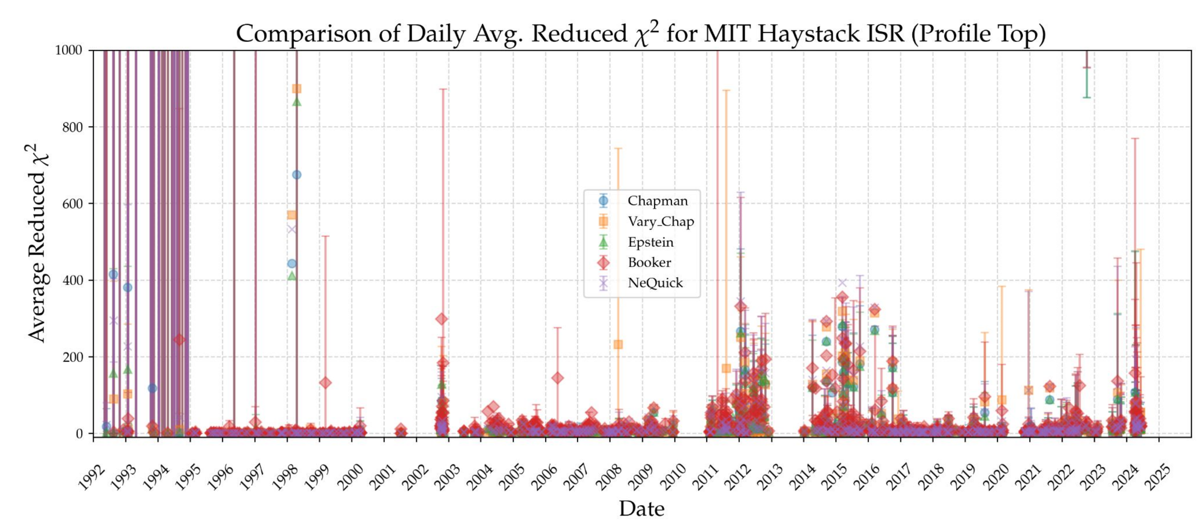
Parameterizations

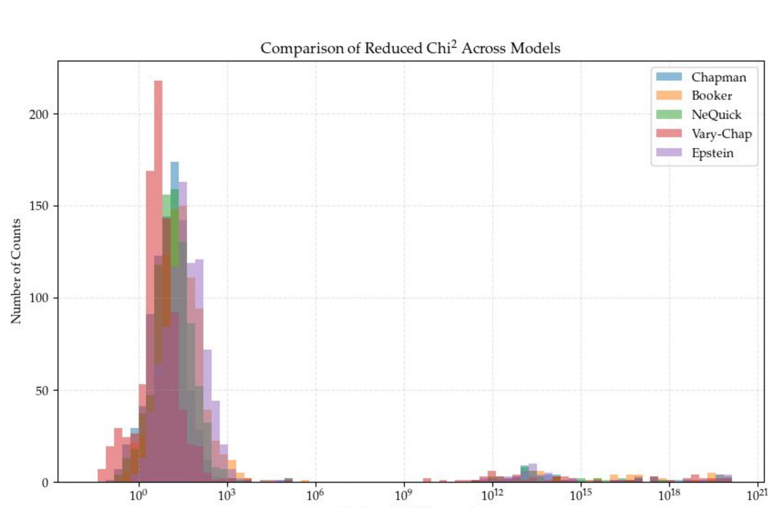
We compared five specific models of ionospheric parameterizations: Chapman[2], Booker[1], NeQuick[5], Vary-Chap[4], and Epstein. We tested the models using Millstone Hill Incoherent Scatter Radar (ISR) data from 1992 - 2024. Comparisons were made using statistical variables recorded during the fitting process using reduced Chi-squared (χ^2), representing the goodness-of-fit of a model to the observed data.

$$N_e(h) = N_m F_2 \exp[0.5(1 - z - e^{-z})] \qquad H(h) = \begin{cases} A_b(h - h_m) + H_m, & \text{if } h < h_m \\ A_t(h - h_m) + H_m, & \text{if } h \geq h_m \end{cases}$$

Initial testing showed Vary-Chap had the best performance across regional testing, making a model candidate to be used for topside reconstructions using s-TEC from LEO satellites.



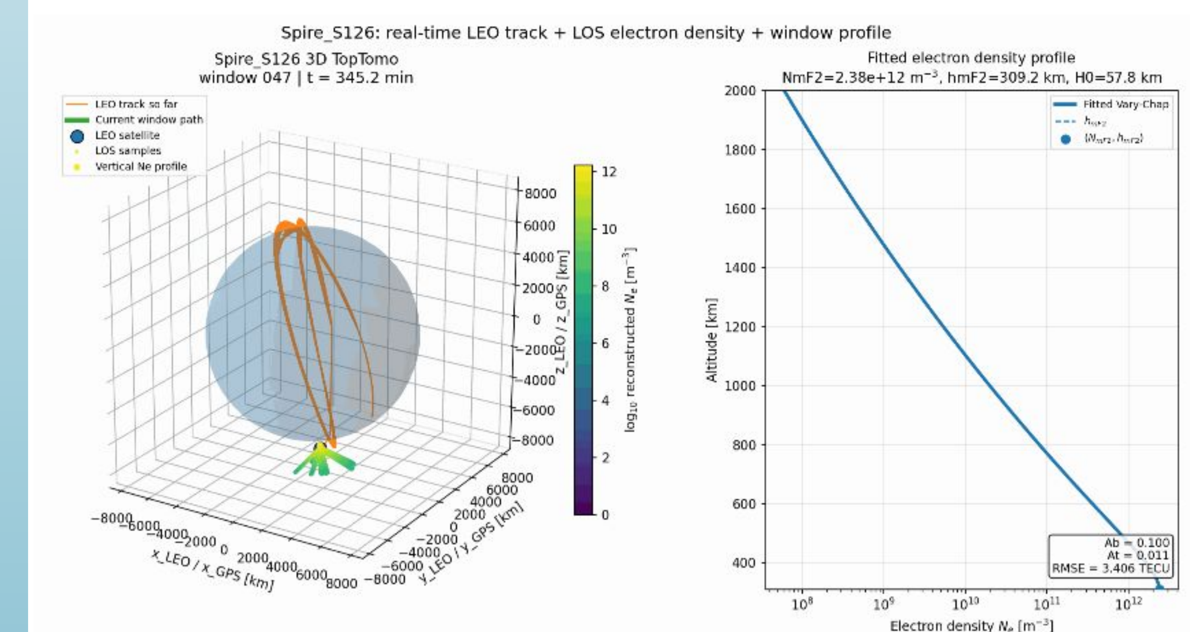


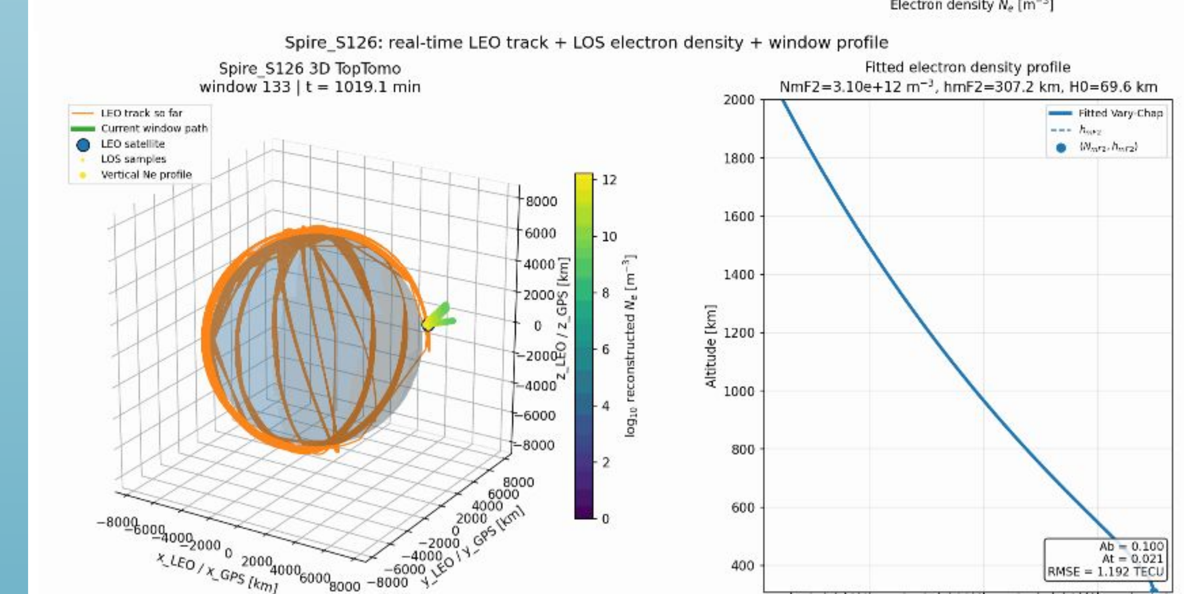


Results

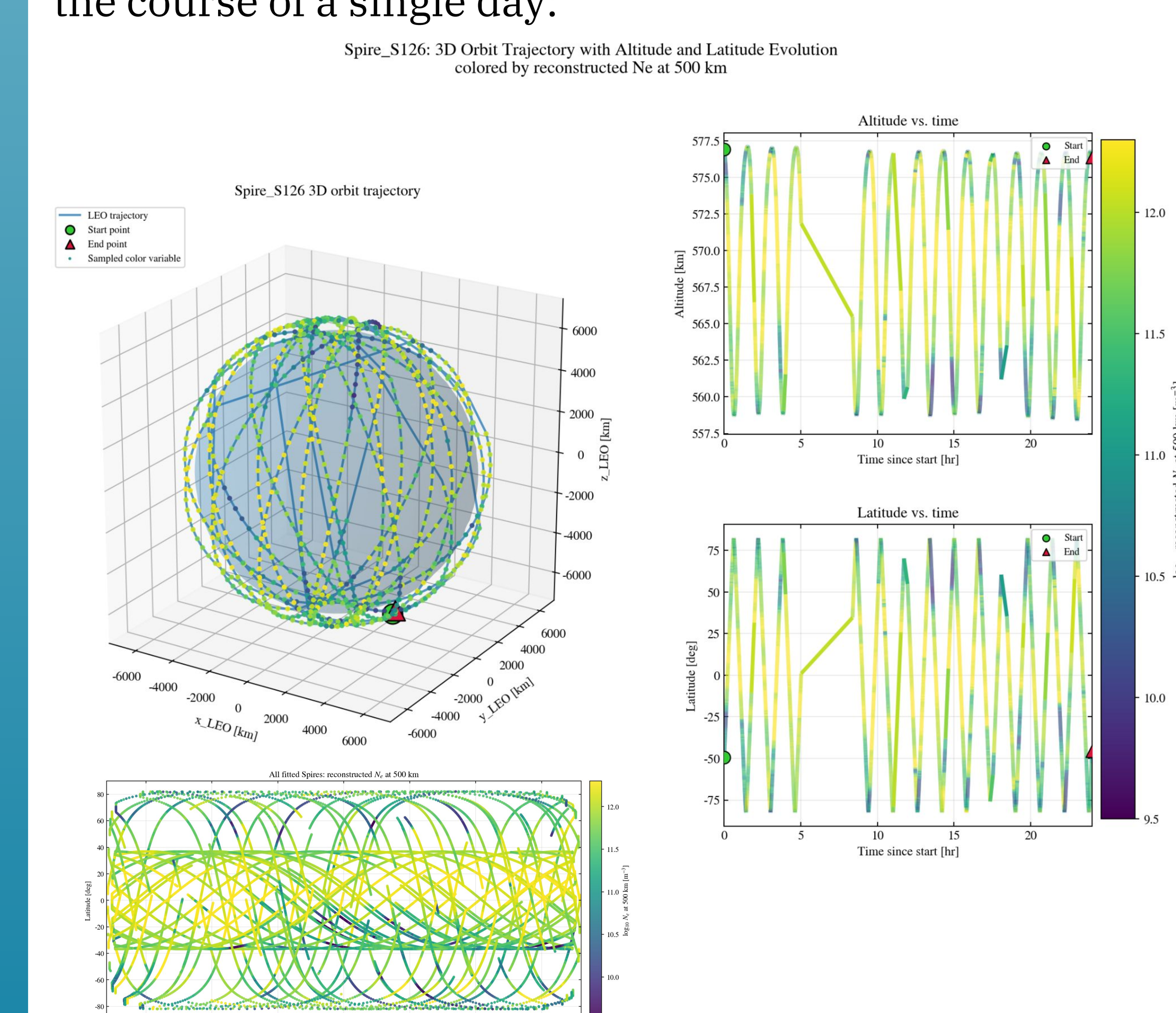
Preliminary fits demonstrate that the parameterized Vary-Chap model can reproduce vertical structures within the topside of the electron density profile while using a multiple consecutive LEO orbital windows. Using sliding windows localizes the reconstruction area, making the capture of local electron density changes easier.

This method is especially useful for identifying storm-driven effects, particularly geomagnetic storms. Spire LEO satellites provide sTEC measurements allow storm-time changes to be sampled across multiple regions. We focused on looking at the storm that occured on August 11th & 12th 2024.

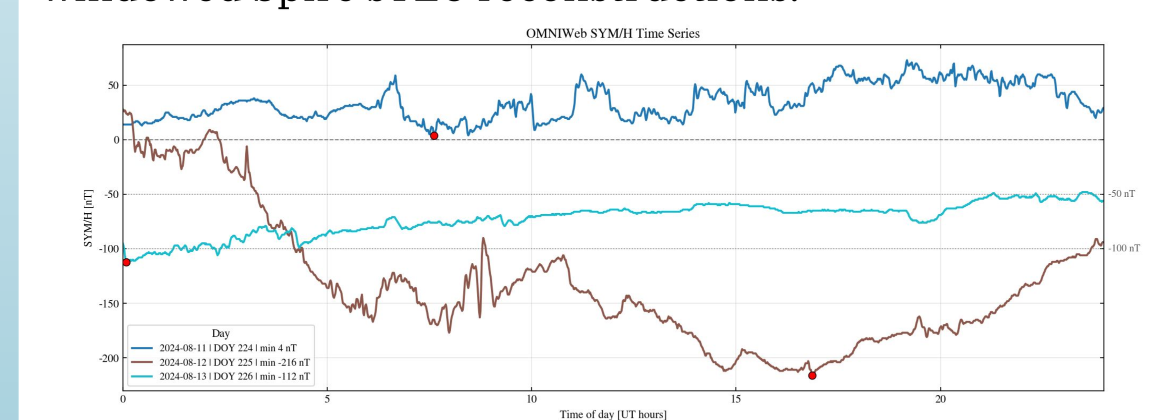




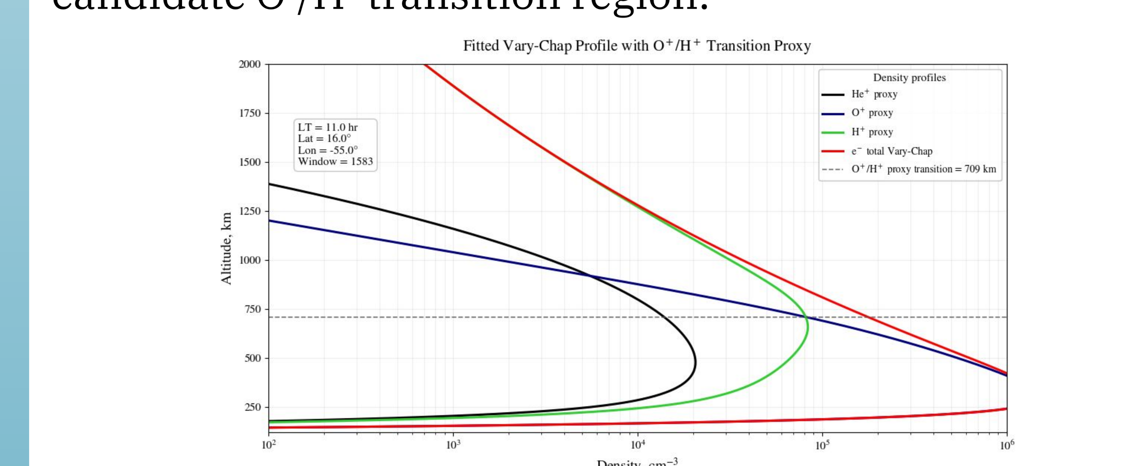
For each fitted time window, s-TEC measurements are used to reconstruct the topside electron density profile and track how reconstructions vary along the orbital path. This method allows changes in the fitted density structure as the satellite moves through different regions. This is an example of what one Spire satellite sees over the course of a single day:



SYM/H data from NASA OMNIWeb was used to identify the timing and intensity of the geomagnetic storm. This time series can be compared with the results from the windowed Spire sTEC reconstructions.



The piecewise Vary-Chap scale-height function allows the topside scale height to change, this behavior was then used to make some preliminary results of estimating a candidate O⁺/H⁺ transition region.



Conclusion

This project focuses on using the **Vary-Chap parameterization method to create reconstructions using Spire LEO sTEC observations for topside electron density.** This method could be ideal for capturing **changes in density during geomagnetic storms**, which disrupt the neutral ionosphere. SYM/H data was used to identify geomagnetic storm intervals and relate storm intensity to changes in the reconstructed profiles. These results may help reveal storm-driven restructuring of the topside ionosphere and possible variability near the O⁺/H⁺ transition region.

Acknowledgements

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