Revisiting Ionospheric Tomography Across Scales: Nonlinear Fitting with Electron Density Profiles and Gravity Wave Signatures

M. McKean [1, 2] , E. Rojas [1]

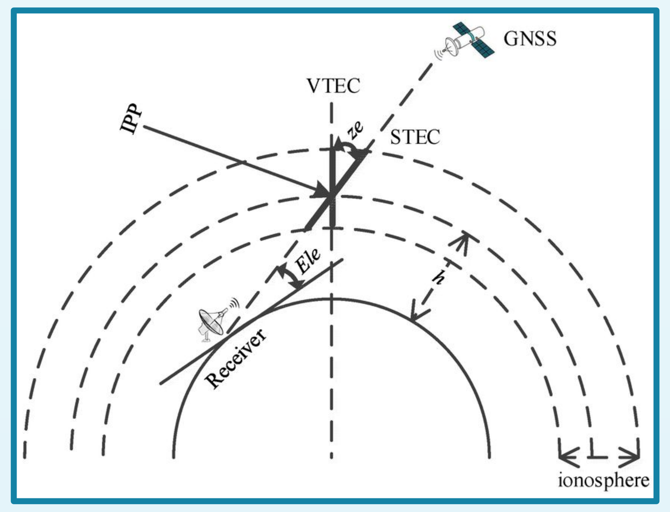
1. MIT Haystack Observatory, 2. Embry-Riddle Aeronautical University

Abstract

Measurements of total electron content (TEC) that are taken by ground-based receivers can provide insights into the structure and behavior of the ionosphere. In this work we present a framework for **reconstructing ionospheric electron density distributions along with traveling ionospheric disturbances (TID) associated with gravity waves**, by using slant TEC observations from ground receivers. We **compare various vertical parameterizations** by using a non-linear least squares minimization algorithm for the electron density profiles. We applied the fitting methods to try and recover gravity wave parameters and reconstruct the characteristics of the TID assuming a background electron density with no horizontal variation. **Initial tests were performed in a 3D** capacity to attempt to use the fitter to estimate electron density parameters using slant TEC measurements along multiple lines of sight (LOS).

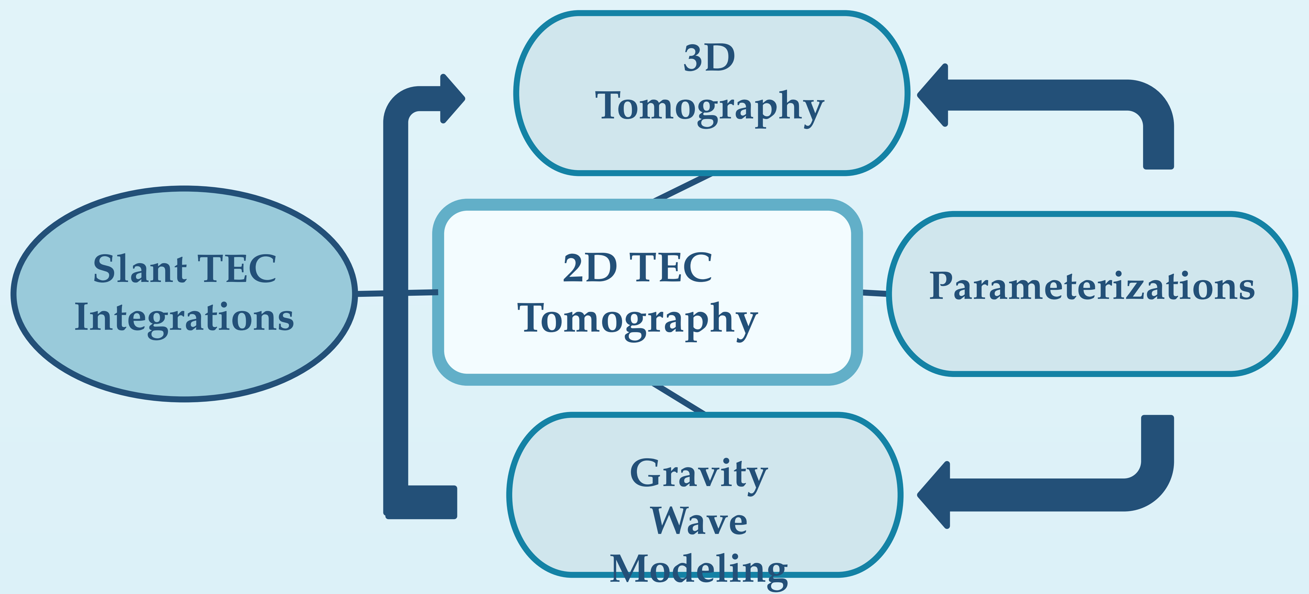
Introduction

TEC is often measured using a ground-based GNSS (Global Navigation Satellite System) receivers and low Earth orbit (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. This is beneficial for ionospheric tomography.



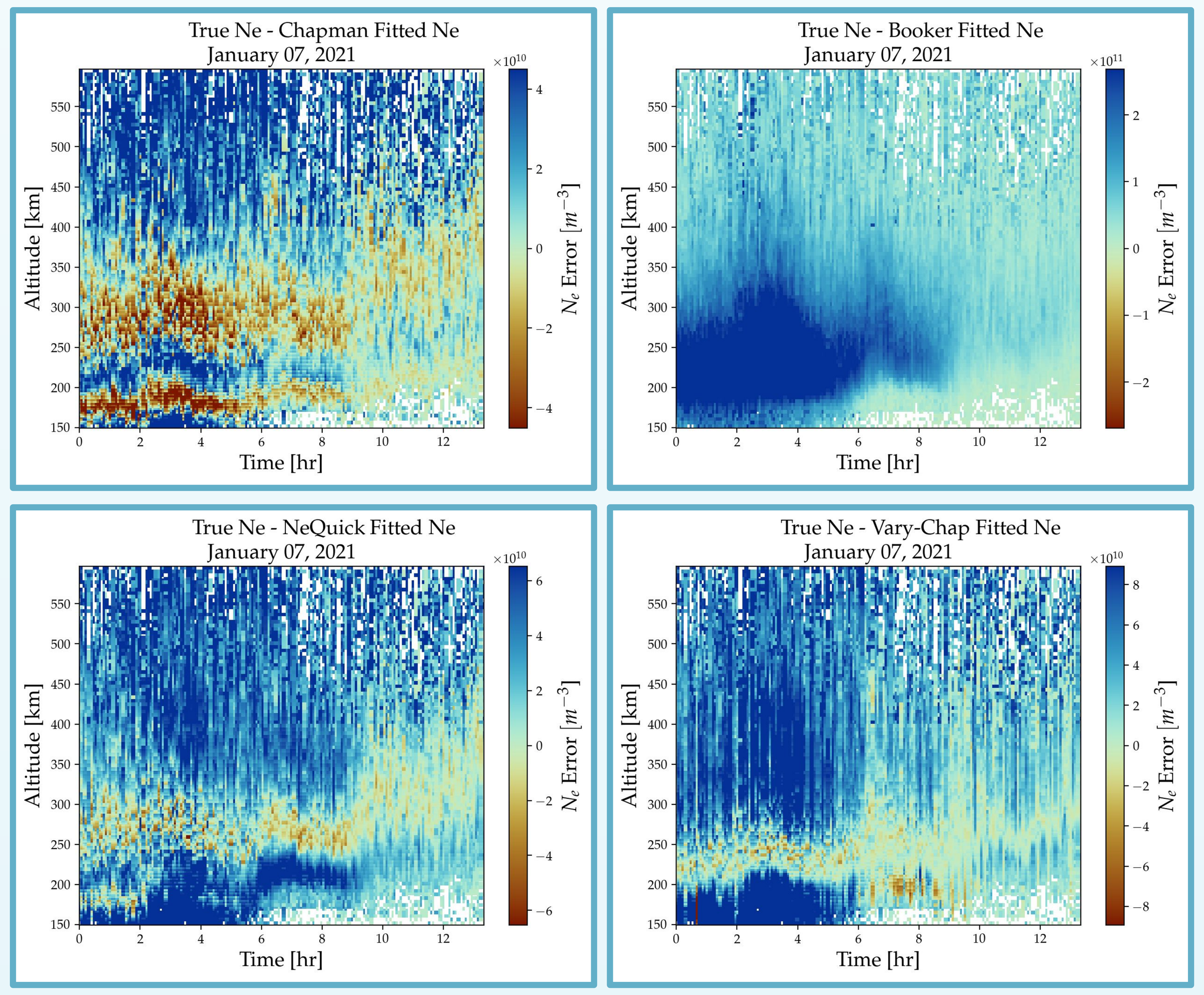
[4]

This work explores **three different types of ionospheric tomography**, each having a relation to another. Focusing on improving a specific part, improves the tomographic model as a whole providing more accurate results .

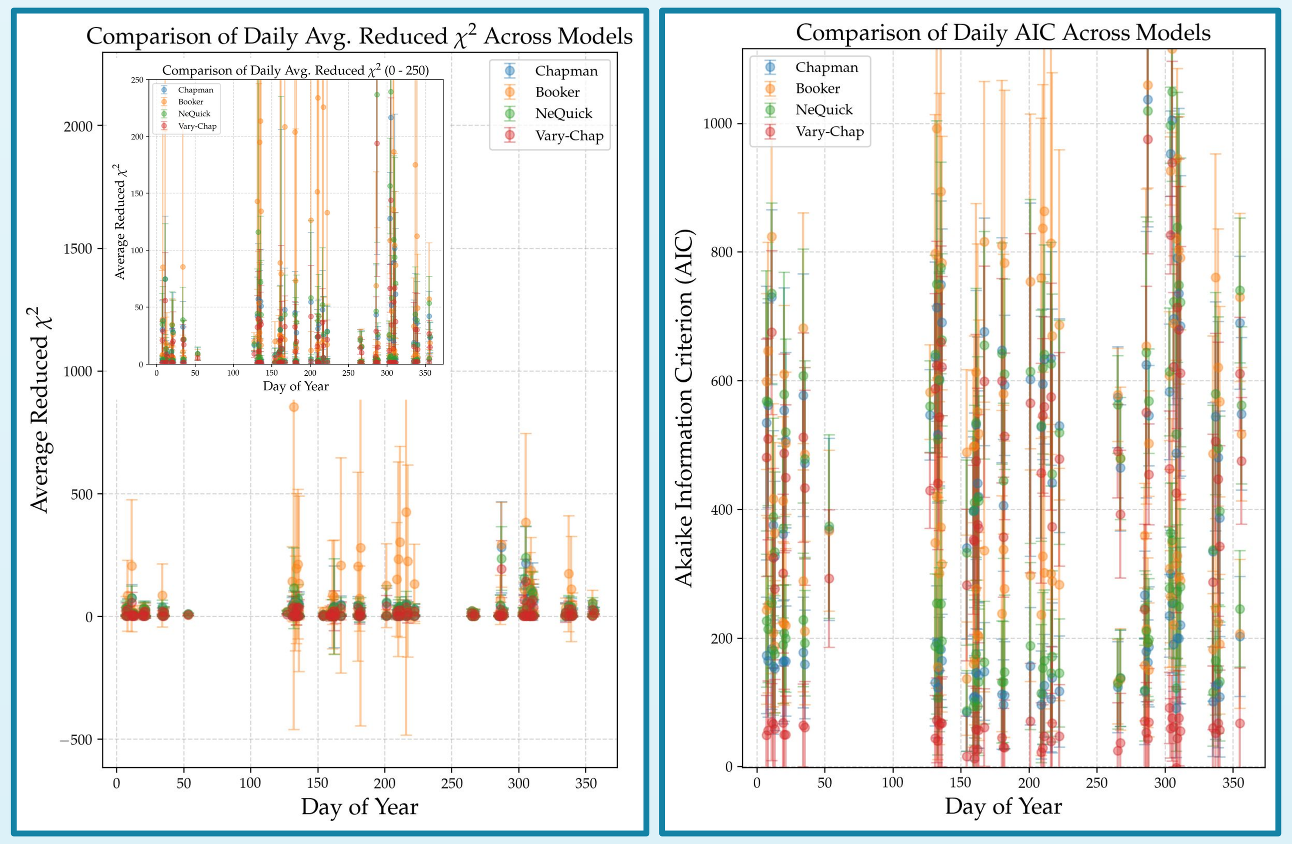


Parameterizations

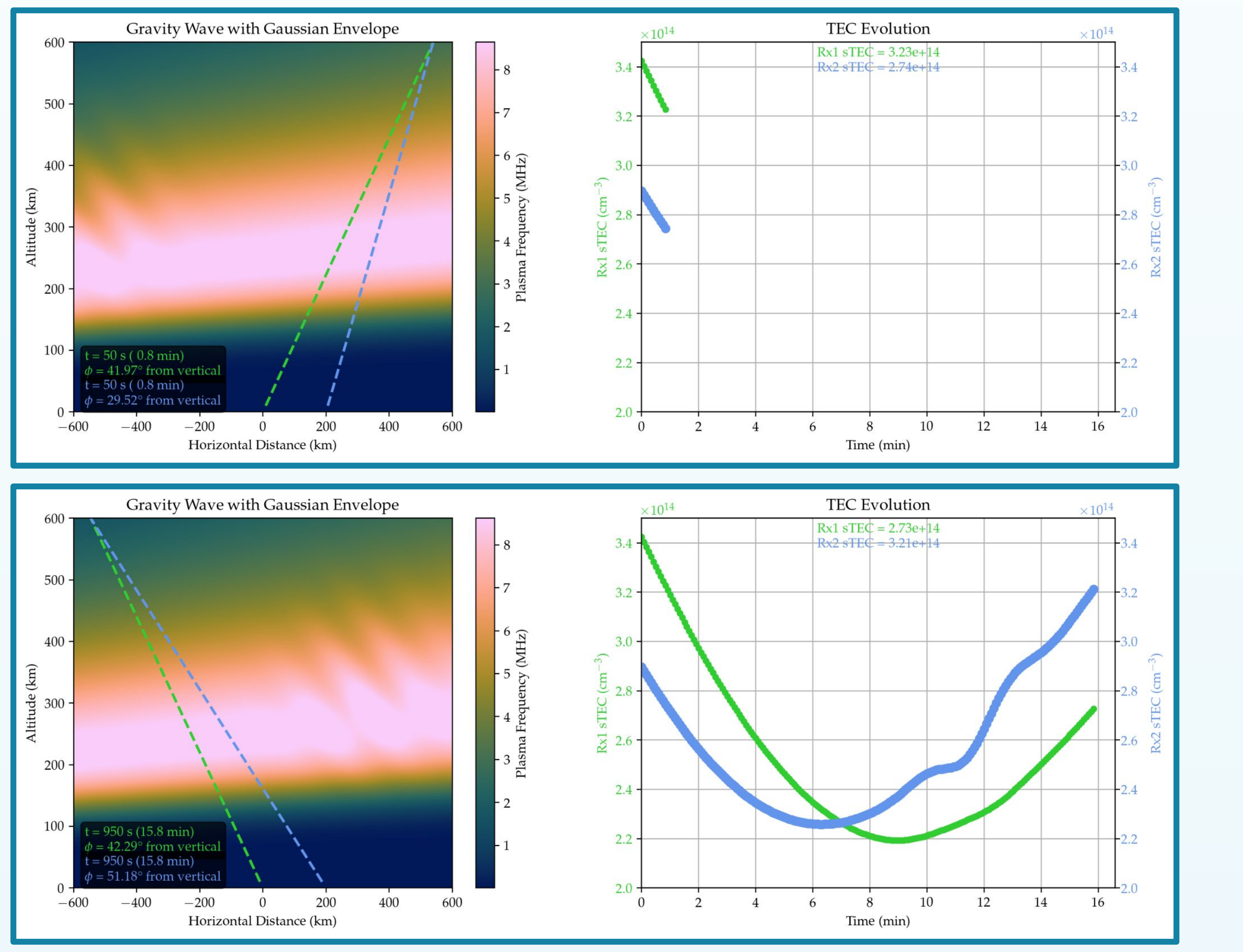
Most analysis reported in literature treat the different methods for ionospheric parameterizations in isolation, here we aim to compare four specific models: Chapman, Booker[1], NeQuick[2], and Vary-Chap[3] directly by using a year's (2021) worth of Millstone Hill Incoherent Scatter Radar (ISR) data. The fitting results from each model were then compared by taking differences between the electron density given by the data for the result of the fitted density, for a given day.

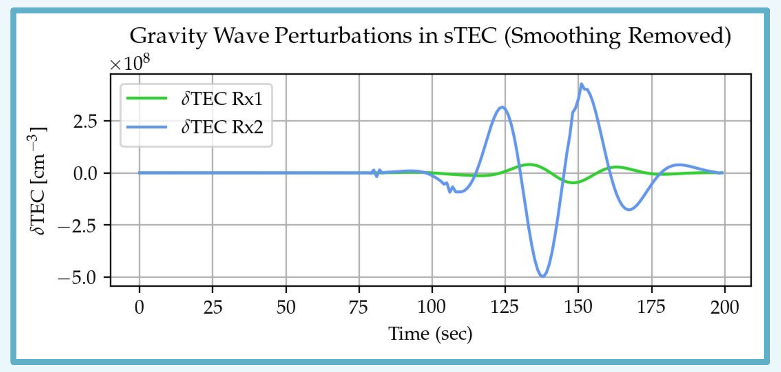


Statistical outputs from each model were considered during the fitting process. These statistical variables give a greater insight into the results of the model and the success of the fitter. Chi squared represents the significance in the difference between the observed and expected data, the Akaike Information Criterion (AIC) value is the economic computation of the model, and the standard deviation for both of these results was also considered.

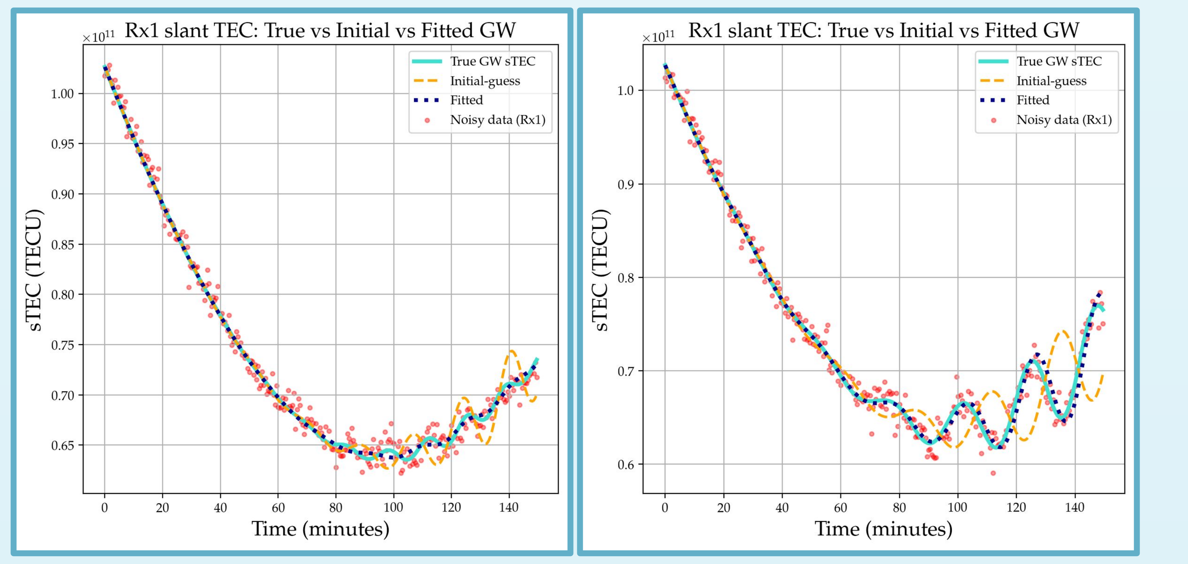


Reconstructing Gravity Waves





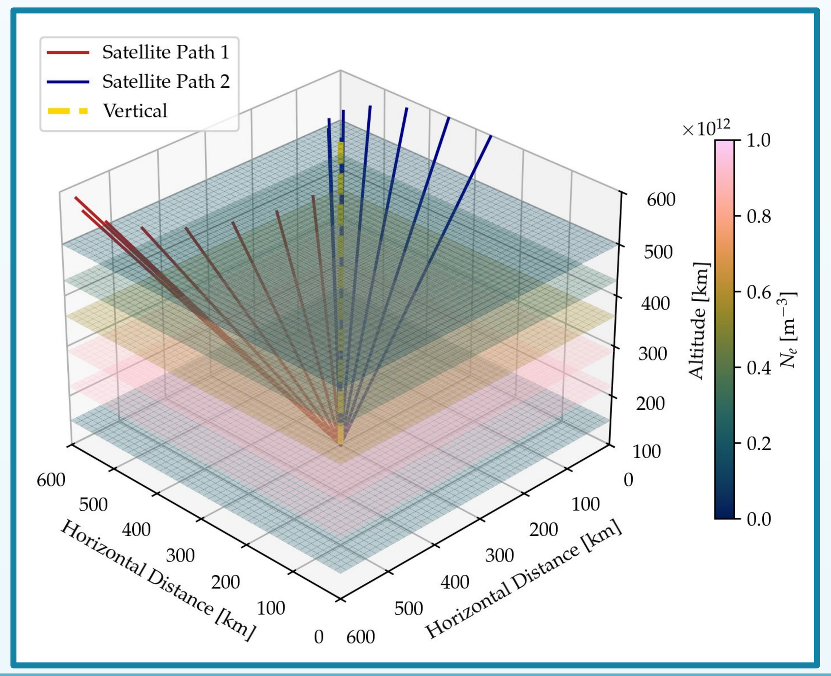
Gravity wave perturbations in the ionosphere are often caused by changes in the energy, temperature, and air patterns in the atmosphere, these perturbations can manifest as fluctuations in the TEC. Characteristics and the appearance of the gravity wave is often undetermined and hidden behind the background electron density. For this project we used simulated gravity waves for reconstruction, and limited the number of receivers needed by assuming the wave could be parameterized. Gravity waves were passed over a electron density background using a gaussian envelope. The slant TEC was measured while the LOS changed as the simulated satellite moved across the sky.

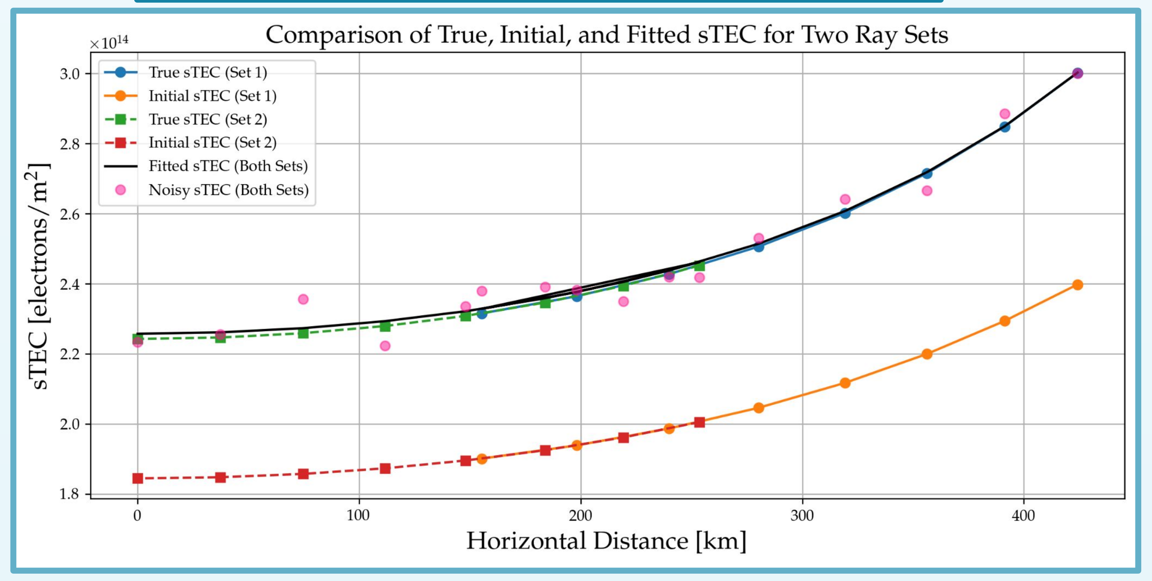


Using only a single receiver in this simulation, we were able to use the fitter to determining the estimated gravity wave parameters using the sTEC measurements gathered at each time frame during the simulation.

3D Reconstructions

Using sTEC values to recreate ionospheric tomographic surfaces is useful for 3D reconstructions, here the electron density parameters were recovered using the slant TEC that was measured along each set of rays. Each set was used to represent the path of a satellite as it moved past the receiver, at the origin.





Conclusion

The **Vary-Chap parameterization had the most favorable** results in terms of chi squared and AIC results. **Gravity wave parameters were recoverable using a single receiver** and a stable electron density. Parameters of the electron density where able to be **estimated using two sets of sTEC data from multiple sources in 3D**. Future applications of these preliminary results include using potential hybrid TEC datasets for volumetric reconstructions and to resolve fine-scale ionospheric structures.

Acknowledgements

This projects was funded by NSF Award 2243909.
Special thanks to A. Coster and K. Carigila (MIT Haystack), and REU students A. Abubakar and P. Kolla.

References

[1] Booker, H. G. (1977). Fitting of multi-region ionospheric profiles of electron density by a single analytic function of height. *Journal of Atmospheric and Terrestrial Physics*, *39*(5), 619–623.

[2] Lei, J. (2004). A statistical study of ionospheric profile parameters derived from Millstone Hill incoherent scatter radar measurements. *Geophysical Research Letters*, *31*(14).

[3] Nava, B., Coïsson, P., & Radicella, S. M. (2008). A new version of the NeQuick ionosphere electron density model. *Journal of Atmospheric and Solar-Terrestrial Physics*, *70*(15), 1856–1862.

[4] Wang, H.-N., Zhu, Q.-L., Dong, X., Ou, M., Zhi, Y.-F., Xu, B., & Zhou, C. (2025). A Regional Ionospheric TEC Map Assimilation Method Considering Temporal Scale During Geomagnetic Storms. *Remote Sensing*, *17*(6), 951–951. https://doi.org/10.3390/rs17060951