Evaluation of TEC from PFISR
Validation with Observation and Models Data

Atheer, Allison, Brian, Daniel, David, Prakash

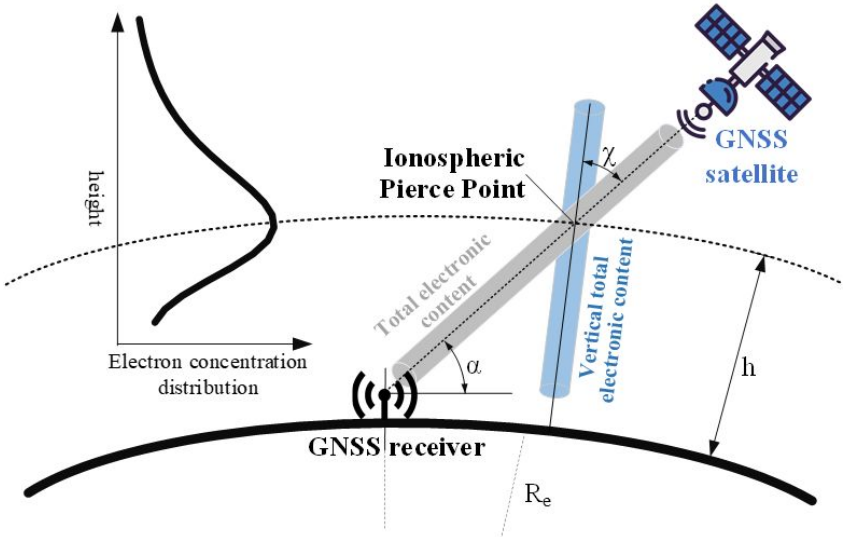
Outline

- Introduction
  - Total electron content (TEC) significance and calculation
  - Experimental setup and methods
- Data
  - PFISR Data
  - Models: TIEGCM, CTIPe
  - Instruments: GNSS receivers, ionosonde
- Analysis
  - Savitzky-Golay Filter
  - TEC estimate
  - Data Comparison

TEC Calculated from Electron Density

Estimated by integrating the electron density within a column of unit area between a receiver and transmitter, such as a GPS receiver and GPS satellite. Credit: NOAA

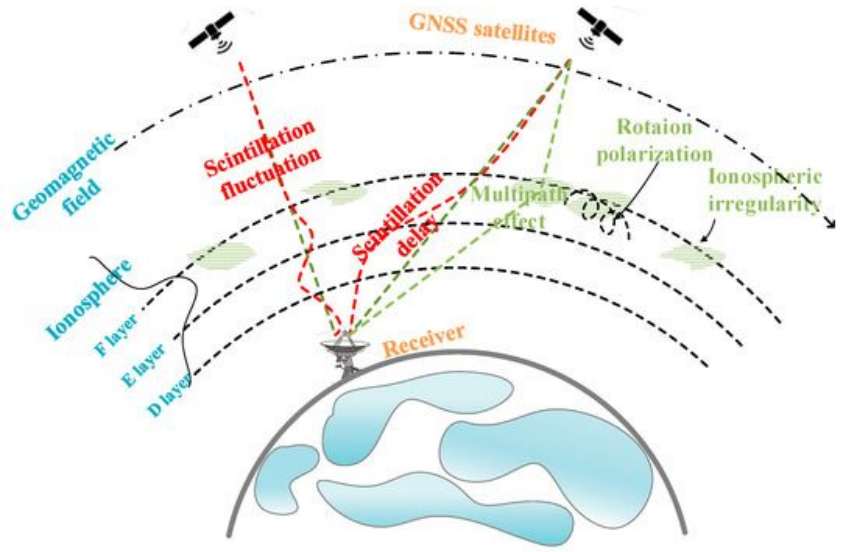
$$\mathrm{TEC} = \int n_e(s)\, ds \quad \text{Unit: TECU,} \quad 1\ \mathrm{TECU} = 10^{16}\ \text{electrons/m}^2$$



Creidt:Khmarskiy et al. (2024)

TEC Affects Propagation of Signals

- Radio wave amplitude and phase are affected by the presence of electrons (scintillation).
- The more electrons in the path of the radio wave, the more the radio signal will be affected.
- For ground to satellite communication and navigation, TEC is a good parameter to monitor for possible space weather impacts.
    - Credit: NOAA



M. Lin et al, 2021 [1]

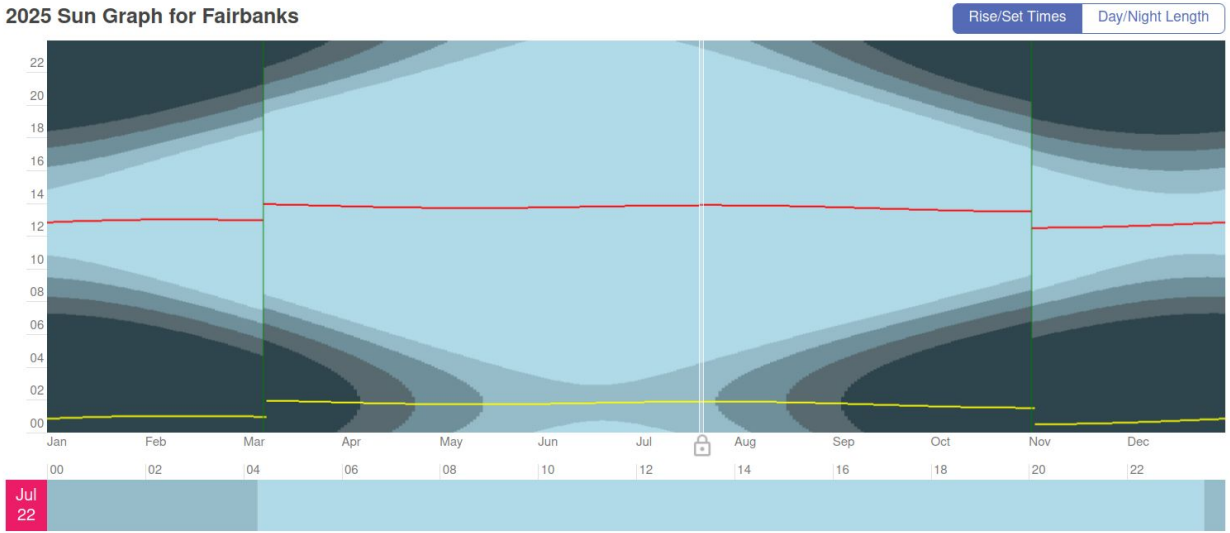
Experiment Goals

1. **Calculate TEC form PFISR.**

2. **Compare TEC derived from PFISR with instrument data (GNSS and ionosonde), Modeling data (TIEGCM and CTIPe)**

Methods: Time of Experiment

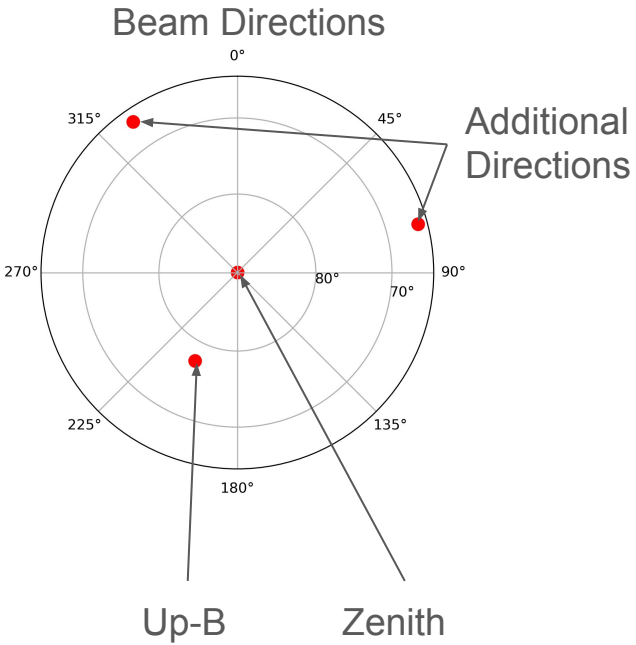
- **Time**
  - 04:00-06:00 UTC, 20:00-22:00 ADT
  - Experiment takes place during full daylight hours



Credit: [timeanddate.com](). Time in ADT

Methods: Waveform Selection

- **Beam Directions**
  - 4 beams
  - Up-B beam aligns with typical LOS to GNSS satellites
  - Zenith beam allows direct calculation of vertical TEC
  - Two additional beams for spatial diversity
- **Pulse Coding**
  - Long Pulse: maximum signal-to-noise, but poor spatial resolution
  - Alternating Code: improved spatial resolution for E-region electron density

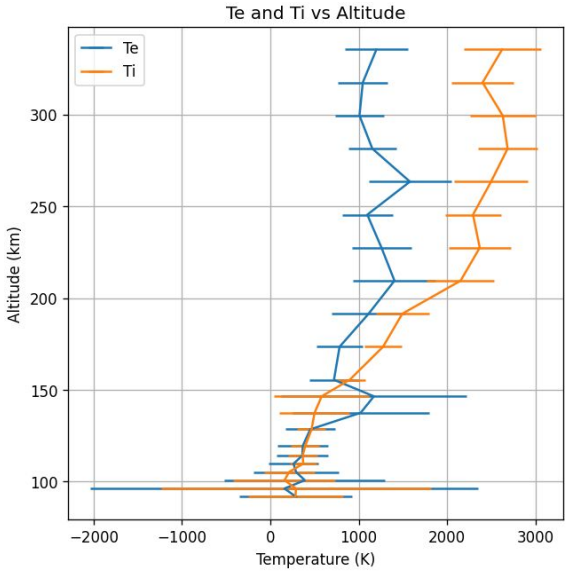


Methods: Waveform Synthesis

- Long pulse (LP) and alternating code (AC) waveforms are optimized for F and E regions respectively
  - Calibrated electron density (Ne) is influenced by estimates of electron and ion temperature (Te and Ti)

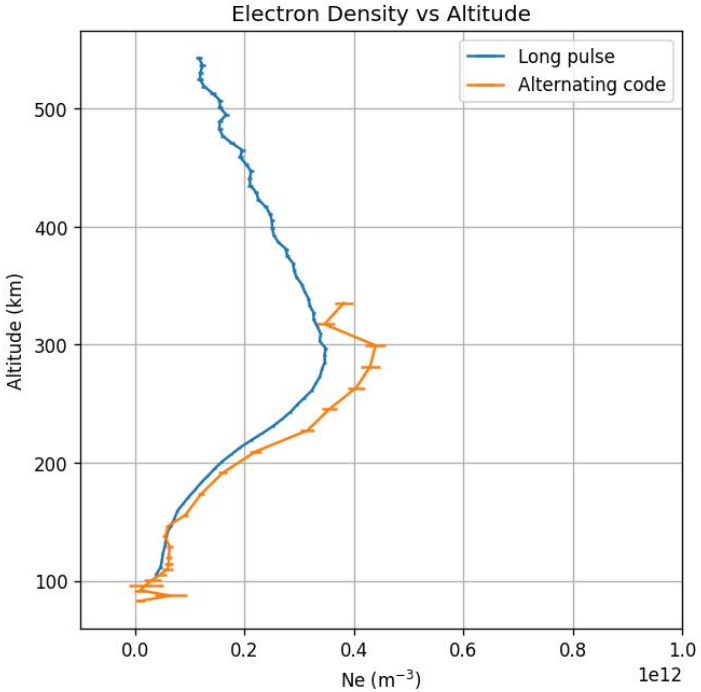
$$P_r = \frac{P_t \tau_p}{R^2} K_{sys} \frac{N_e}{(1 + k^2 \lambda_{De}^2)(1 + k^2 \lambda_{De}^2 + T_e/T_i)}$$

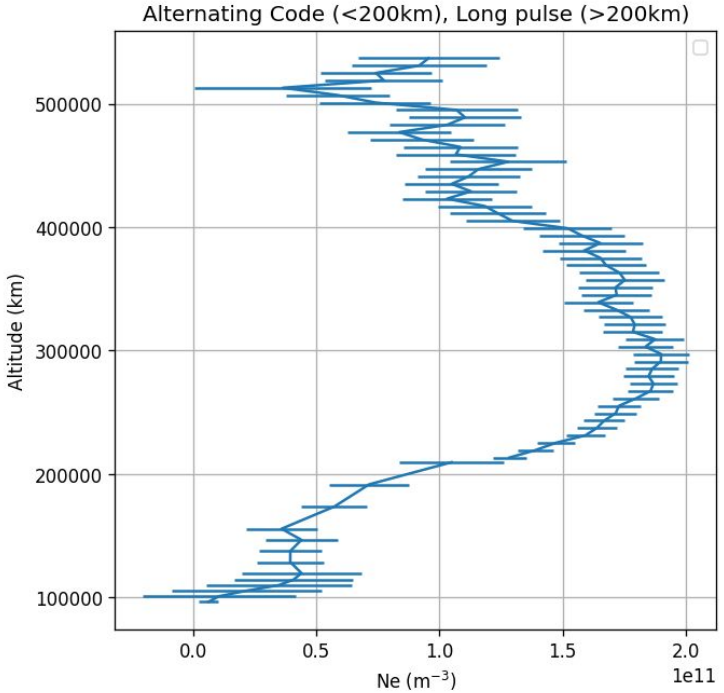
  - Low altitude (<200km) temperature variations are captured by AC with better spatial resolution than LP
  - LP provides upper altitude returns (350-550 km)



Methods: Waveform Synthesis

- For accurate estimates of TEC both waveforms must be stitched together





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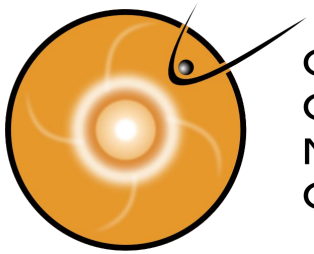
TIEGCM (Model)

- **Thermosphere-Ionosphere- Electrodynamics General Circulation Model:**
  - A three-dimensional, time-dependent, numerical model of Earth's ionosphere and thermosphere (IT)
  - Solves the coupled hydrodynamic, thermodynamic and continuity equation for neutrals, electron and ion energy equations, major and minor species chemistry, and ionospheric dynamo processes in the IT system (97-700 Km)
  - Specifications:
    - Horizontal resolution of 1.25°x1.25° in latitude & longitude
    - 1/8 scale height vertical resolution.
    - 1 minute time resolution
    - Realistic F10.7 solar flux
    - Potential model= Heelis

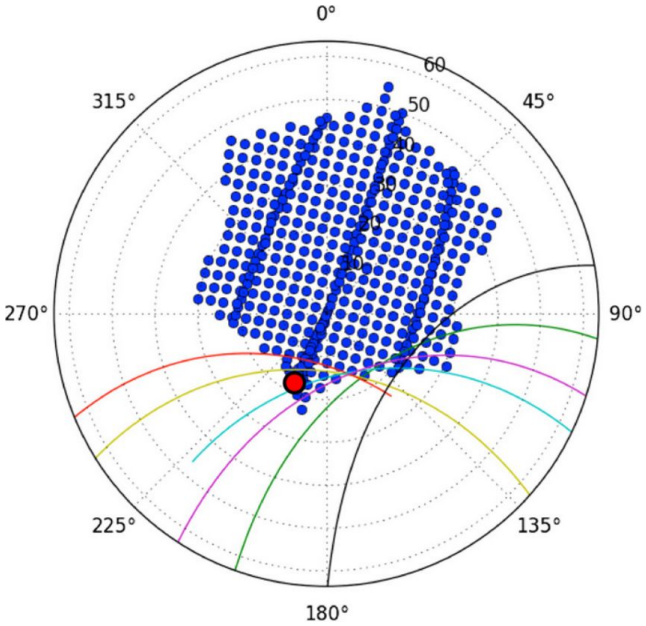
CTIPe (Model)

- **Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics**
  - 3D, time-dependent model of the IT system.
  - Thermosphere: solves momentum, energy, and continuity for neutrals (O, N_2, O_2).
  - High-latitude ionosphere: solves ion motion with ExB drift and collisions.
  - Electric field: global dynamo, calculated self-consistently.
  - Specifications:
    - Horizontal resolution: 2° lat × 18° lon.
    - Vertical: 80-700 km.
    - 10 minutes time resolution.



COMMUNITY COORDINATED MODELING CENTER

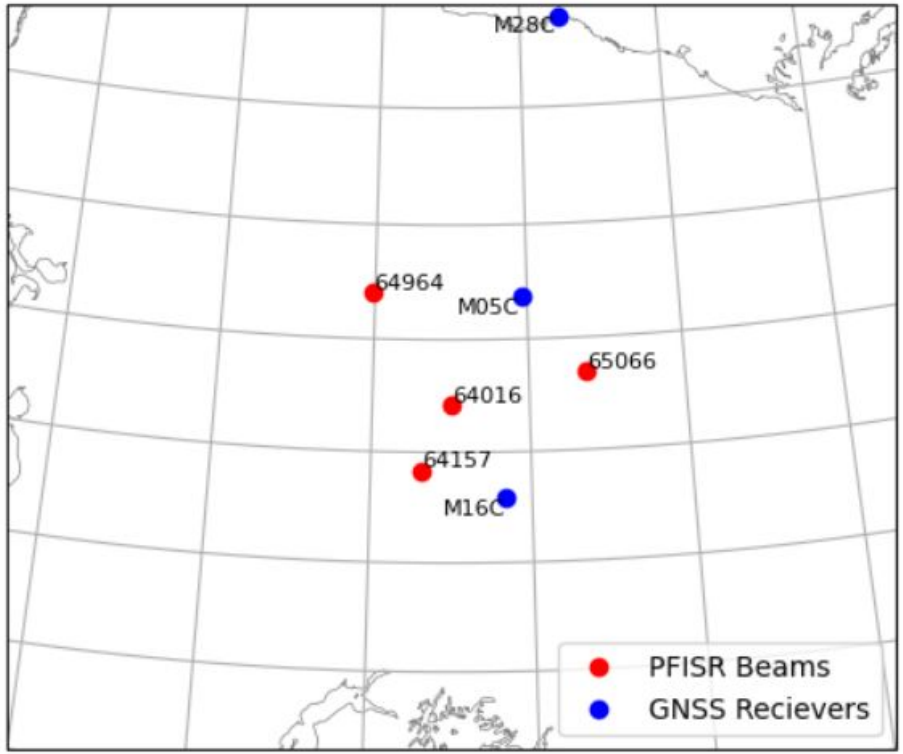
GNSS Receivers (Instrument)



J. Semeter, et al, 2016. [3]

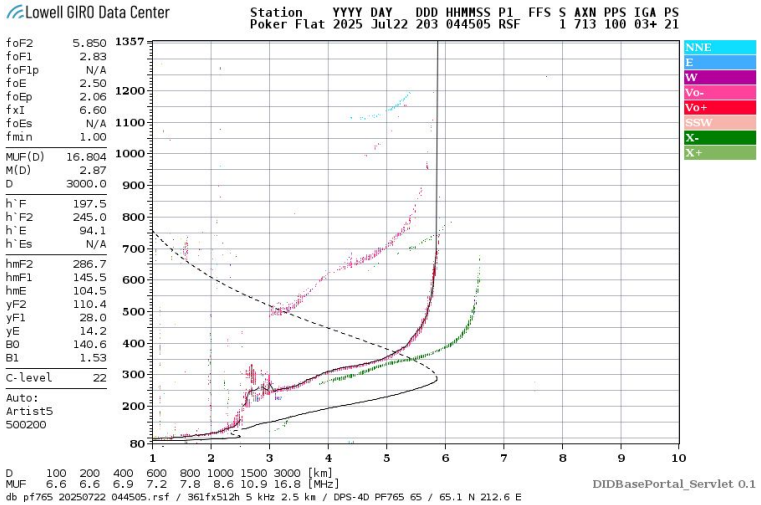
- **Background**
  - There is a network of receivers that use GNSS transmissions to calculate VTEC (vertical TEC) [4].
- **Considerations**
  - The data must be filtered to be more or less relevant to the beam location.
  - At ~55 degrees latitude, GNSS signals begin to degrade due to limits of orbit.
  - 64157 is the only beam that actually lies within the GNSS paths.

GNSS Receiver Coverage



Ionosonde (Instrument)

- **Background**
  - Measures virtual height (apparent height) by sweeping through the lower HF range.
  - Plots range of reflected signal, and uses measured plasma frequency to derive electron density and plots it vs true height (height of reflection).
  - From this, TEC can be calculated.
- **Considerations**
  - Lower half of the TEC is from physical measurement; upper half is derived from the α-Chapman function and scale height [2].
  - Data is generated every 15 minutes.



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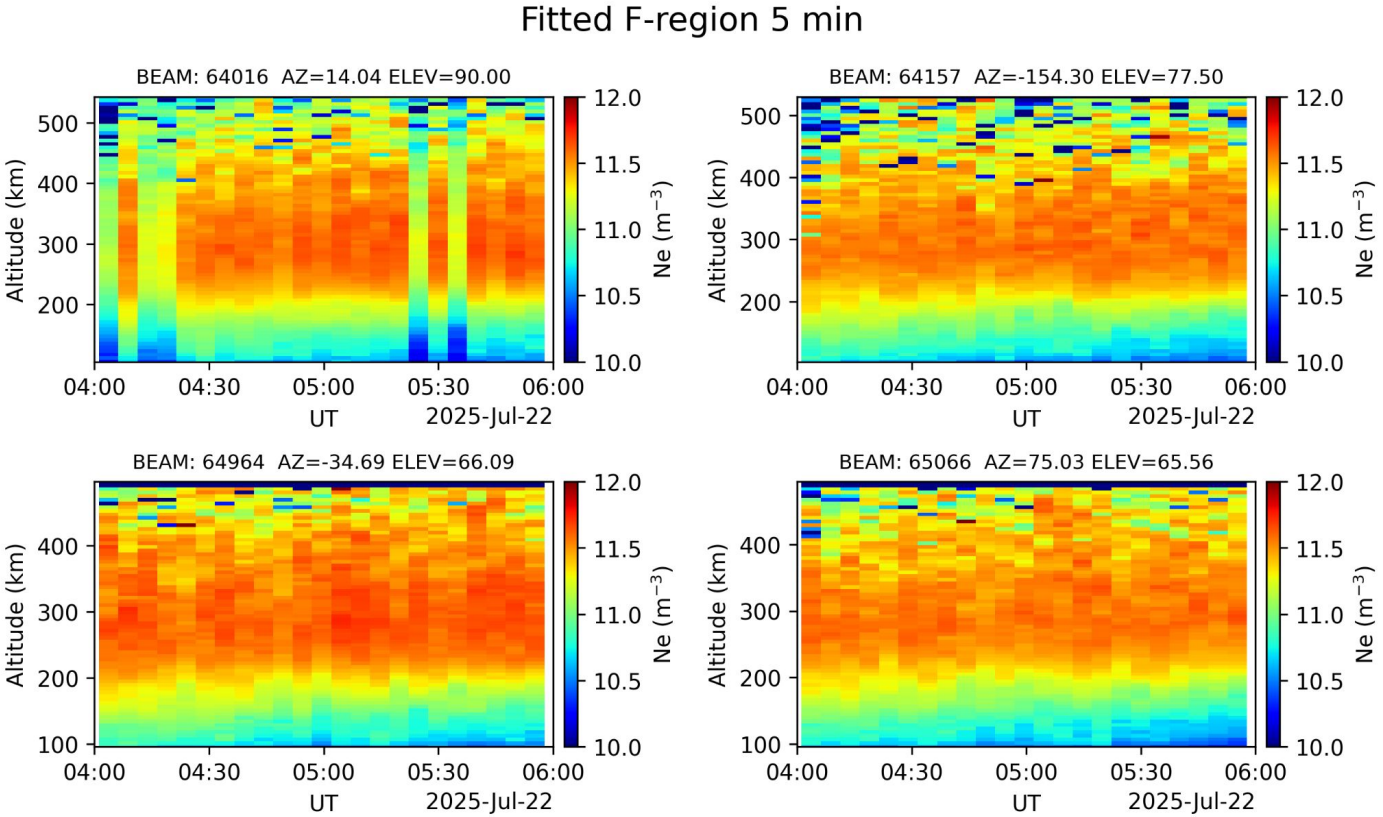
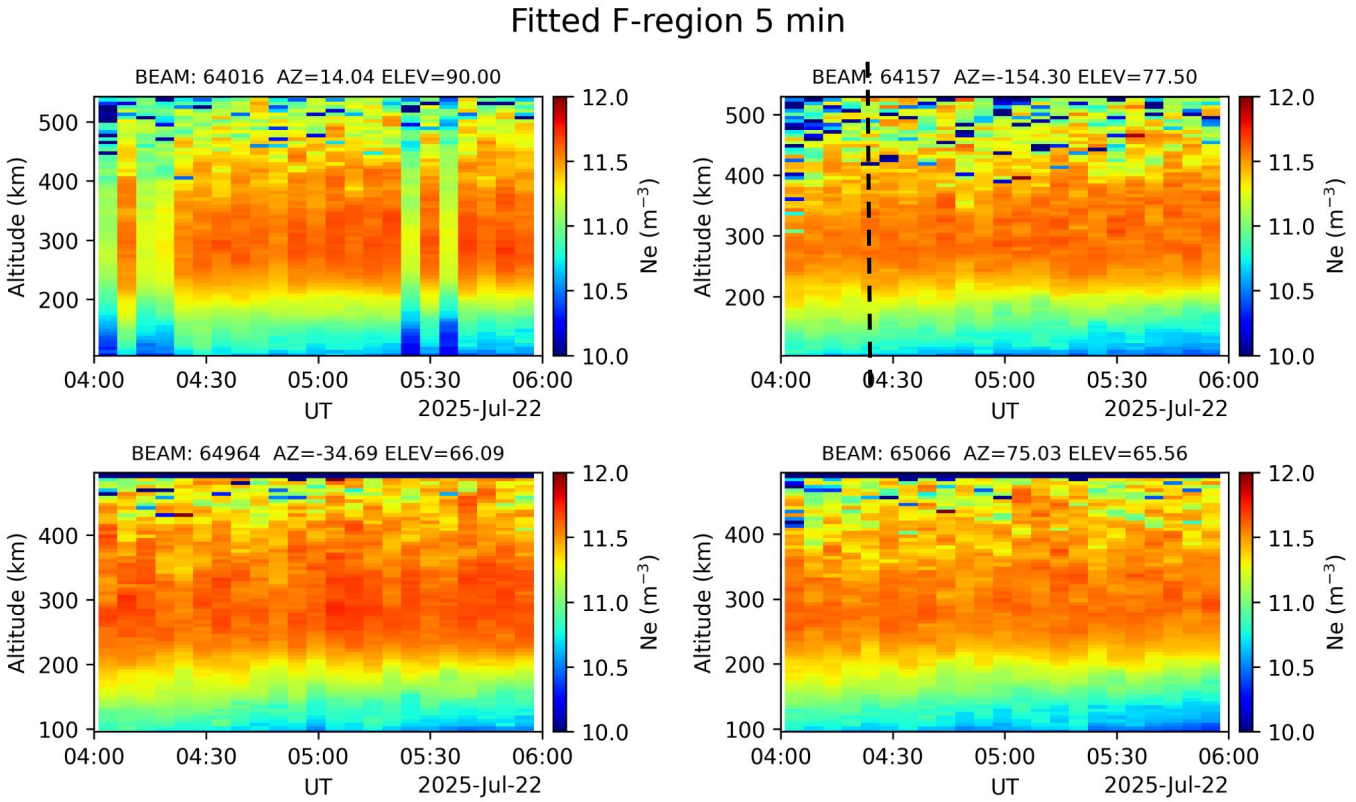
Ne Observed from PFISR



Savitzky-Golay Filter

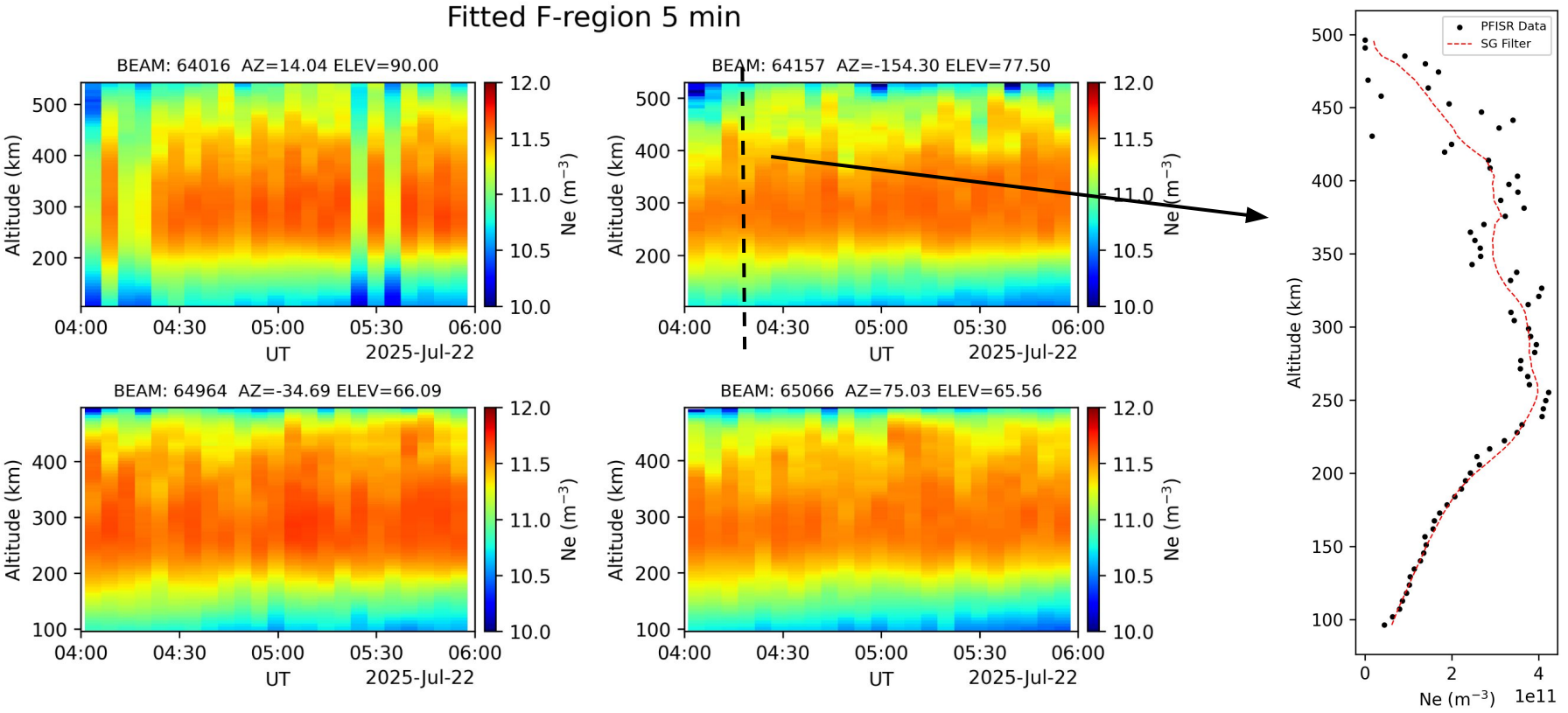


$$\min_{a} \sum_{i=-M}^{M} \left(y_{k+i} - \sum_{j=0}^{p} a_j x_{k+i}^{j} \right)^2$$

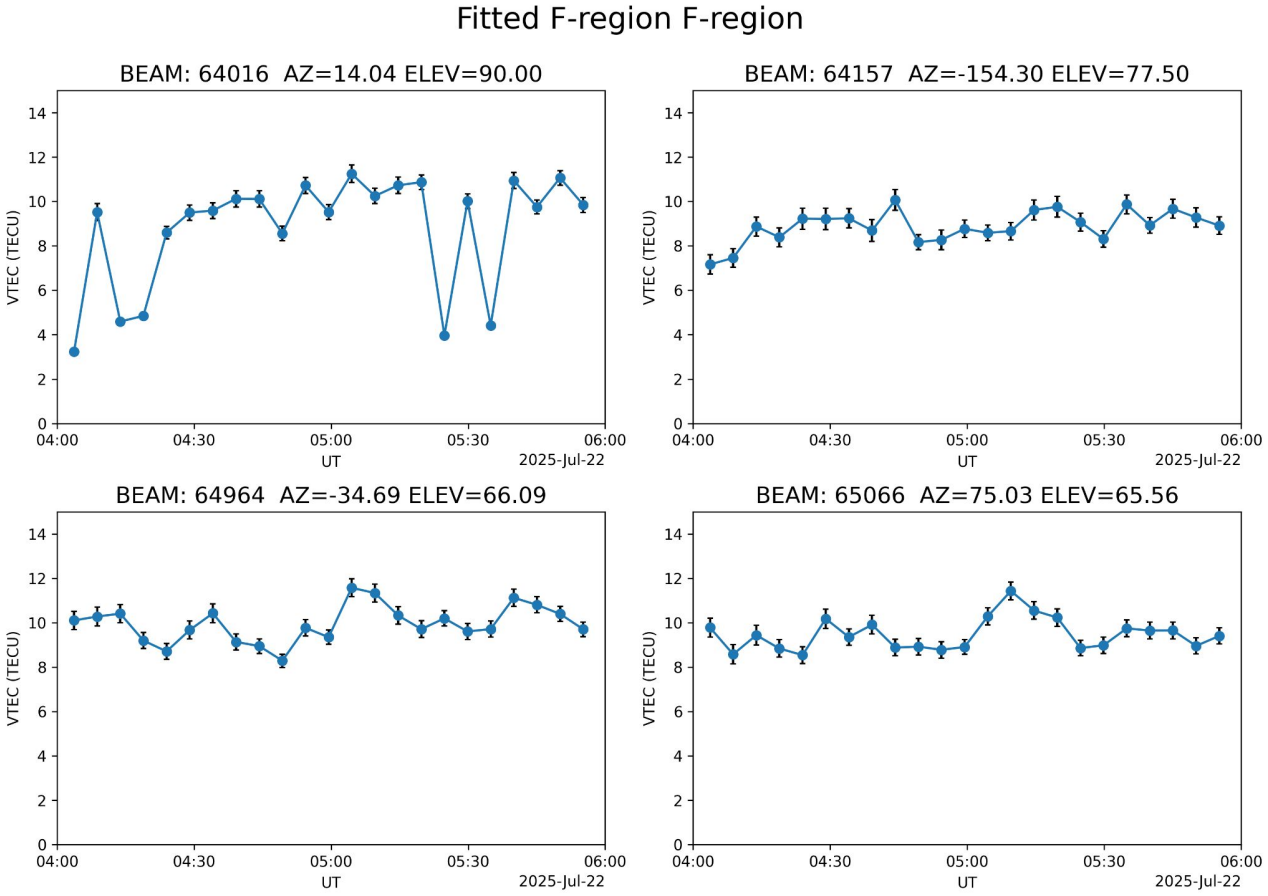
SG FIlter Features:

- Window Length: 20
- polyorder=3

Savitzky-Golay Filter

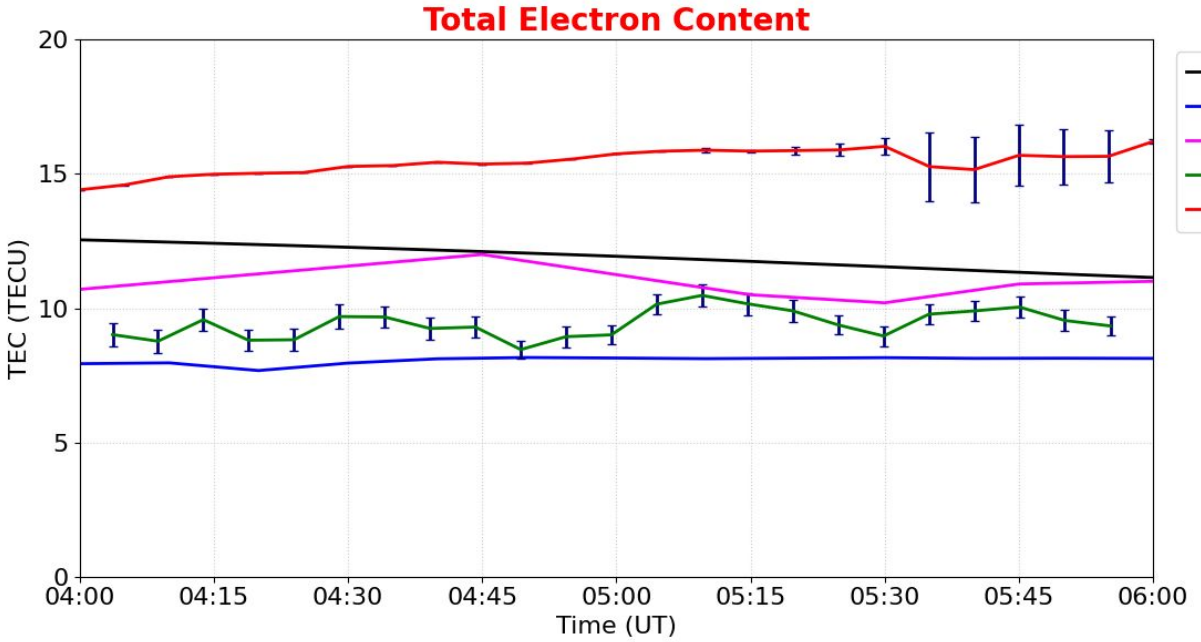


TEC Estimation



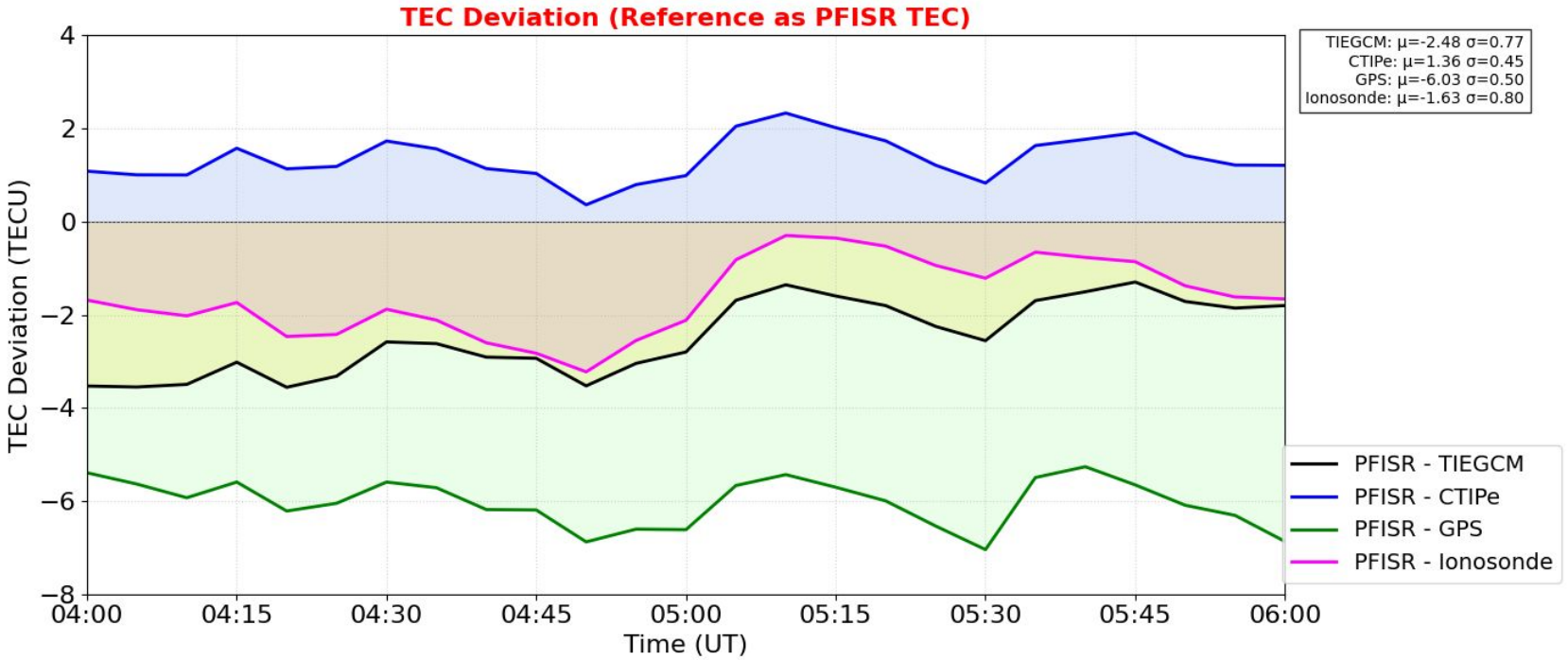
$$\mathrm{TEC} = \int n_e(s)\, ds$$

Comparison between Observation and Models

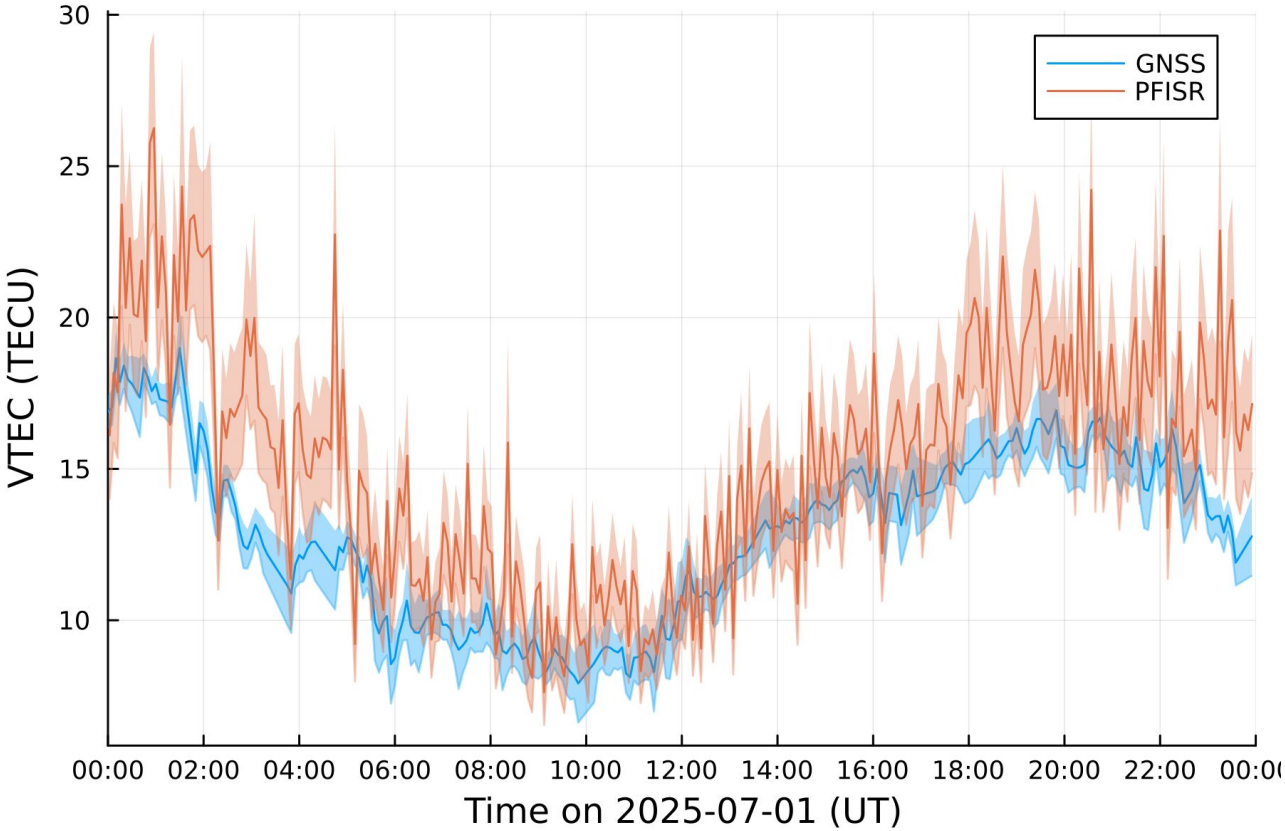


- GPS TEC overestimates all the derived TEC
- CTIPe underestimates TEC
- Ionosonde and PFISR have similar measurements

Statistical Comparison



Comparison With Historical Data



Conclusion

- **GNSS TEC far exceeds TEC measured and modeled.**
  - **Possible explanation**
    - GNSS TEC is integrated from MEO (~20,000km). Data was taken during extremely quiet geomagnetic conditions, and PFISR cannot measure to the limit of the expanded plasmasphere.
    - Each receiver has a TEC bias on the order of a few TECu, but this is supposed to be resolved before the final VTEC product.

References

[1] M. Lin, X. Zhu, T. Hua, X. Tang, G. Tu, and X. Chen, “Detection of Ionospheric Scintillation Based on XGBoost Model Improved by SMOTE-ENN Technique,” *Remote Sensing*, vol. 13, no. 13, p. 2577, Jul. 2021, doi: https://doi.org/10.3390/rs13132577.

[2] X. Huang and B. W. Reinisch, “Vertical electron content from ionograms in real time,” *Radio Science*, vol. 36, no. 2, pp. 335–342, Mar. 2001, doi: https://doi.org/10.1029/1999rs002409.

[3] J. Semeter, M. Hirsch, F. Lind, A. Coster, P. Erickson, and V. Pankratius, “GNSS‐ISR data fusion: General framework with application to the high‐latitude ionosphere,” *Radio Science*, vol. 51, no. 3, pp. 118–129, Jan. 2016, doi: https://doi.org/10.1002/2015rs005794.

[4] J. Vierinen, A. J. Coster, W. C. Rideout, P. J. Erickson, and J. Norberg, “Statistical framework for estimating GNSS bias,” *Atmospheric Measurement Techniques*, vol. 9, no. 3, pp. 1303–1312, Mar. 2016, doi: https://doi.org/10.5194/amt-9-1303-2016.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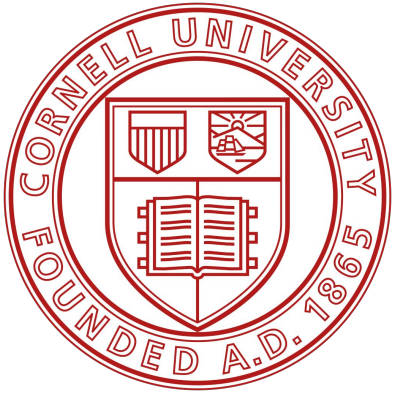
VIRGINIA TECH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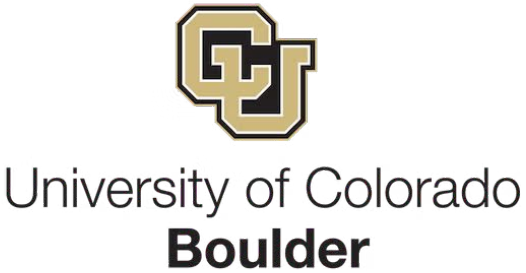
Thank You


MIT
Lincoln
Laboratory


THE UNIVERSITY OF MICHIGAN
ARTES · SCIENTIA · VERITAS
1817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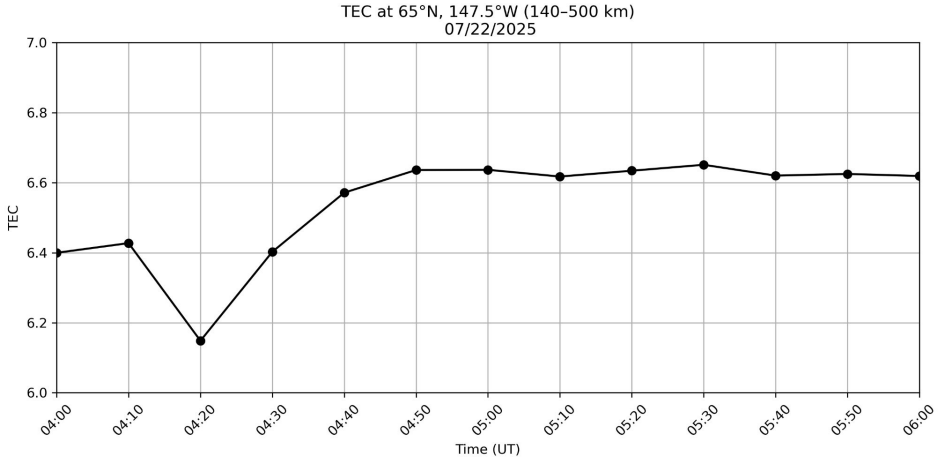
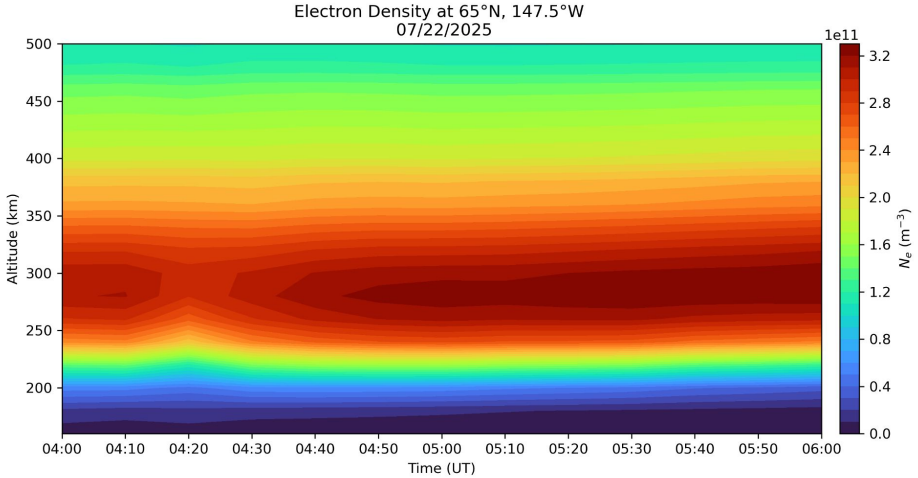
Boulder

Backup Slides

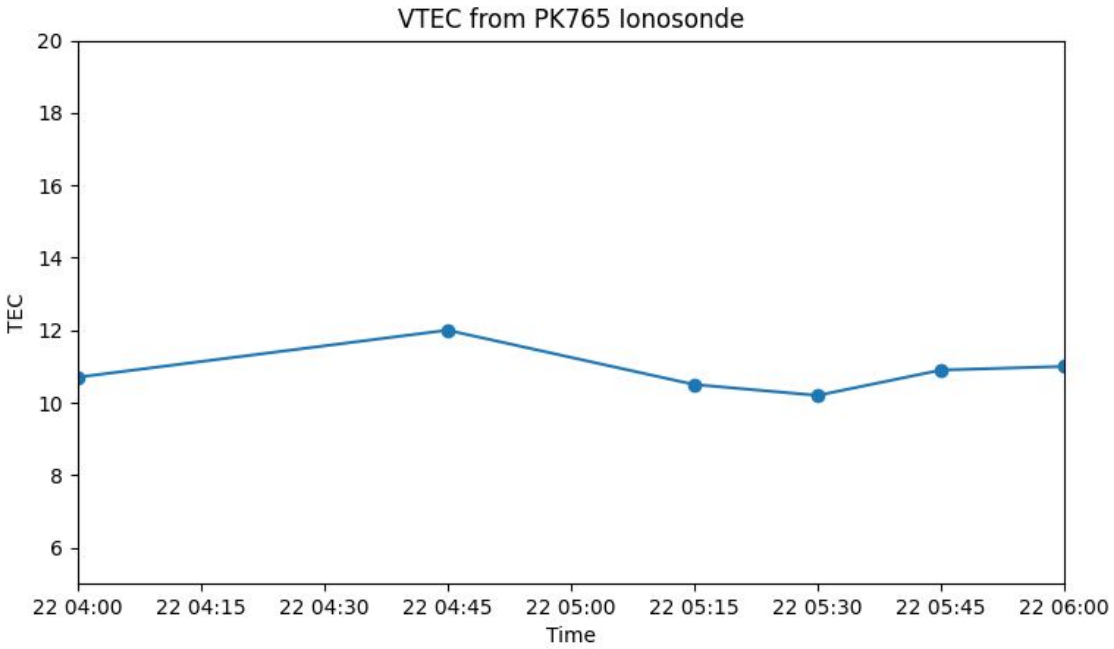
Ne and TEC from CTIPe



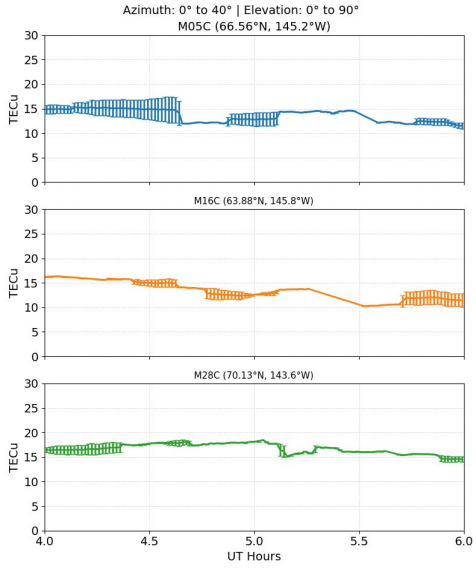


Ionosonde Data

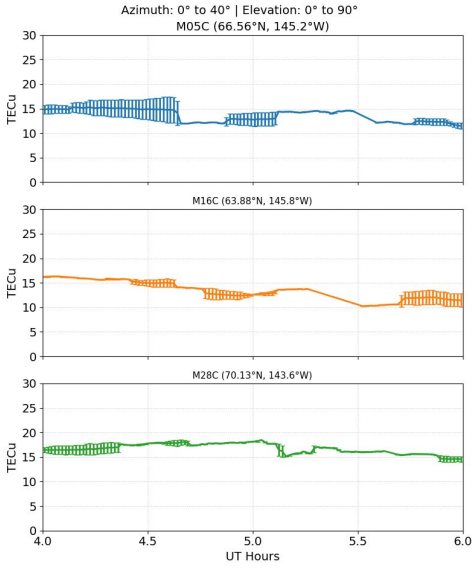
- Ionosonde did not collect data for 04:15 and 04:30, 05:00



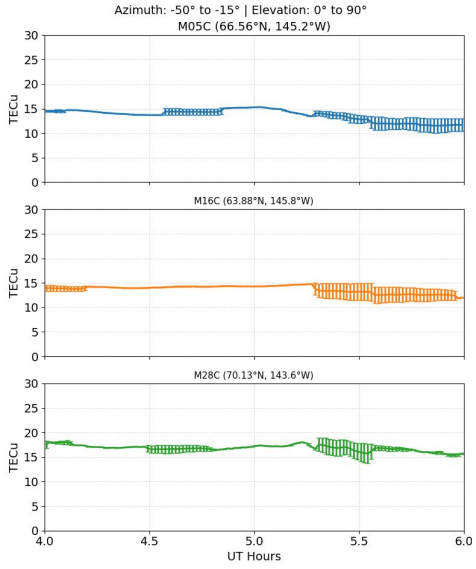
GNSS Data



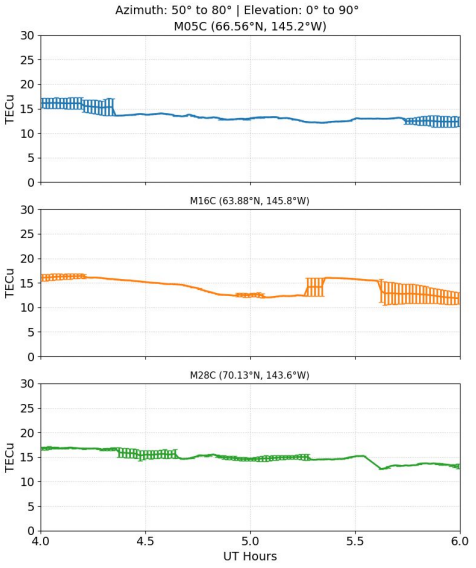
64016: Vertical beam



64157: Vertical beam

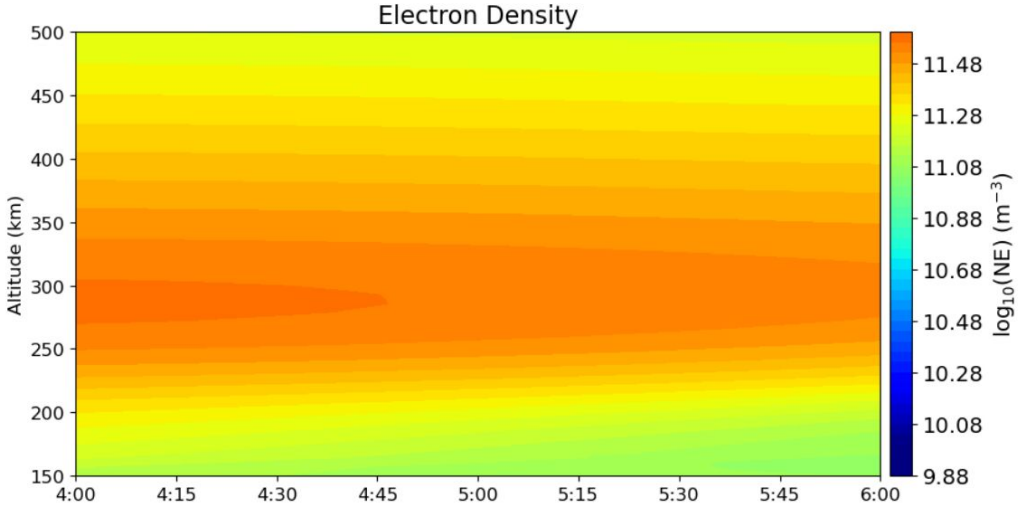


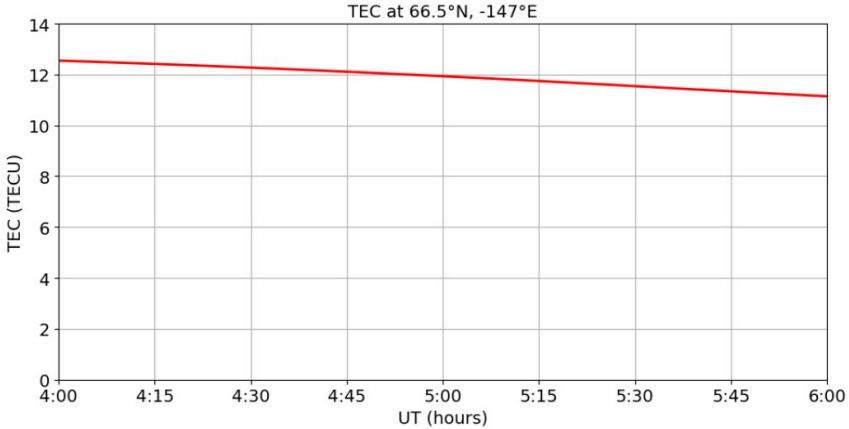
64016: Vertical beam



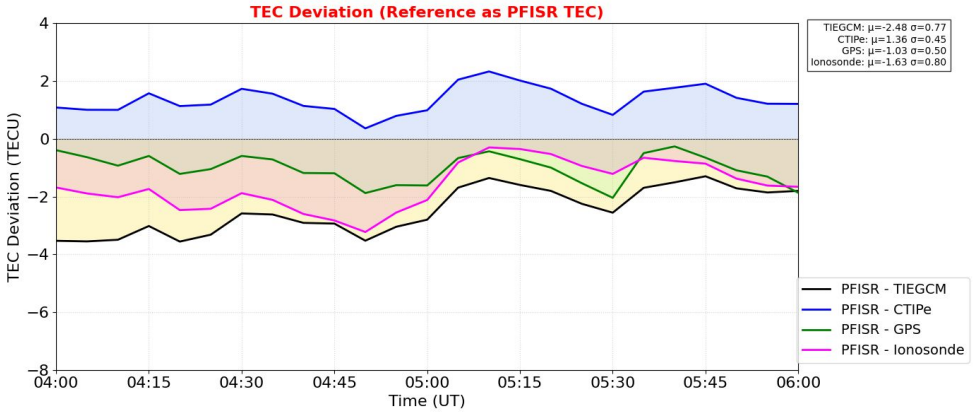
65066: Vertical beam

TIEGCM Model



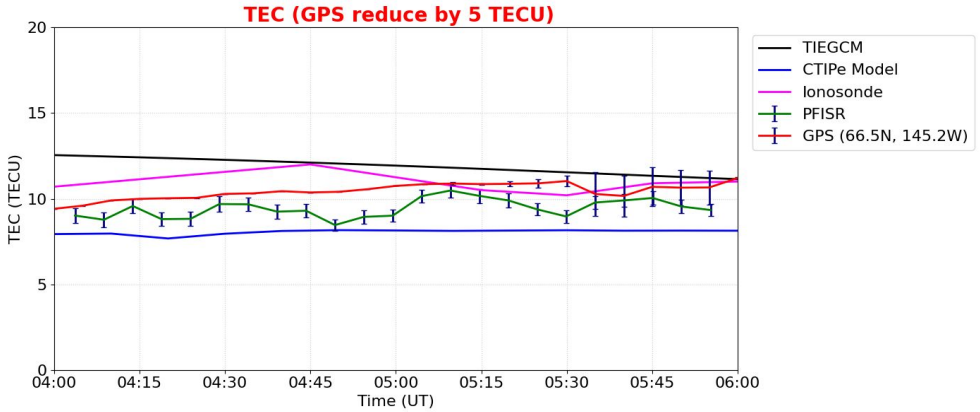


Magic No. 5

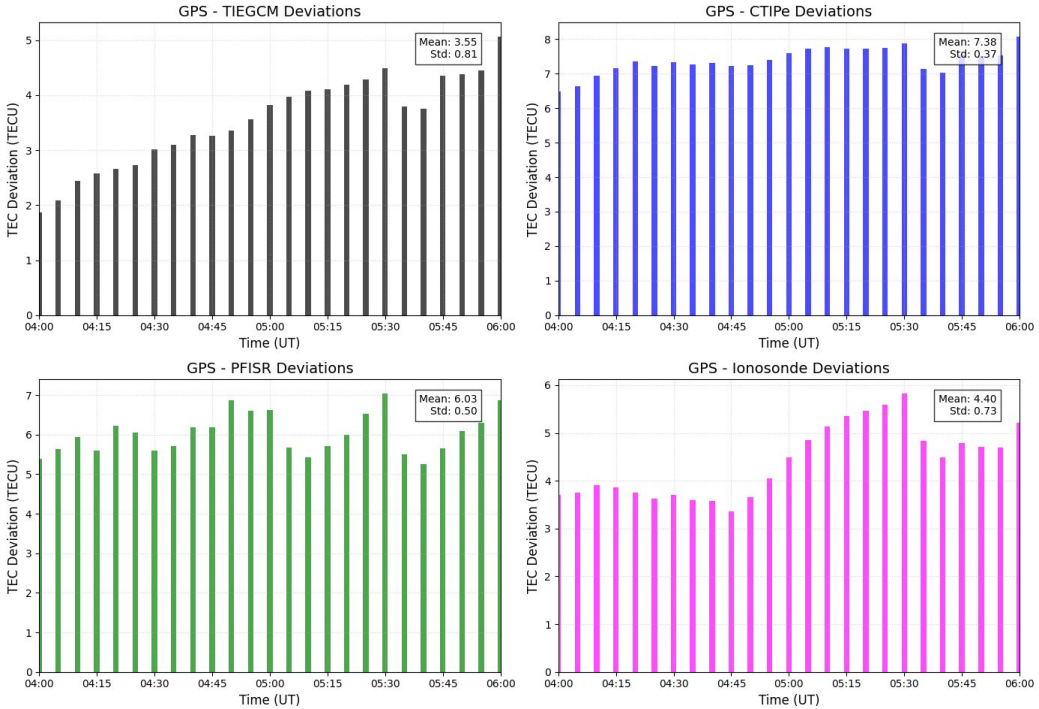


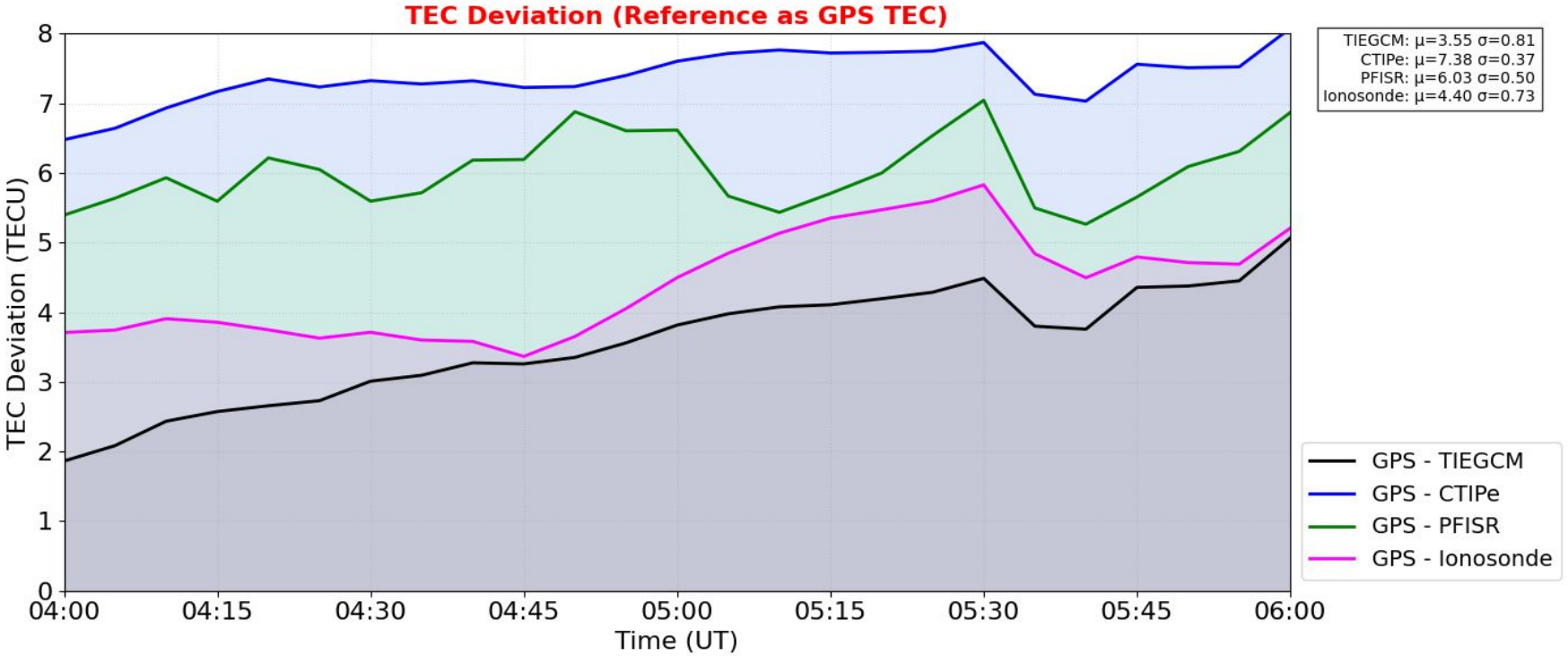
When GPS TEC is reduced by 5 TECU, It is close to derived PFISR TEC.

- Is the GPS data we have are well calibrated?
- Is that due to receiver bias ??



Individual Deviation




TEC Deviation (Reference as GPS TEC)
TEC Deviation (TECU)
Time (UT)
0
1
2
3
4
5
6
7
8
04:00
04:15
04:30
04:45
05:00
05:15
05:30
05:45
06:00
TIEGCM: μ=3.55 σ=0.81
CTIPe: μ=7.38 σ=0.37
PFISR: μ=6.03 σ=0.50
Ionosonde: μ=4.40 σ=0.73
GPS - TIEGCM
GPS - CTIPe
GPS - PFISR
GPS - Ionosonde