Assessing Potential Radio Occultation Constellations for Specifying Neutral Mass Density

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1. The Issue: Limited Knowledge of Low Earth Orbit Neutral States

1.1 Motivation

a. Orbit position errors in Low Earth Orbit (LEO) come primarily through atmospheric drag and need better neutral density estimates.
b. **Current neutral observations are limited.**

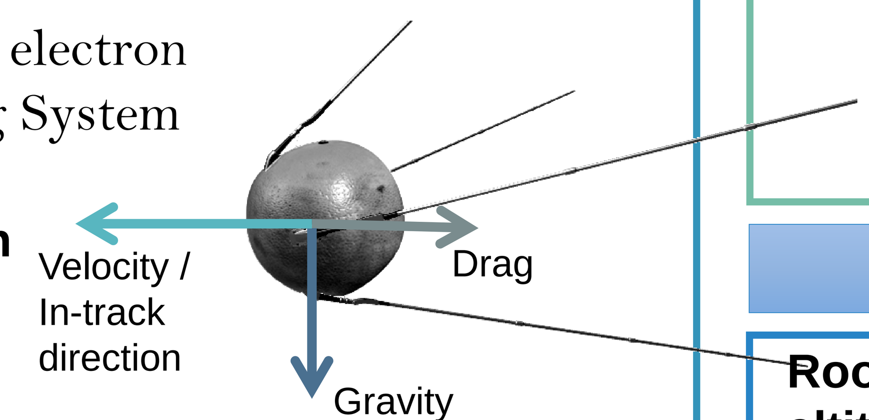
$$\boldsymbol{a}_{drag} = -\frac{1}{2} C_D \frac{A}{m} \rho v \boldsymbol{v}$$

ρ (neutral density) is the most impactful term

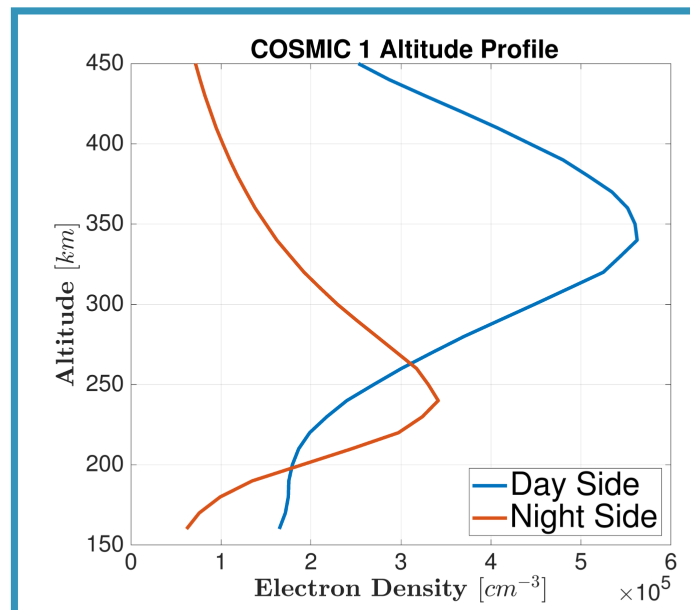
1.2 Goal

Infer neutral density using electron density observations in an Observing System Simulation Experiment (OSSE)

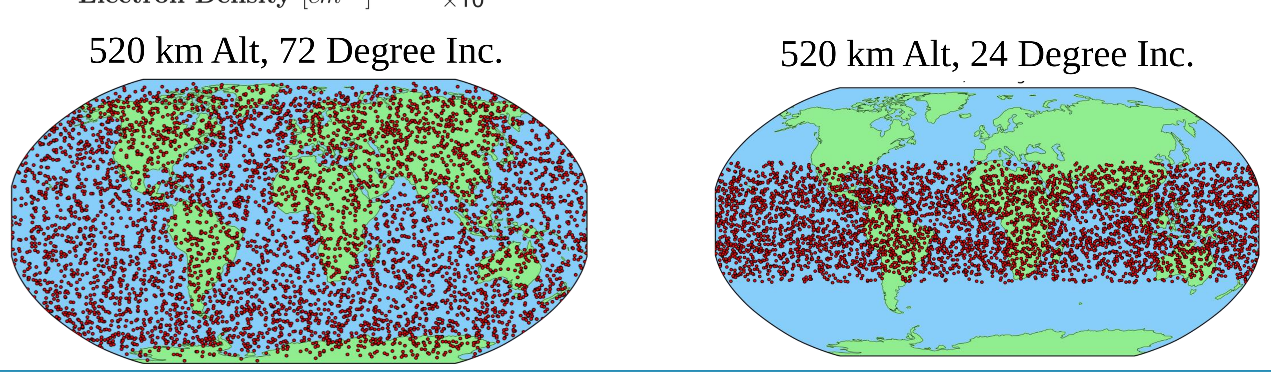
Perform with different observation constellations and different truth models: TIEGCM and WAM-IPE.



Observations: COSMIC Radio Occultation



COSMIC satellites use Radio Occultation (RO) to measure changes in radio signals from Global Navigation Satellite Systems (GNSS) as they pass through the ionosphere. Produces electron density profiles (EDPs) of the ionosphere. Thousands available per hour. ***Used as an alternative to neutral density observations.***



Model: DART-TIEGCM

Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) developed by NCAR is a first-principles model that can capture the strong coupling between the thermosphere and ionosphere. Altitudes 90 ~ 550 km. Run using DART software.

References

[1] N. Dietrich, T. Matsuo, C.T. Hsu. Specifying Satellite Drag Through Coupled Data Assimilation of Radio Occultation Electron Density Profiles. *In review at Space Weather, 2022*

[2] T. Matsuo and C.T. Hsu. Inference of Hidden States by Coupled Thermosphere-Ionosphere Data Assimilation, pgs. 343–363, 2021.

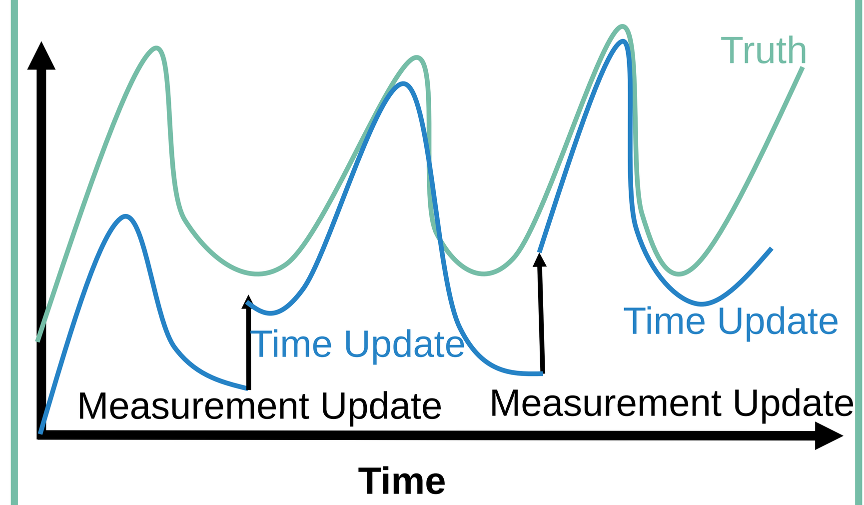
[3] J.L. Anderson. An ensemble adjustment filter for data assimilation. *Monthly weather review,* pgs. 2884-2903, 2001.

Acknowledgements

The study is supported by the NSF award AGS 1848544 and the NOAA Office of Projects Planning and Analysis. The DART software was obtained from NCA (http://www.image.ucar.edu/DAReS/DART). The TIEGCM software was obtained from High Altitude Observatory, NCAR (http://www.hao.ucar.edu/modeling/tgcm/tie.php). The COSMIC data were obtained from COSMIC Data Analysis and Archival Center (https://www.cosmic.ucar.edu/what-we-do/cosmic-1/data/). We acknowledge NCAR and UCAR for their community software and data support.

2. Methods: Ensemble Adjustment Kalman Filter (EAKF) by DART

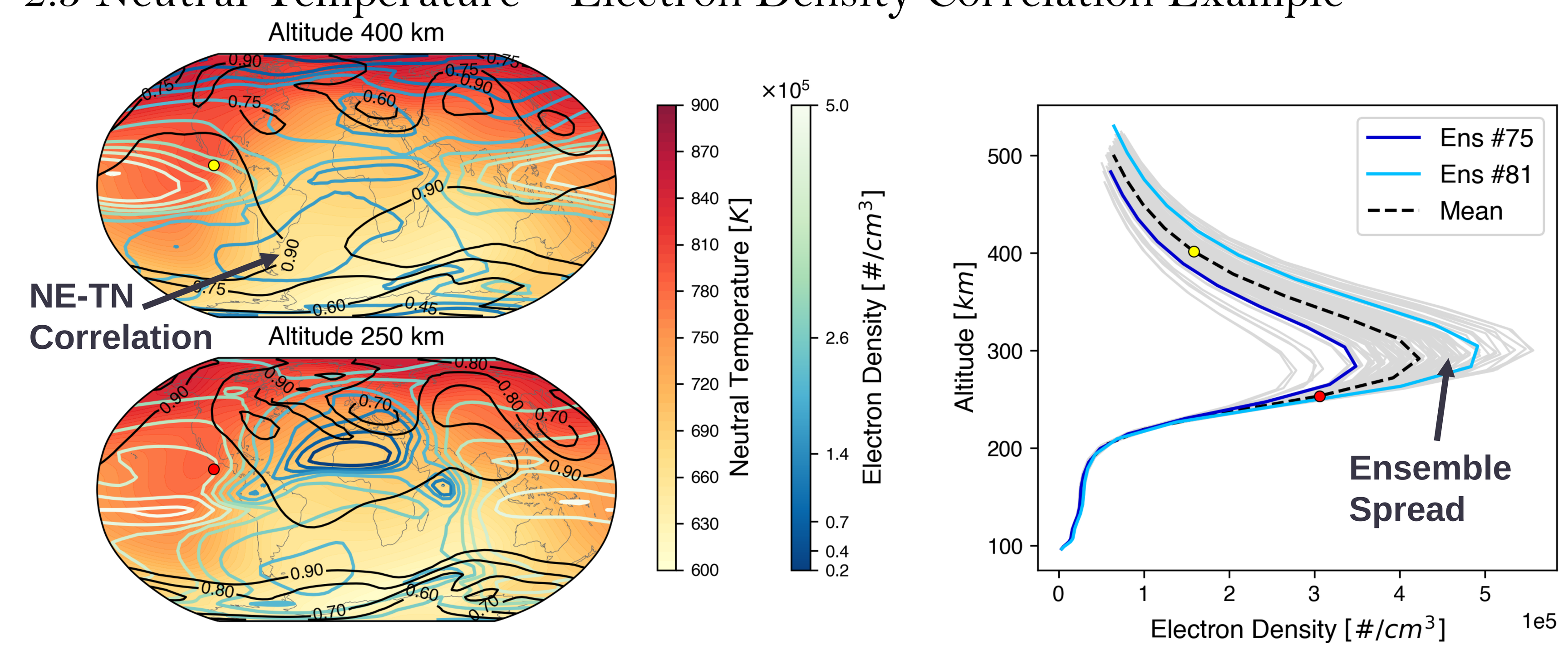
2.1 Data assimilation cycle



2.2 OSSE EAKF Outline

Initialization	Perturbed states made through a normally distributed 90-member ensemble of solar and magnetospheric drivers: F10.7 index, hemispheric power (HP), cross-tail potential (Φ). 10-day spin-up period.
Time Update	Monte Carlo propagation of ensembles $i = 1, \ldots, 90$ using TIEGCM dynamics.
Measurement Update	States sequentially updated in observation space and mapped to model space using linear regression. Regression coefficients found using sample statistics from ensembles [3].
Observations	Sample RO EDPs from the truth model: TIEGCM (Sect. 3) or WAM-IPE (Sect. 4).

2.3 Neutral Temperature – Electron Density Correlation Example



3. Results – TIEGCM as Truth Model

Root Mean Square Errors (RMSE) at LEO altitudes in TIEGCM- Fig. 3.1

a. Synthetic COSMIC 1 (72 deg. Inc.) used for observations
b. Updating temperatures using COSMIC RO has a sustaining improvement to neutral density estimation of **70%** [1,2].
c. High correlation exists between temperature and hmF2 [1] (Not shown).
d. A propagated orbit shows a **70%** improvement to in-track errors [1] (Not shown).

Exp	Updated States: $X \sim$ 7.5e4 states/variable
1	$[f_{e^-}; f_{O^+}; f_T]$
2	$[f_{e^-}; f_{O^+}; f_{VN}; f_{UN}]$
3	$[f_{e^-}; f_{O^+}; f_T; f_{VN}; f_{UN}]$

Fig 3.1 Includes altitudes 300 ~ 530 km. RMSE decreases for temperature, neutral density and neutral winds.

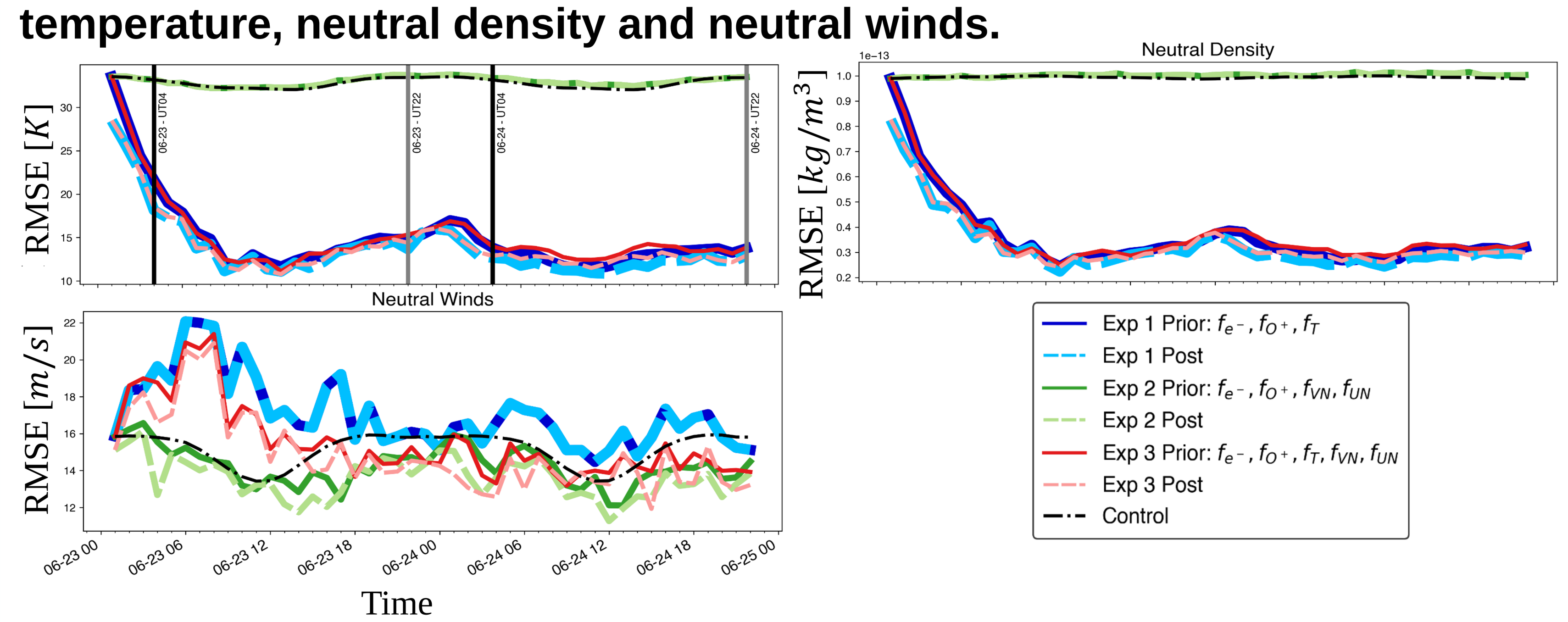
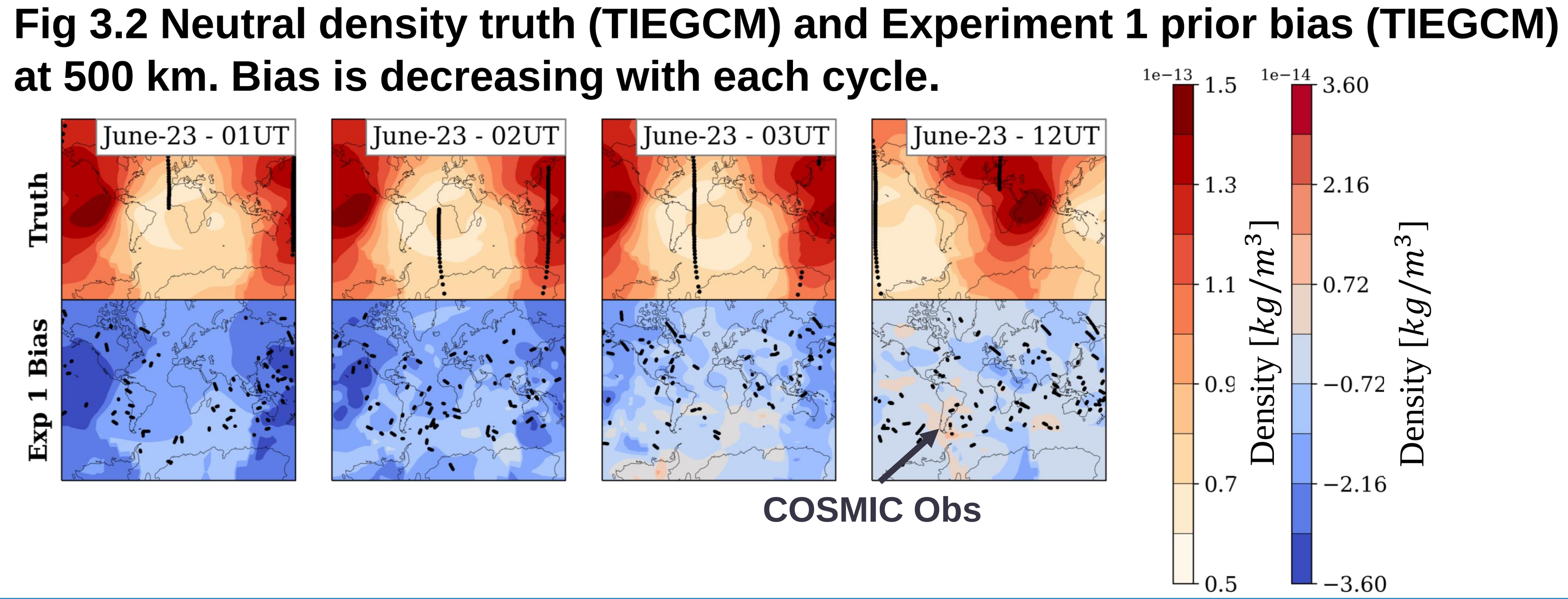


Fig 3.2 Neutral density truth (TIEGCM) and Experiment 1 prior bias (TIEGCM) at 500 km. Bias is decreasing with each cycle.



4. Results – WAM-IPE as Truth Model

RMSE at 500 km altitude in TIEGCM- Fig. 4.1

a. Updating temperatures improves neutral density by **50%**.
b. Similar neutral density errors for both constellations.

Exp	Updated States: $X \sim$ 7.5e4 states/variable
24 Inc	$[f_{e^-}; f_{O^+}; f_T]$
72 Inc	$[f_{e^-}; f_{O^+}; f_T]$

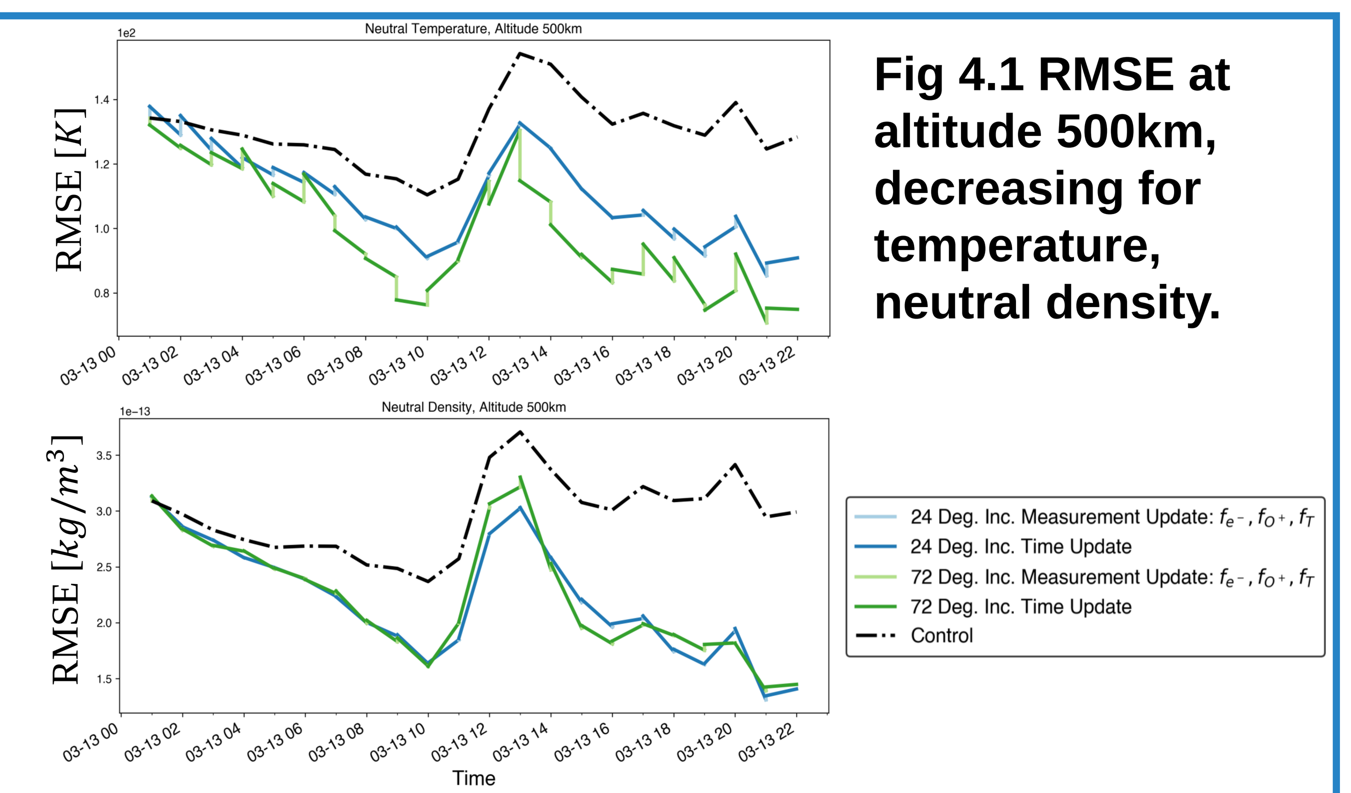


Fig 4.1 RMSE at altitude 500km, decreasing for temperature, neutral density.

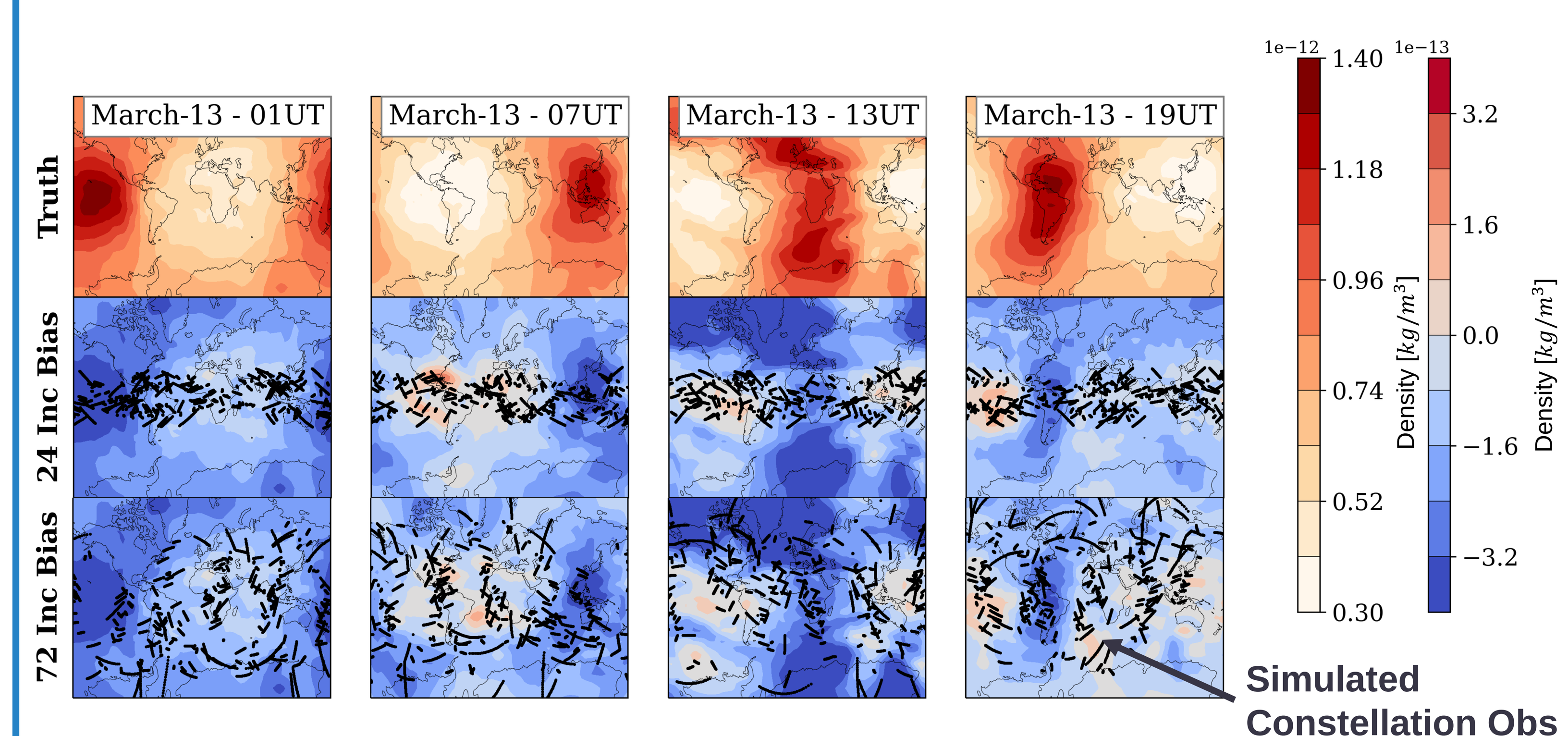


Fig 4.2 Neutral density truth (WAM-IPE) and exp prior biases (TIEGCM) at 500 km alt.

5. Conclusions

1. Orbit errors in LEO are reduced by **70%** through better estimated neutral densities. Comes primarily through improved temperature estimation from assimilation of COSMIC RO EDPs.
2. Compared with WAM-IPE truth run, the 24 and 72 inclination RO constellations see a peak of **50%** reduced neutral density RMSE in one day.