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ANCHOR: A New Approach to the Ionospheric Data Assimilation

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Next-generation Ionosphere Model for Operations (NIMO)

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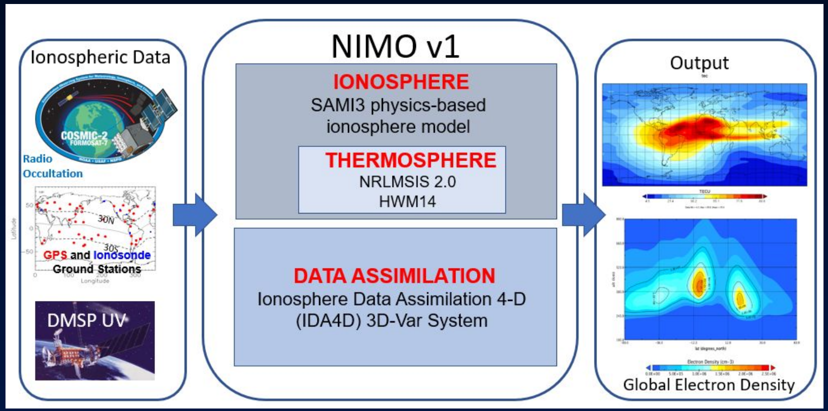
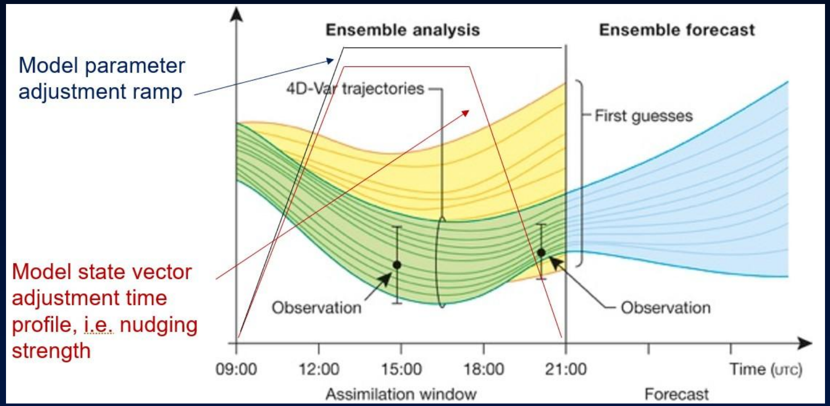
- NIMO is DOD-owned ionospheric model and data assimilation (DA) capability to support high-frequency (HF) communication performance predictions

NIMO 1.0 – 1.2 (operational)



- Background: SAMI 3
- DA: IDA4D
- Forecast: 15-min

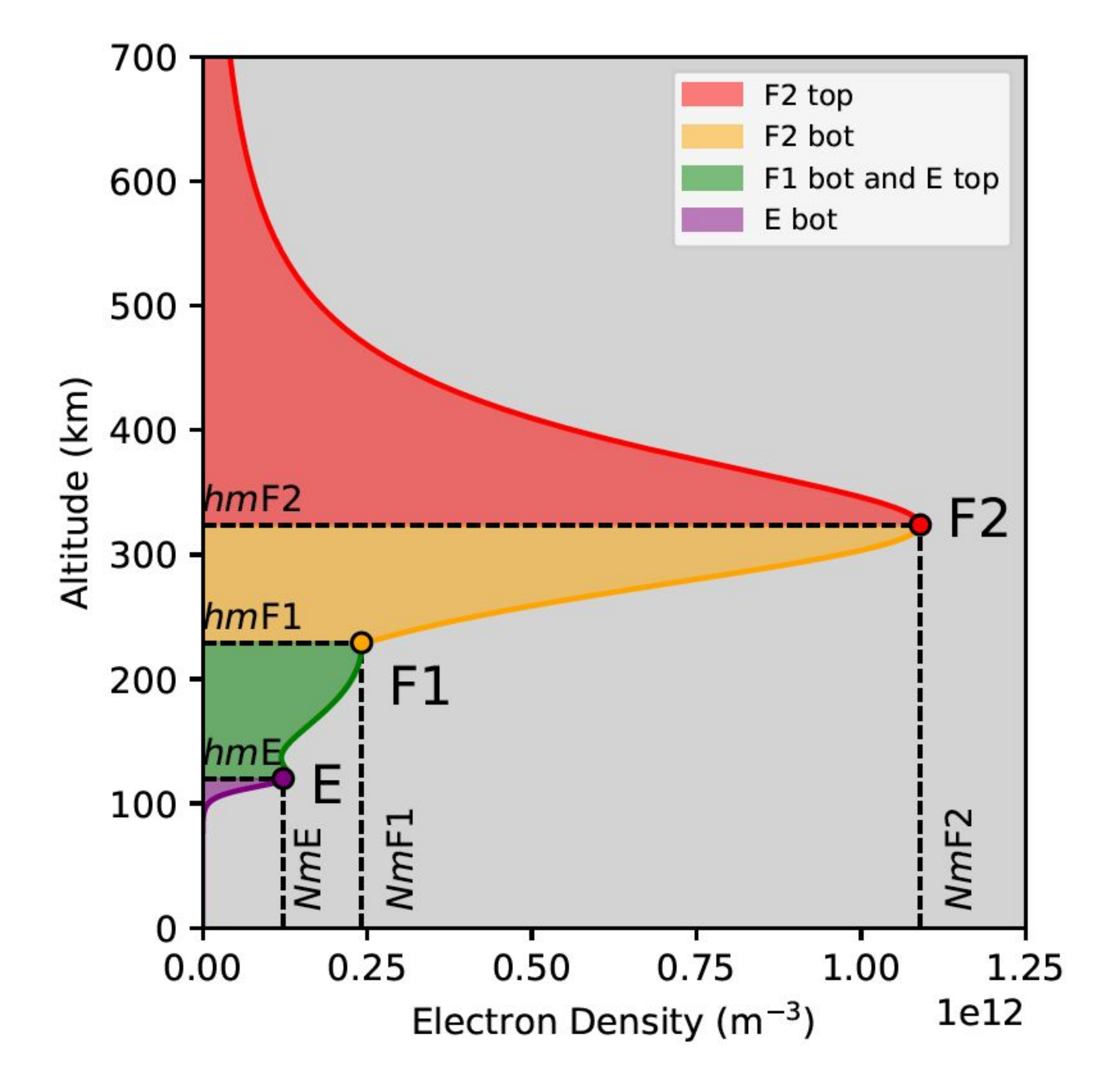
NIMO 2.0



- Background: SAMI 4
- DA: ANCHOR
- Forecast: 72-hours

LETKF methods to nudge an ensemble of forecasts to capture envelope of uncertainty in model parameters

ANCHOR: Parametrization



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ANCHOR: Global Parametrized Ionospheric Data Assimilation

Victoriya V. Forsythe, Sarah E. McDonald, Kenneth F. Dymond, Bruce A. Fritz, Angeline G. Burrell, Katherine A. Zawdie, Douglas P. Drob, Meghan R. Burleigh, Dustin A. Hickey ... See all authors

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A realistic EDP can be constructed with 12 parameters:

12 anchor points

Fixed at model:
- hmE
- B^{E}_{bot}
- B^{E}_{top}

Updated as model:
- NmF1
- hmF1
- B^{F1}_{bot}

Assimilation:
- NmF2
- hmF2
- B^{F2}_{bot}
- B^{F2}_{top}
- NmE

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PyIRI: Background $\vec{x}_h$

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PyIRI: Whole-Globe Approach to the International Reference Ionosphere Modeling Implemented in Python

Victoriya V. Forsythe, Dieter Bilitza, Angeline G. Burrell, Kenneth F. Dymond, Bruce A. Fritz, Sarah E. McDonald

First published: 05 April 2024 | https://doi.org/10.1029/2023SW003739 | Citations: 3

- The first step in ANCHOR development was the creation of PyIRI, a redesigned and simplified version of the classical IRI model, optimized for high spatial and temporal resolution grids.
- A daily run with an irregular grid and 15-min resolution requires ~6 million FORTRAN IRI executions. With PyIRI, the same run completes in 3 seconds.
- A dedicated module enables generation of global ionospheric parameters for an entire year in just 3 seconds.
- Ongoing development: the upcoming PyIRI v0.0.5 will bring PyIRI closer to IRI [Bilitza, 2022] by incorporating additional models.

PyIRI

global and fast

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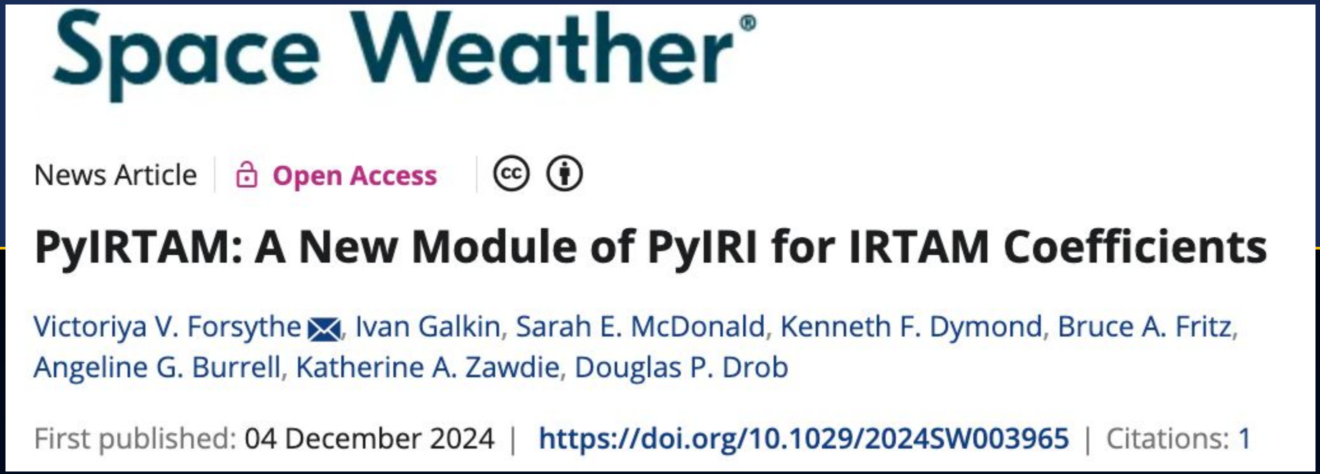
PyIRTAM: Parametrized DA

- The pioneer in parametrized ionospheric DA is the IRTAM model [Galkin et al., 2020], which updates Fourier series coefficients based on ionosonde observation time series.
- This approach is difficult to apply to measurements without continuous time series (e.g., radio occultation data).
- Since IRTAM uses the same formalism as IRI, PyIRI was extended to handle IRTAM coefficients, resulting in the PyIRTAM software.
- ANCHOR adopts the value of working in parametrized space, but extends it by decoupling the dependence from time to spatial dimensions.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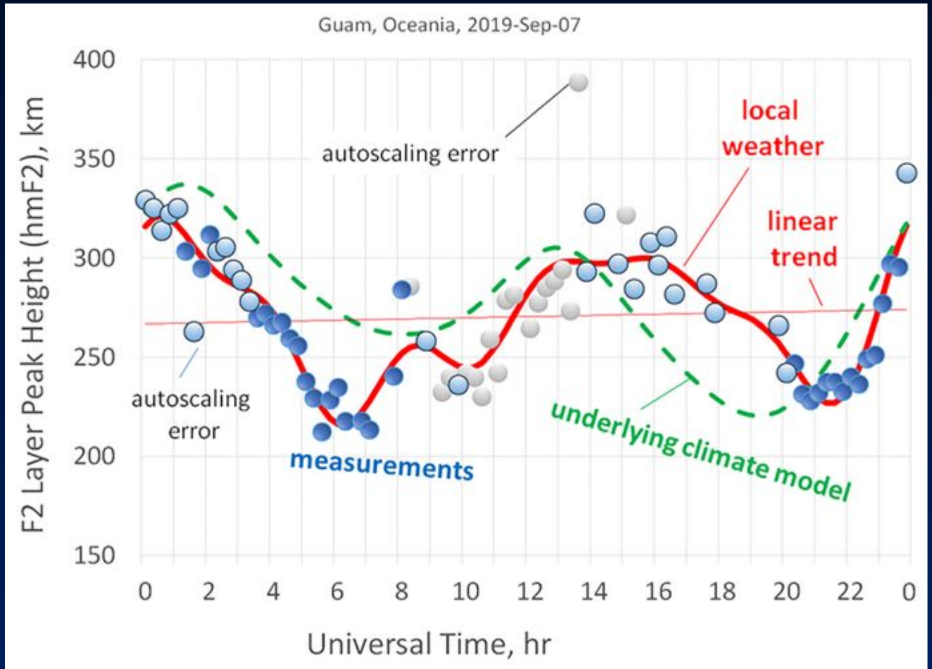
PyIRTAM: A New Module of PyIRI for IRTAM Coefficients

Victoriya V. Forsythe, Ivan Galkin, Sarah E. McDonald, Kenneth F. Dymond, Bruce A. Fritz, Angeline G. Burrell, Katherine A. Zawdie, Douglas P. Drob

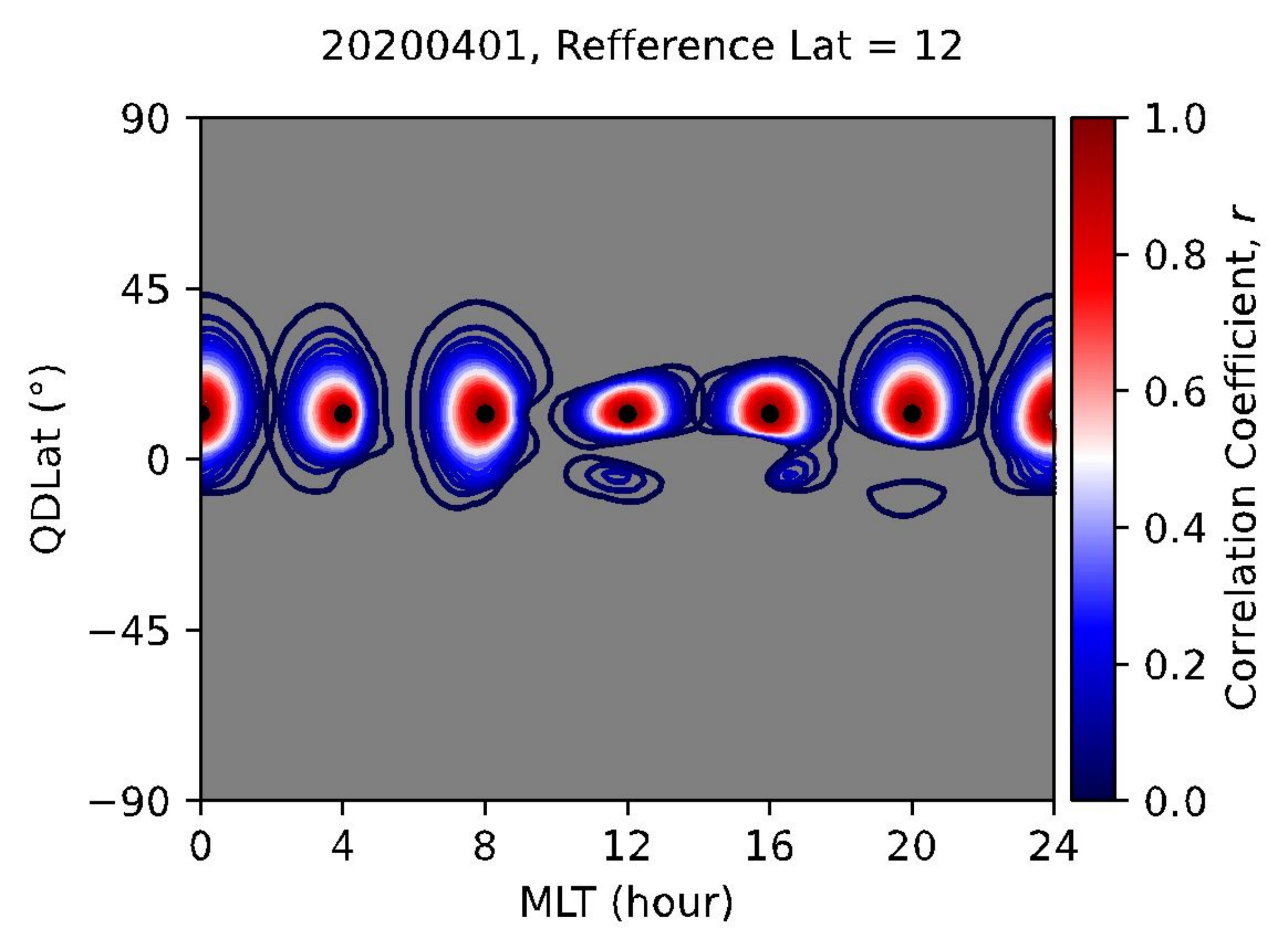
First published: 04 December 2024 | https://doi.org/10.1029/2024SW003965 | Citations: 1



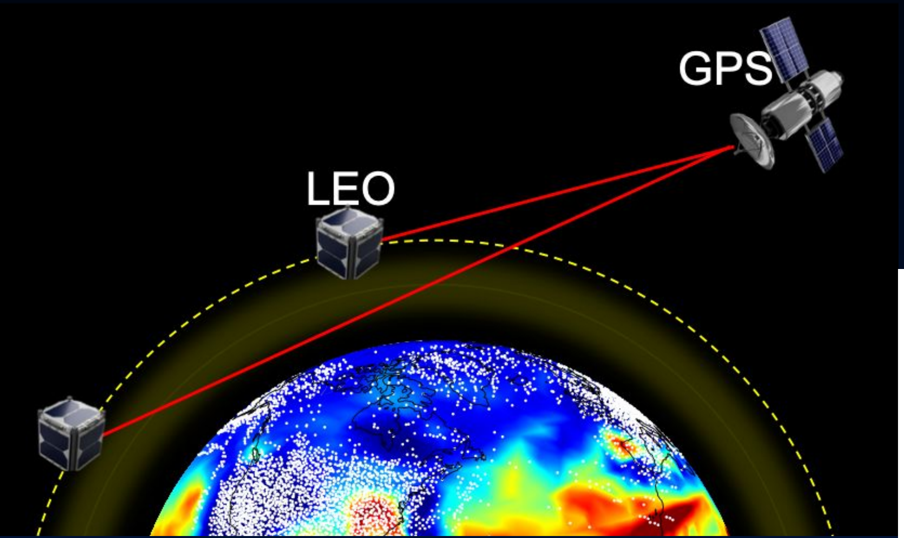
Galkin et al., 2020

Background Error Covariance $\tilde{P}_b$

- Correlations are calculated between deviations of the background and the daily mean in the QDLat-MLT coordinate system.
- Their distribution around reference points reflects magnetic conjugacy in the equatorial region.
- Correlations are localized within 20° great-circle distance (GCD).
- These correlations are used to construct the background covariance matrix.

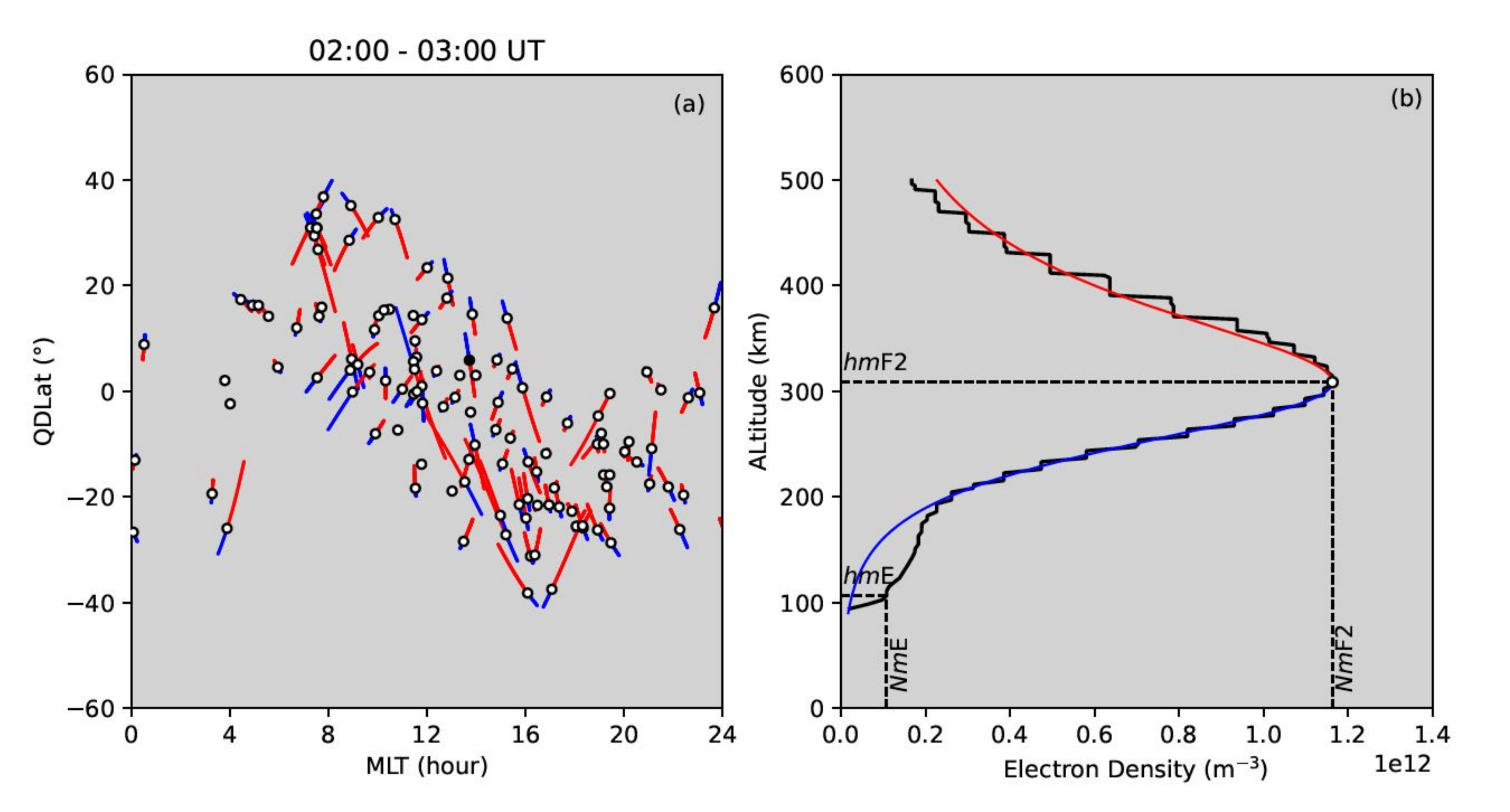


Observations $\vec{y}$



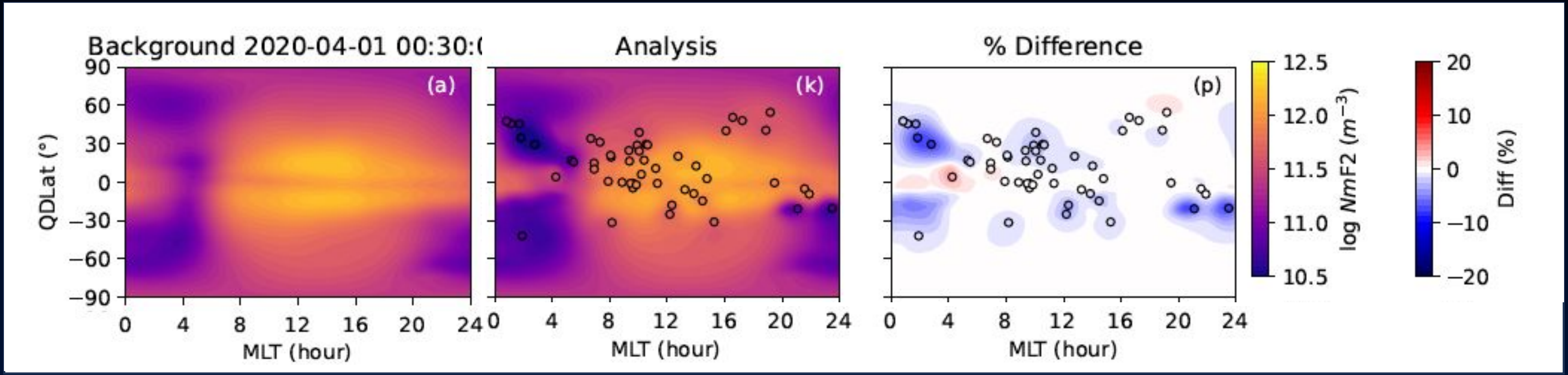
Anchor points are extracted from the data:

- Values and locations are collected for 5 anchor points



- Located at the F2 peak: $NmF2$, $hmF2$, B^{F2}_{bot}, B^{F2}_{top}
- Location of NmE anchor point is slightly different.
- Information is localized to the location of the peak

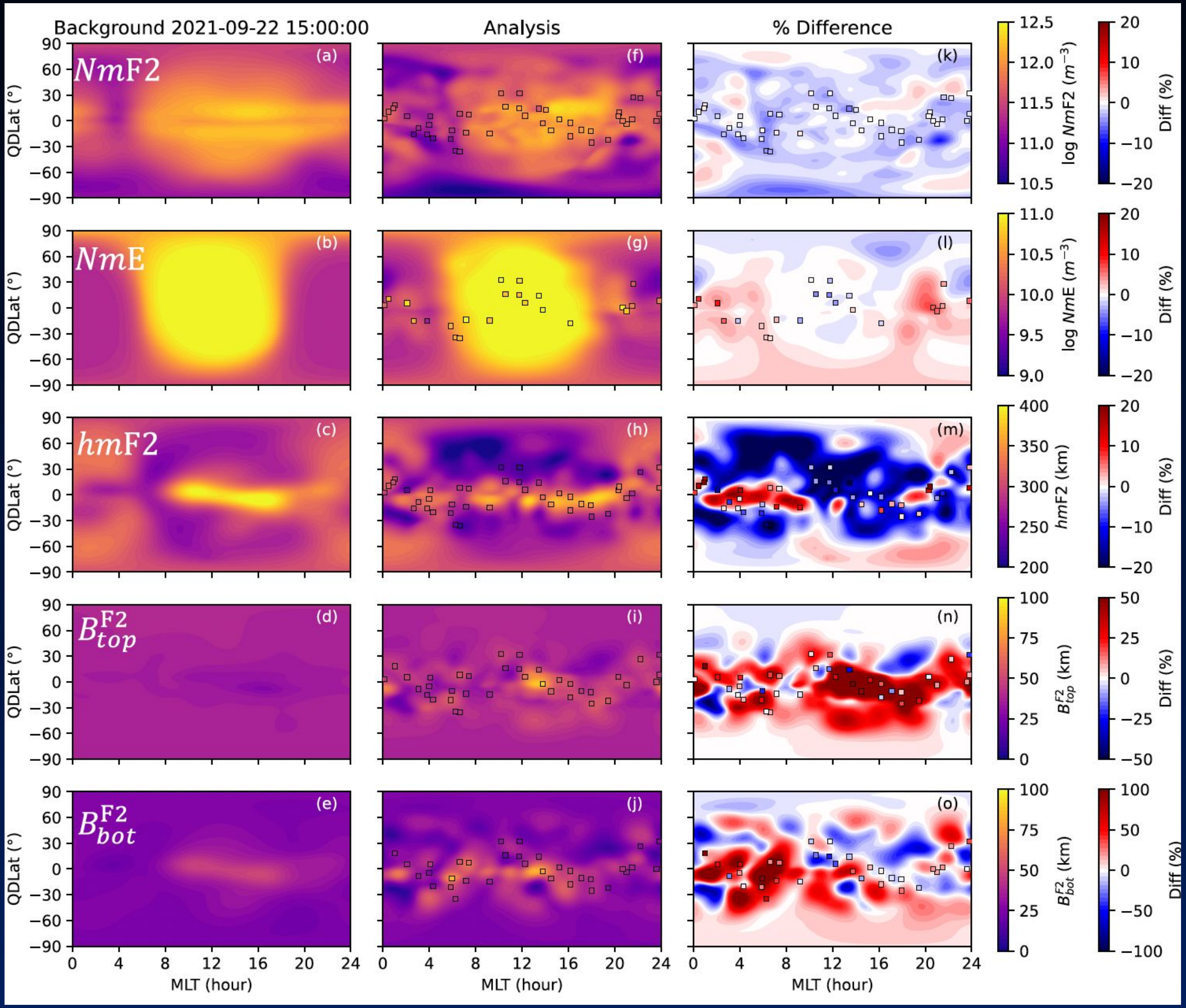
Analysis $\vec{x}_a$: *Nm*F2 Example



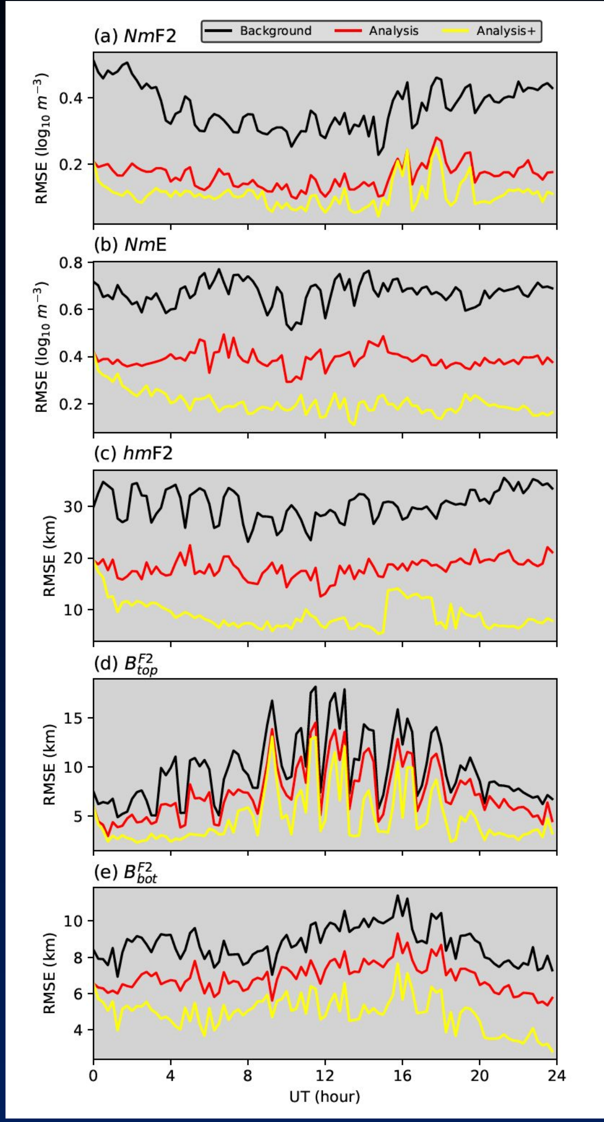
- Anchor points are assimilated into 2-D map of the background parameters as point measurements

$$\vec{x}_a = \vec{x}_b + P_b H^T [H P_b H^T + R]^{-1} [\vec{y}_{data} - H \vec{x}_b]$$

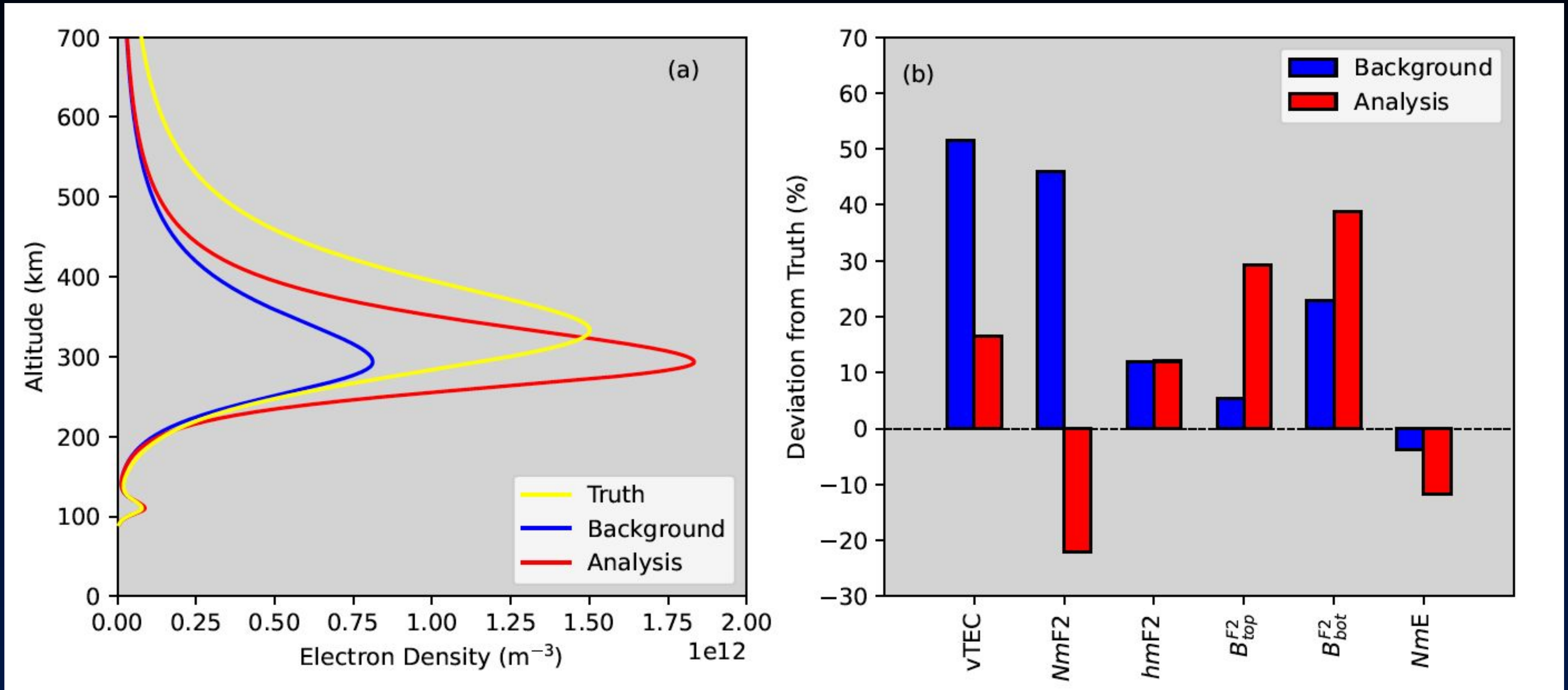
Analysis $\vec{x}_a$: All parameters



- RMSE is reduced for all parameters.
- The vertical structure of the ionosphere is preserved through parametrization.
- The full DA cycle for one day (including preprocessing, covariance calculation, etc.) completes in just a few minutes.



Ingestion of sTEC Data $\vec{y}$



- Abel RO and ionosonde measurements are local
- sTEC data are integral, non-local measurements
- When ingested traditionally, sTEC improves only $NmF2$
- Other parameters remain unchanged ($hmF2$) or degrade (B_{bot}^{F2}, B_{top}^{F2}, NmE)

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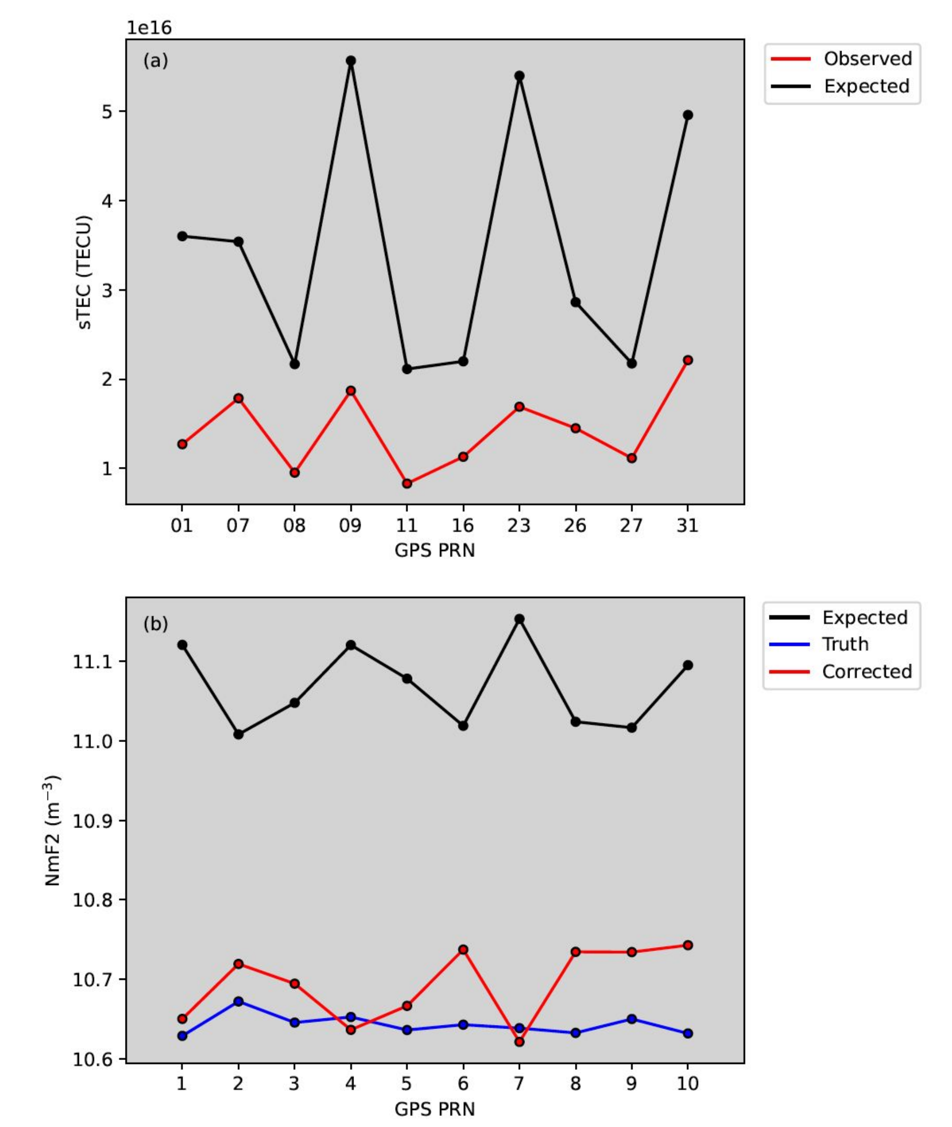
Ingestion of sTEC Data $\vec{y}$

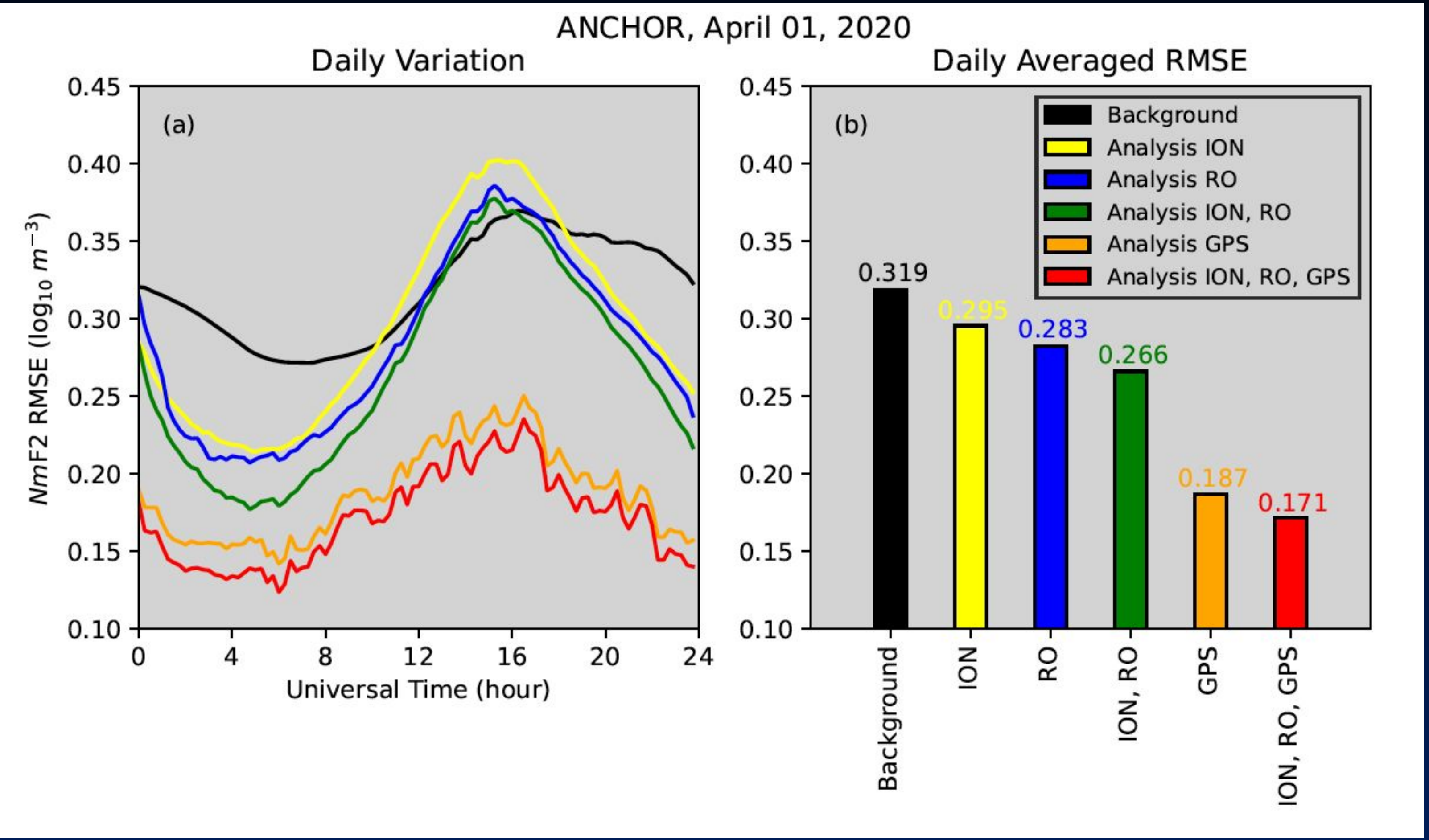
- Since ANCHOR already corrects other parameters with RO and ionosonde data, we focus only on *Nm*F2.
- In the PyIRI formalism:

$$sTEC = \int_{P_r}^{P_t} (F2 + F1 + E)ds$$

- Each layer is represented by an Epstein function
- Only F2 layer depends on NmF2
- Therefore, NmF2 corrections can be calculated analytically from observed sTEC
- The corrected *Nm*F2 values are then ingested as <u>point measurements</u> into the *Nm*F2 background map

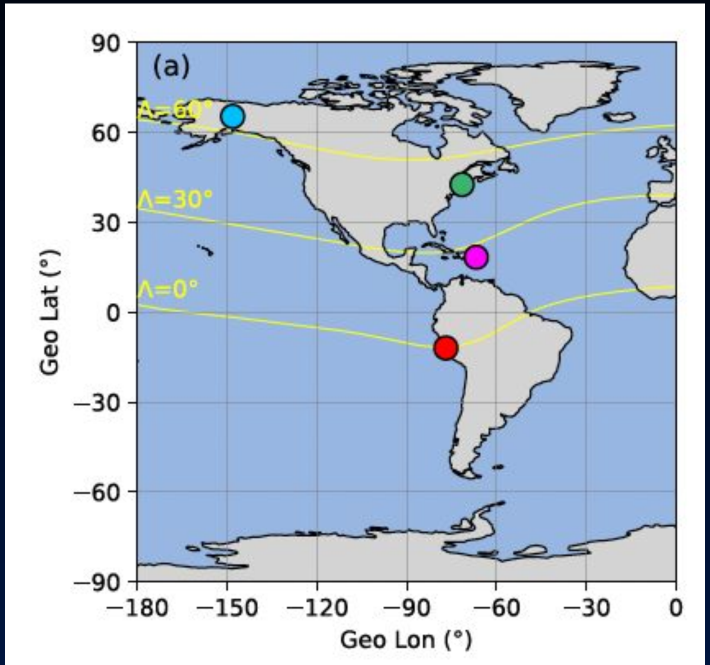


Analysis $\vec{x}_a$: RMSE Reduction

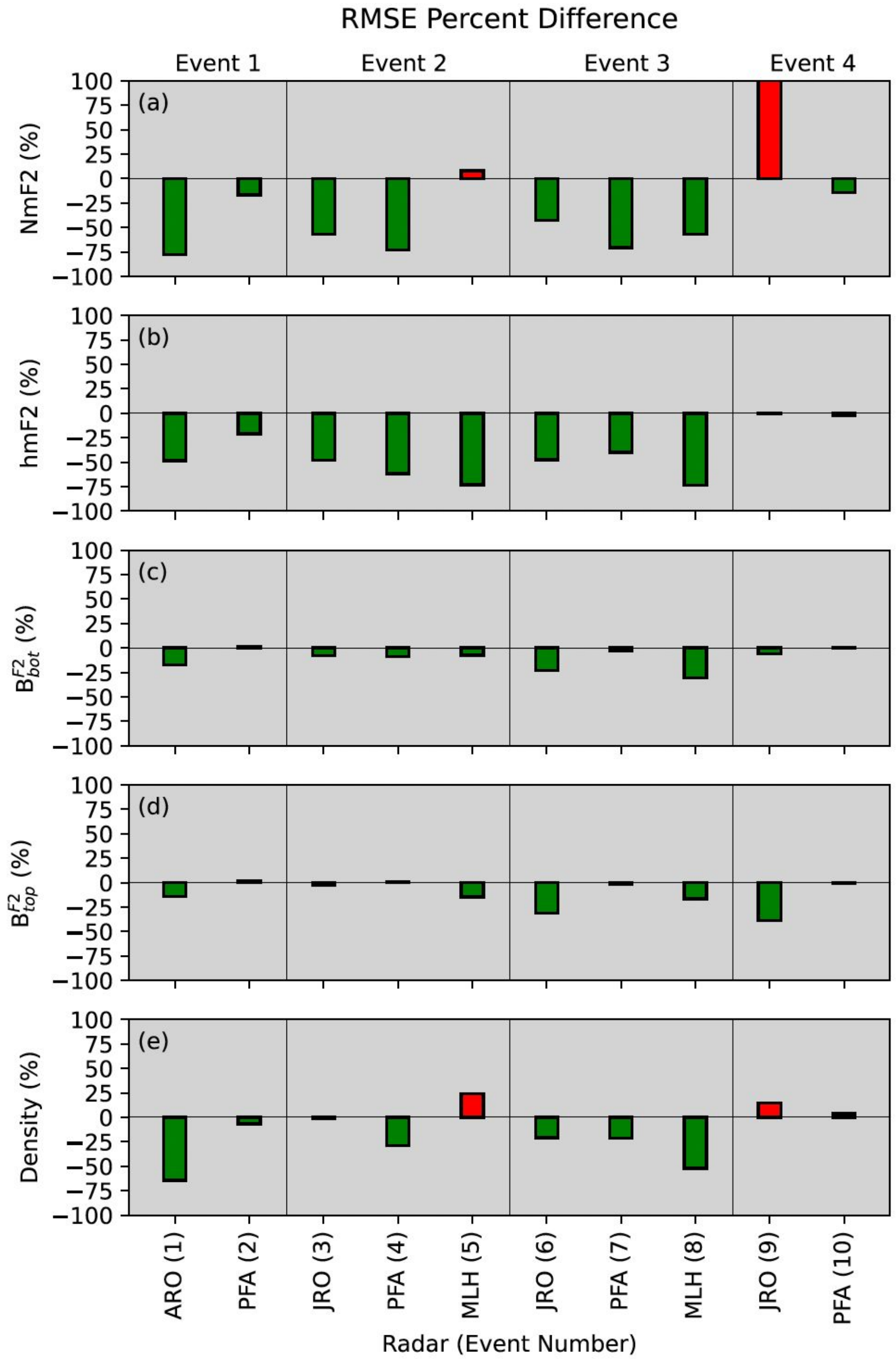


- The sTEC data reduces the daily averaged RMSEs by 42%, when ingested alone, and by 46% when ingested together with the ionosonde and RO data.
- This is a significant improvement over ingesting any other of the available data sources separately or in combination.
- The result were submitted for publication to the DoD Journal

ANCHOR: Validation Campaign (ISR)



- 4 ISR radars
- 4 events (≥2 radars each)
- Up to 75% RMSE reduction
- Strong performance for *hm*F2



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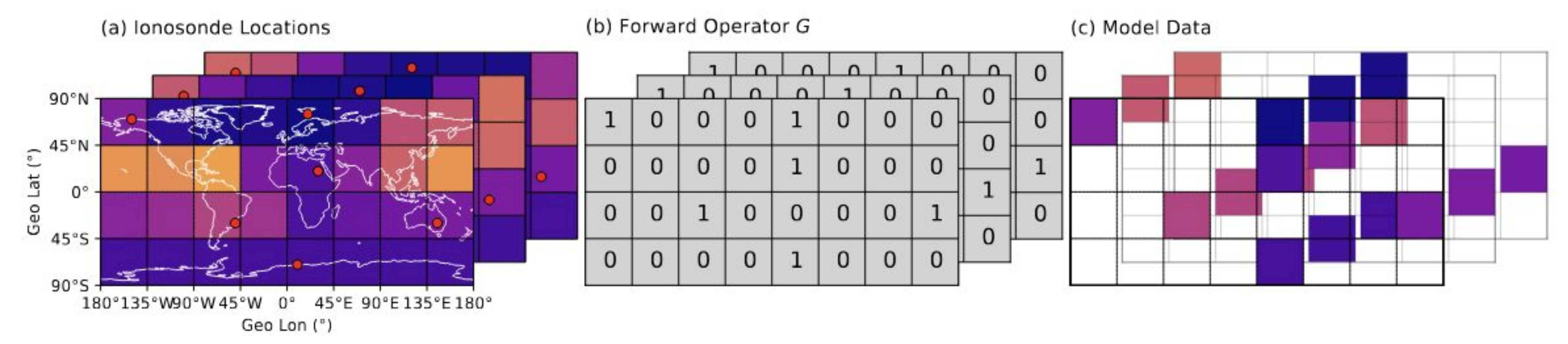
Research Article | Open Access

Validation of ANCHOR Ionospheric Data Assimilation Model Using Incoherent Scatter Radars

Andrew M. Pepper, Victoriya V. Forsythe, Sarah E. McDonald, Katherine A. Zawdie

First published: 01 August 2025 | https://doi.org/10.1029/2024RS008125

Validation: PyVALION Concept



- The need for standardized and reproducible validation practices has become increasingly urgent

- PyVALION introduces a new framework that uses the concept of forward operator

- Enables consistent validation across multiple forecasts and analysis states using a unified methodology.

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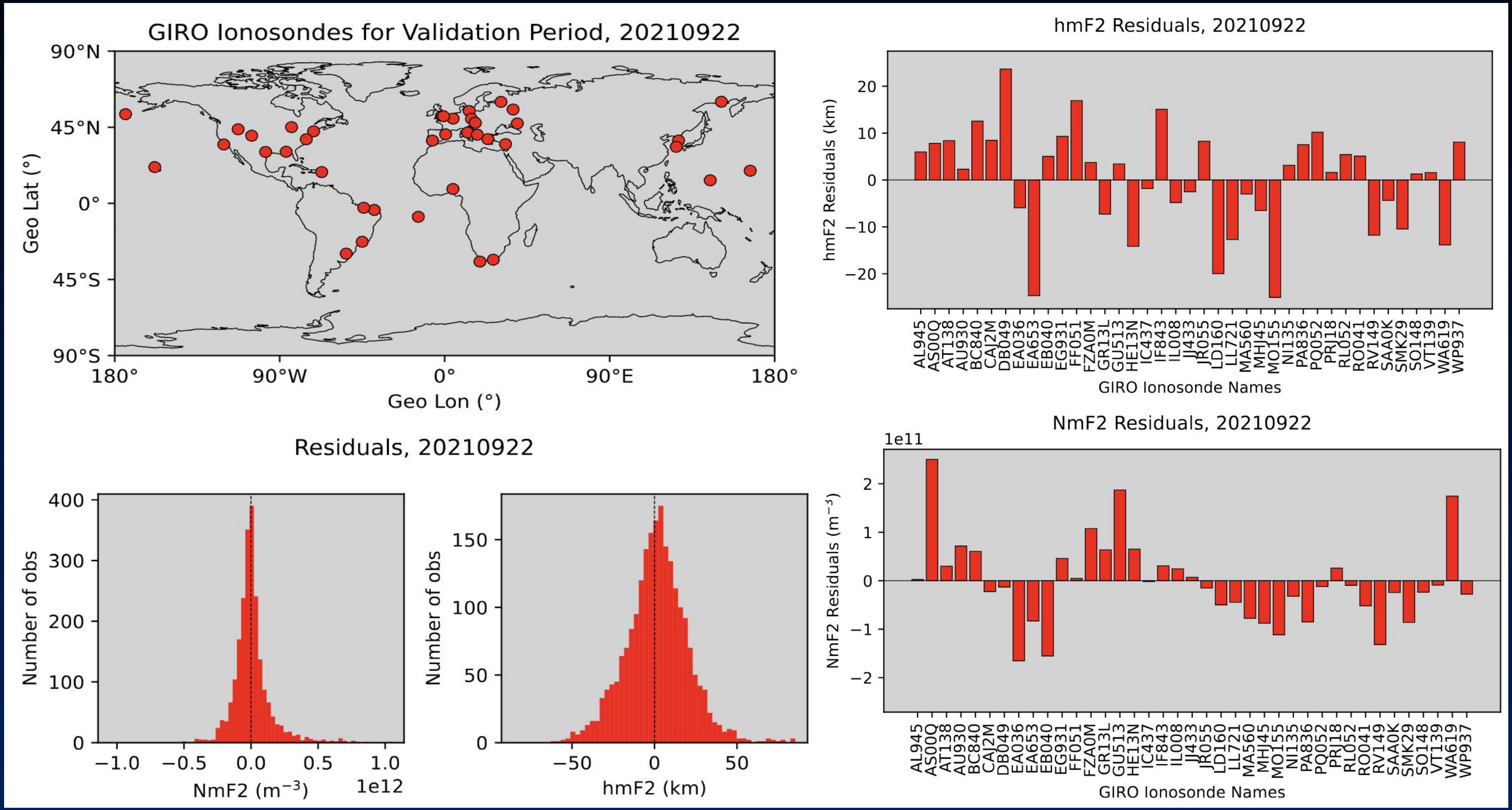
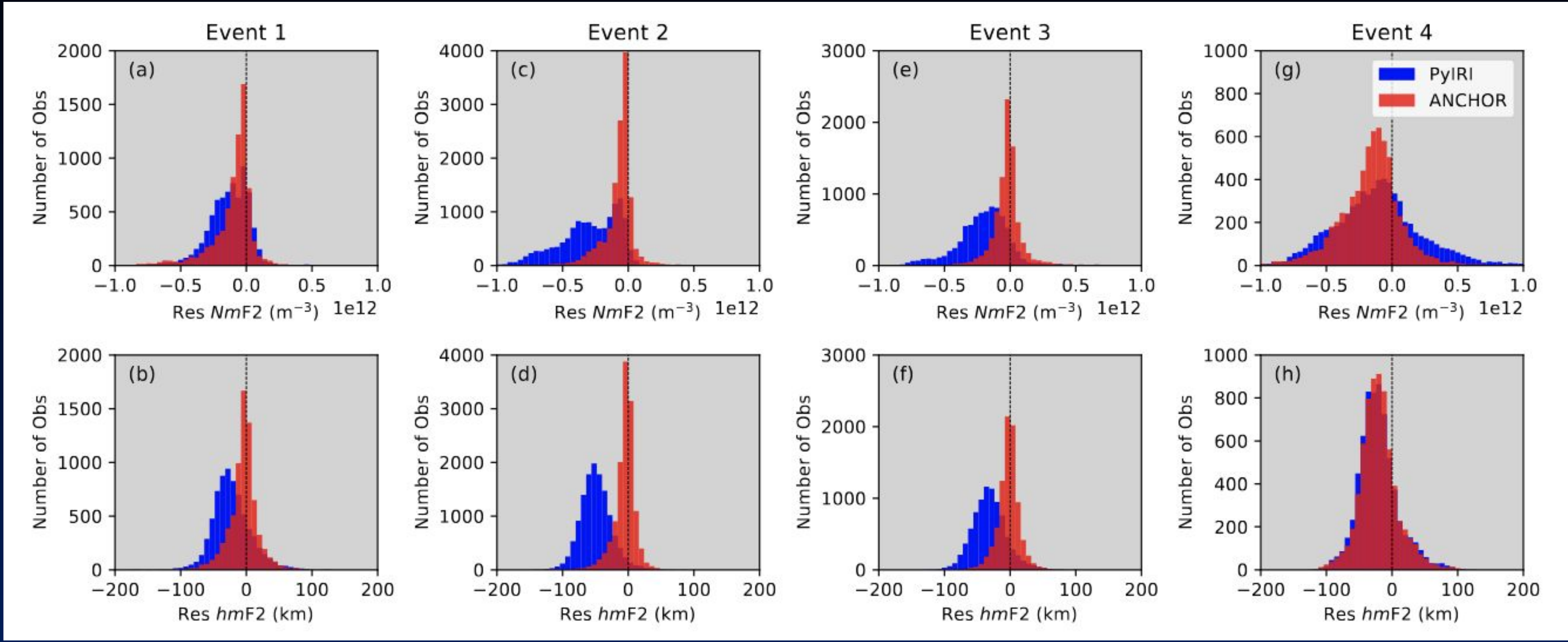
Validation: PyVALION Example



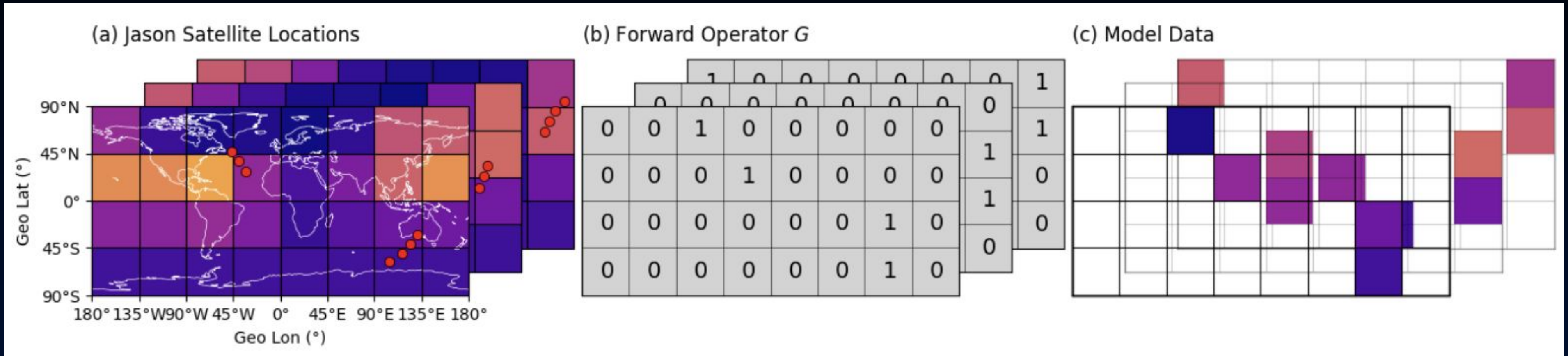
- GIRO data download
- Formation of observation vector $\vec{y}$
- Formation of forward operator matrix $\boldsymbol{H}$
- Plotting functions

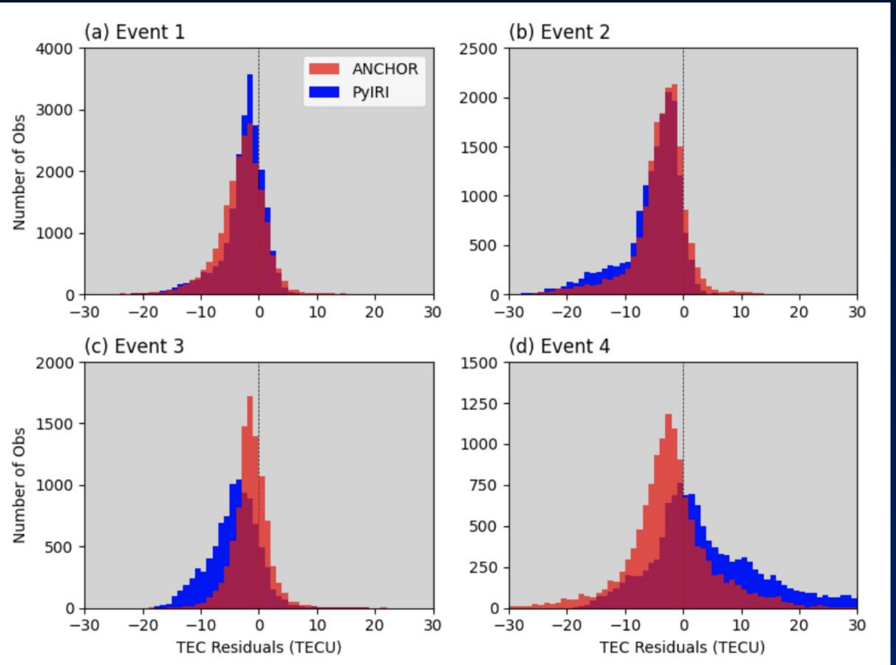
ANCHOR: Validation Campaign (GIRO)



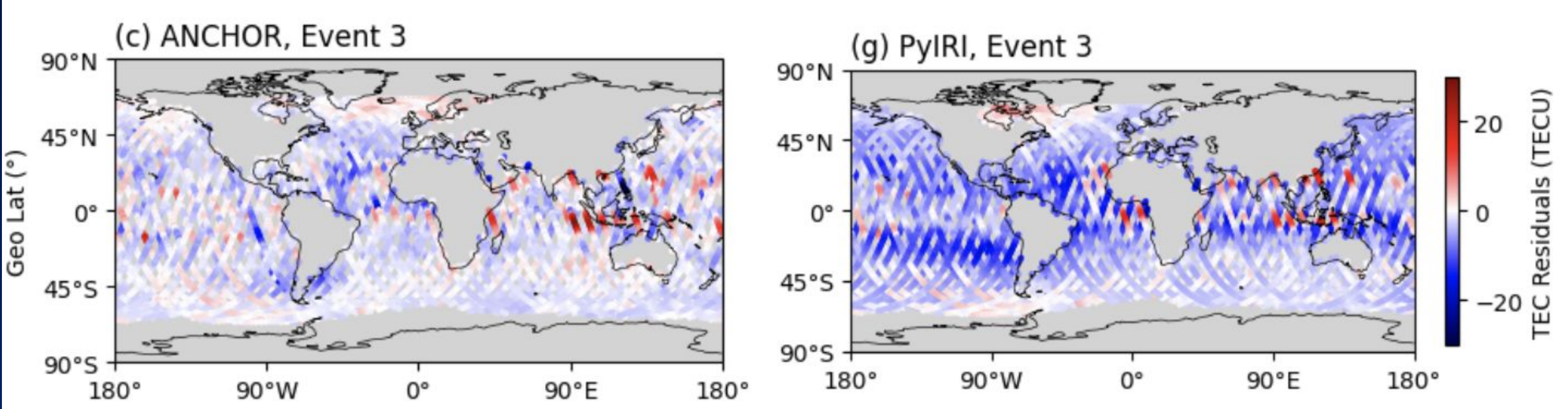
- *NmF2* and *hm*F2 improvement over land

ANCHOR: Validation Campaign (Jason)

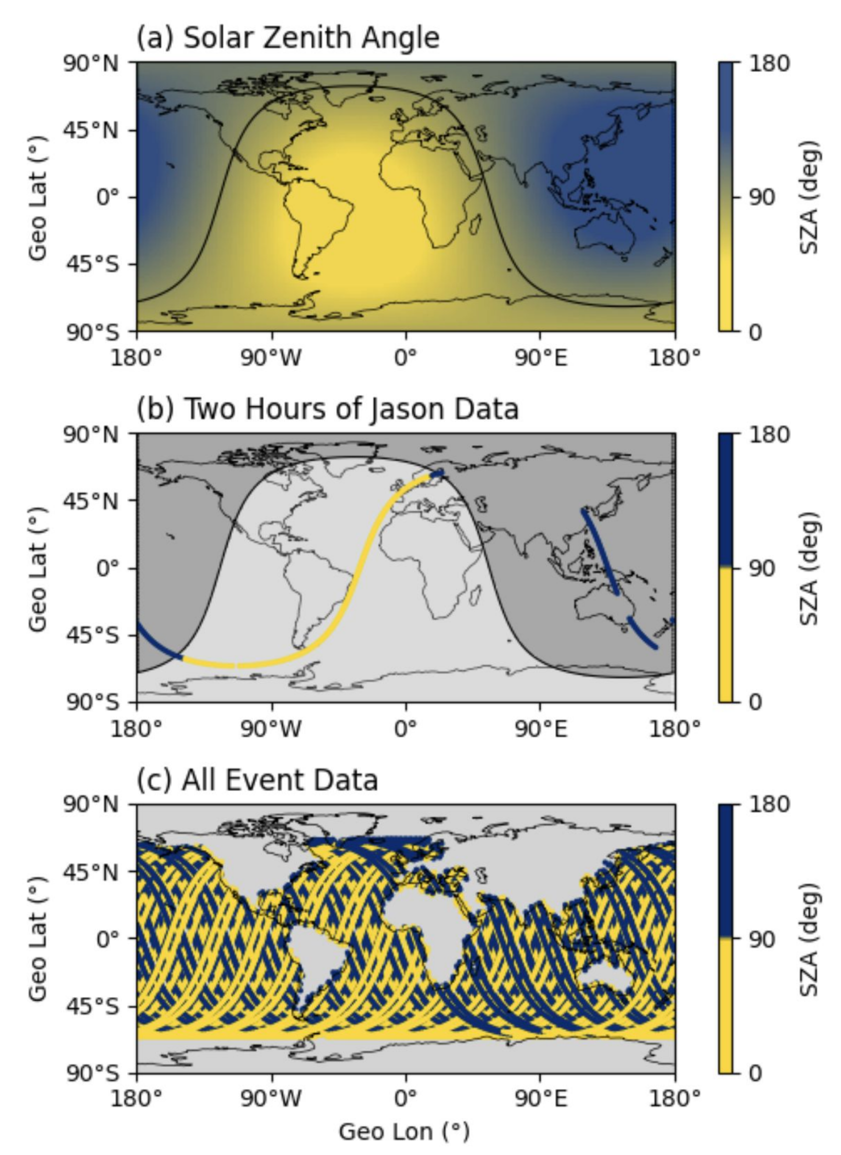




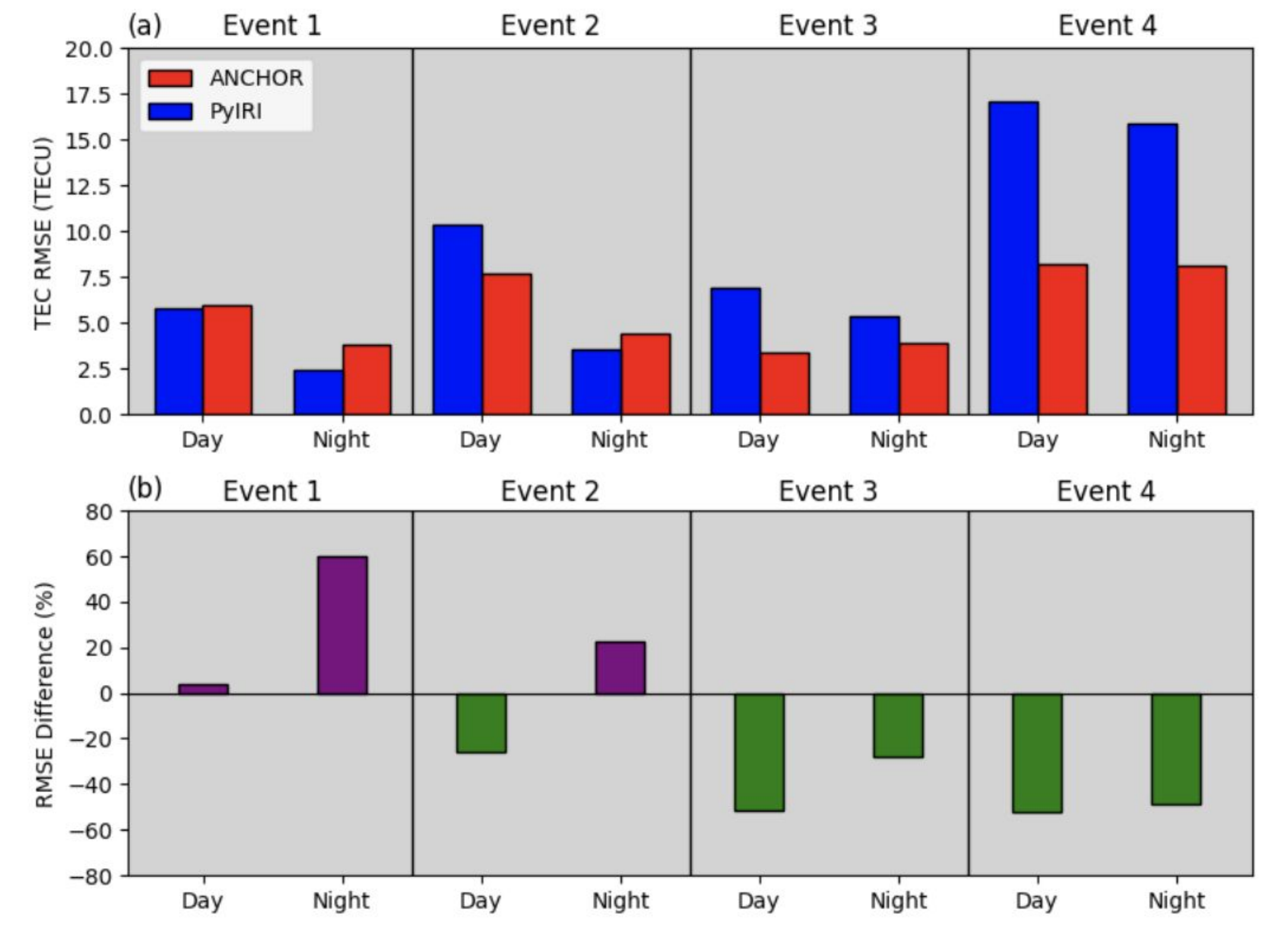
- Performance over oceans
- Calculation of the residuals



ANCHOR: Validation Campaign (Jason)



- Separation between day and night



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Tools For The Community

PyIRI global and fast

https://github.com/victoriyaforsythe/PyIRI

PyIRTAM global and fast

https://github.com/victoriyaforsythe/PyIRTAM

PyVALION Python VALidation for IONosphere

https://github.com/victoriyaforsythe/PyVALION

ANCHOR Ionospheric Data Assimilation

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