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ANCHOR: A New Approach to the Ionospheric Data Assimilation

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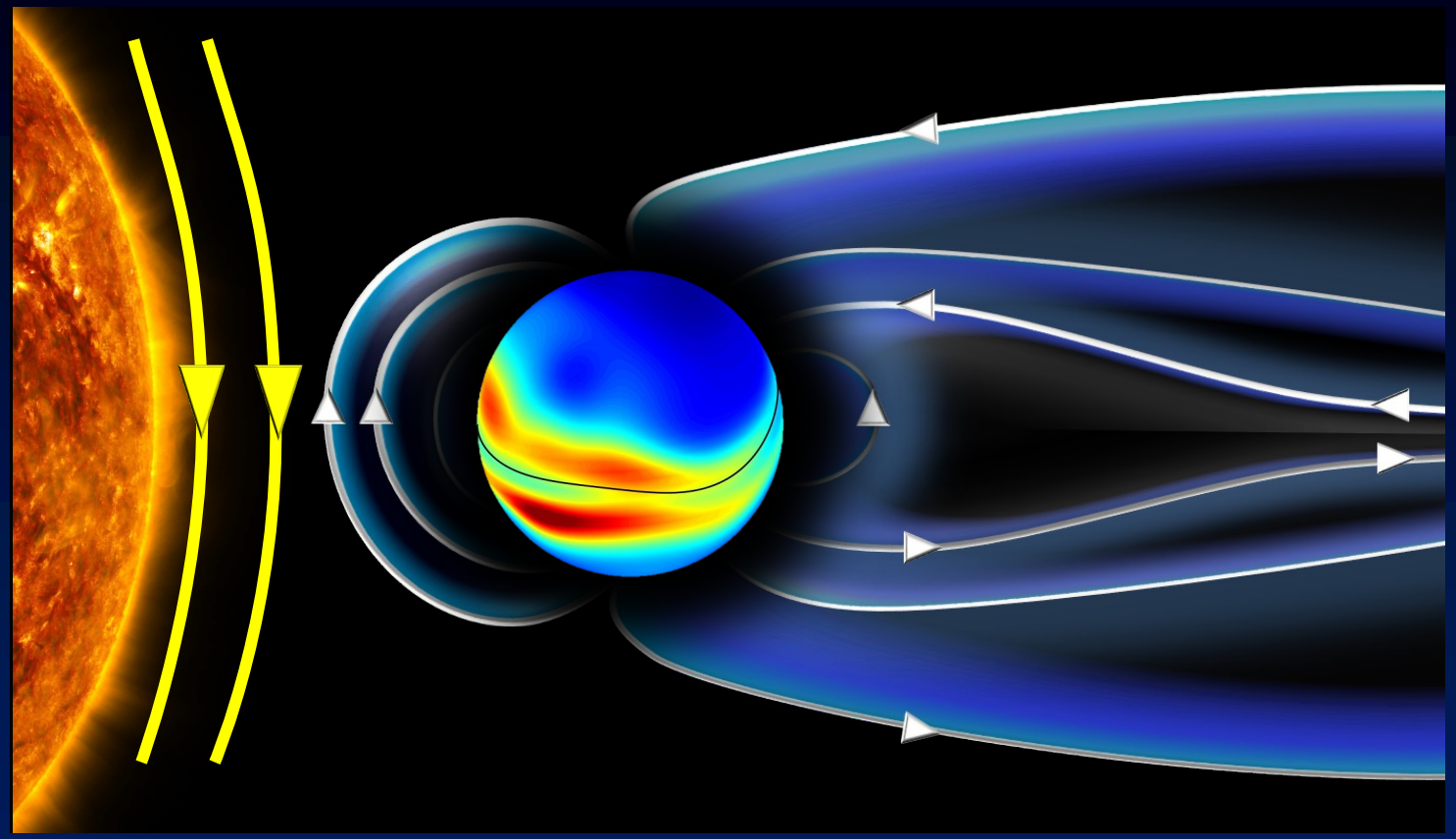
Ionosphere



- The structure of the ionosphere is controlled by solar illumination and plasma transport
- It is tightly coupled with the magnetosphere and the neutral atmosphere
- It is important to nowcast (and to forecast) the global distribution of the ionospheric density
- The nowcasting is obtained by data assimilation, or by fusing the model prediction with the observations

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Why do we need IDA? Operational perspective.

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Why do we need IDA? Scientific perspective.

To study large-scale ionospheric structures:

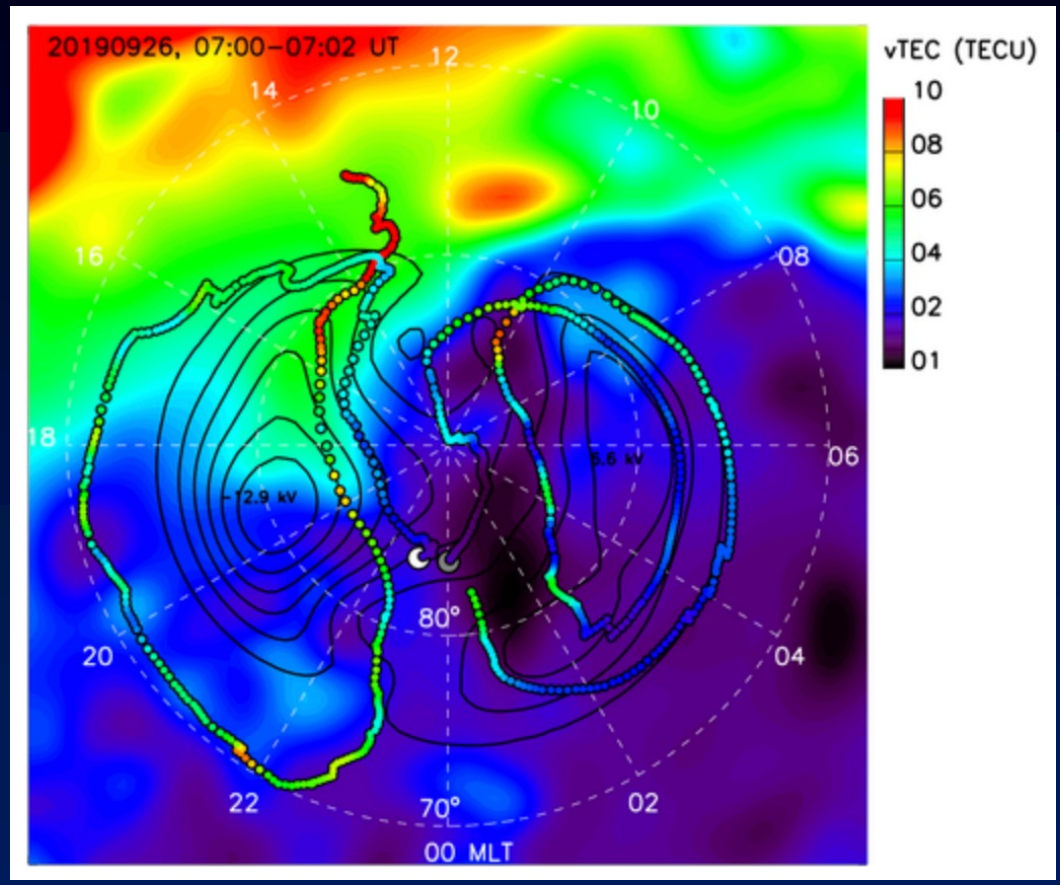
- Storm enhanced density [e.g. Aa et al., 2022]
- Tongue of ionization
- Ionospheric trough
- Equatorial anomalies and plumes

To obtain a bigger picture for smaller events:

- Polar patches [e.g. Negale et al., 2020, Bust et al., 2007]
- Polar holes [e.g. Forsythe et al., 2021]

To study large-scale ionospheric waves:

- Coupling btw sudden stratospheric warming and ionospheric perturbations [e.g. Pedatella et al., 2010]
- Terdiurnal migrating tides [e.g. Luan et al., 2012]
- Tidal waves [e.g. Jhuang et al., 2018]



Forsythe et al., 2021

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Ionospheric DA Goals at NRL

- Better specification of the bottom-side parameters
- Reliable results
- Fast computational time
- Rapid re-analysis

ANCHOR
Ionospheric Data Assimilation

?

- HF Communications
- Over-the-horizon Radars

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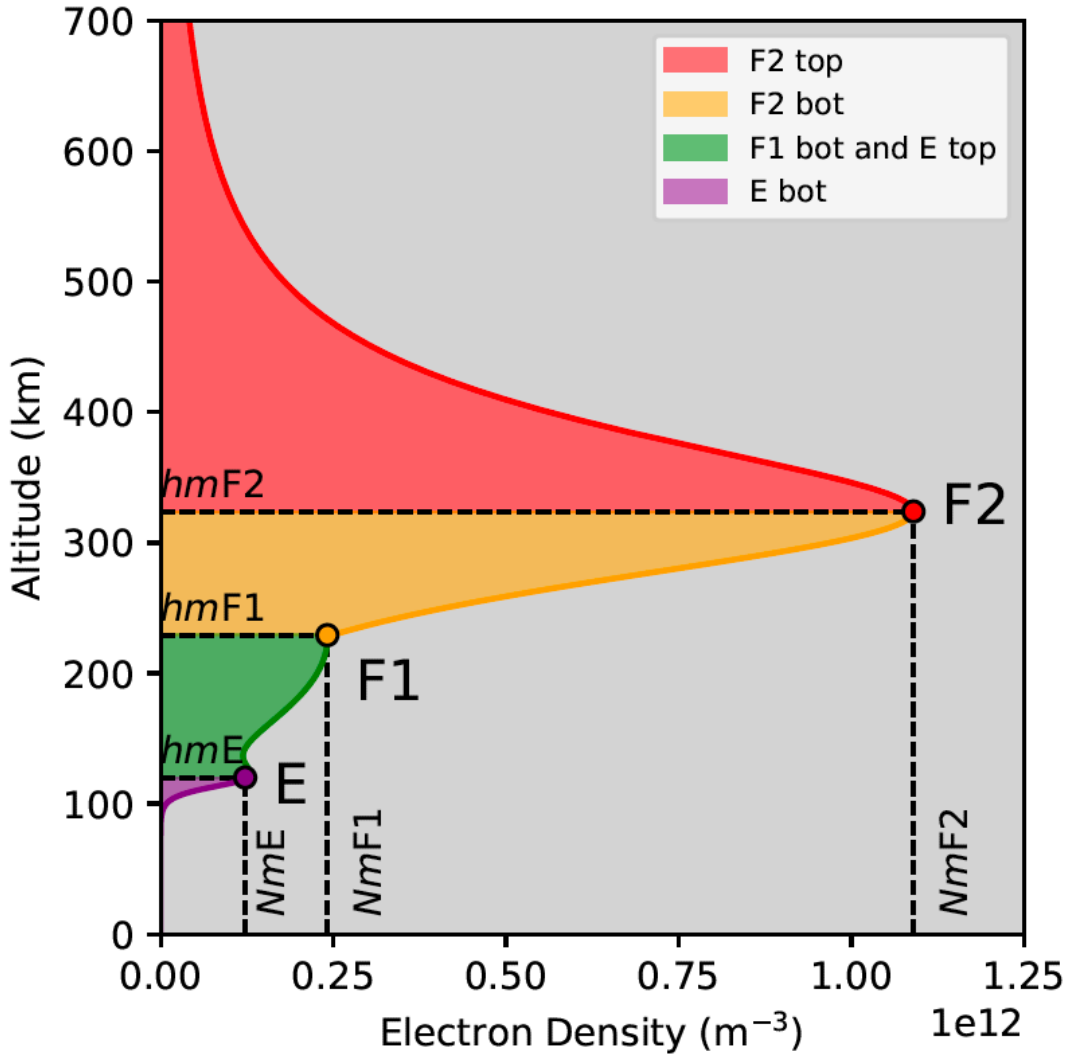
Parametrization in ANCHOR



A realistic EDP can be constructed with 12 parameters:

12 anchor points

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

Updated as model:
- $Nm\mathrm{F1}$
- $hm\mathrm{F1}$
- B_{bot}^{F1}

Assimilation:
- $Nm\mathrm{F2}$
- $hm\mathrm{F2}$
- B_{bot}^{F2}
- B_{top}^{F2}
- $Nm\mathrm{E}$

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Background $\vec{x}_b$

- A novel fully Python tool was developed at NRL
- A classical IRI model was re-designed to be suitable for high spatial and temporal resolution grids
- A daily run with irregular grid and 15-min time resolution, requires 6 million executions of FORTRAN IRI
- Same can be done in 3 seconds with PyIRI
- With a special mode it takes only 3 seconds to obtain global ionospheric parameters for the duration of the entire year

Space Weather®

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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

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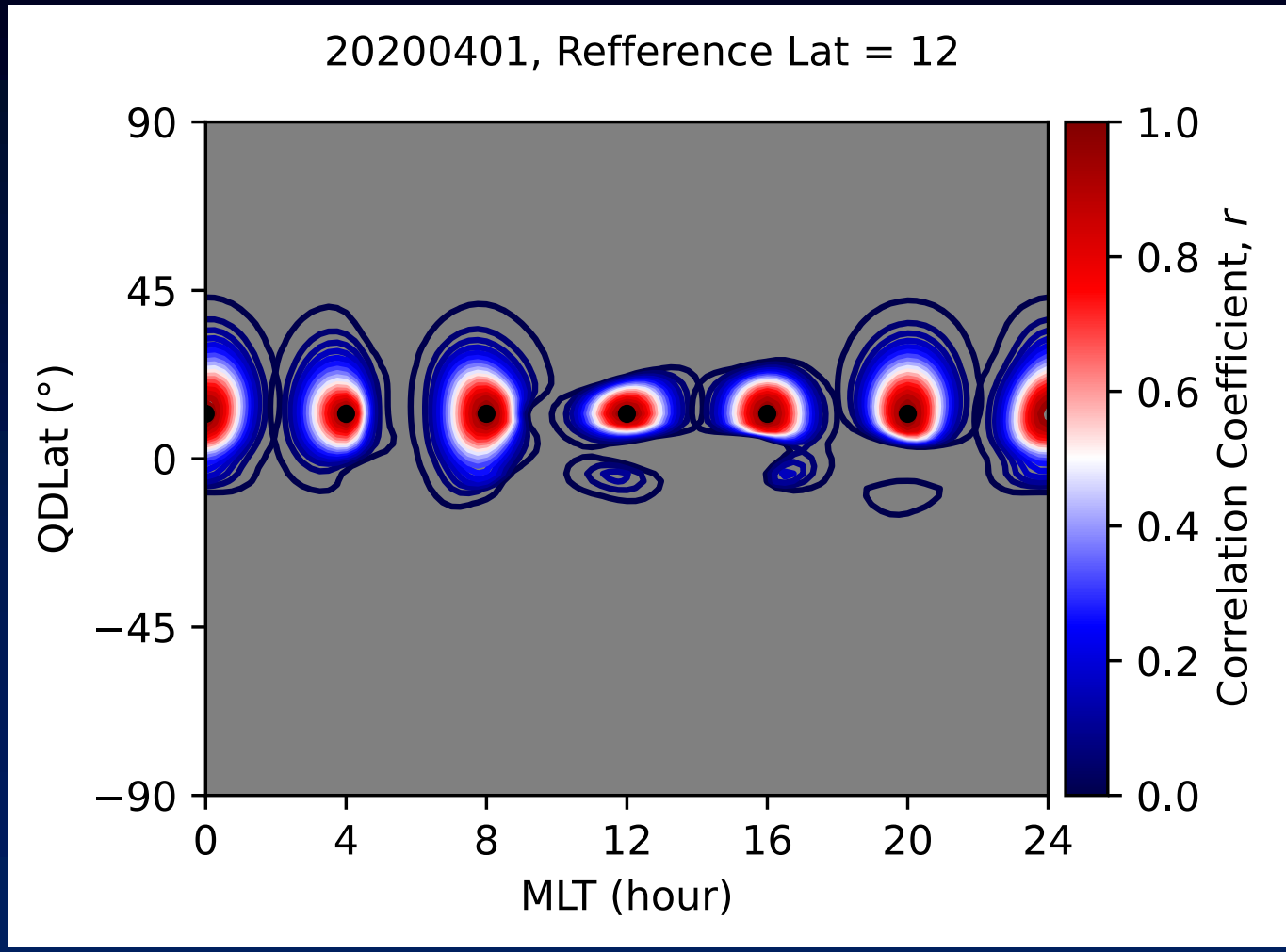
Background Error Covariance $\tilde{P}_b$

- The correlations between deviations of the background from the daily mean are calculated.
- The distribution of the correlations around the reference points reflect the magnetic conjugacy in the equatorial region.
- The correlations are localized to 20 deg of GCD.
- These correlations are used to form the background covariance matrix.



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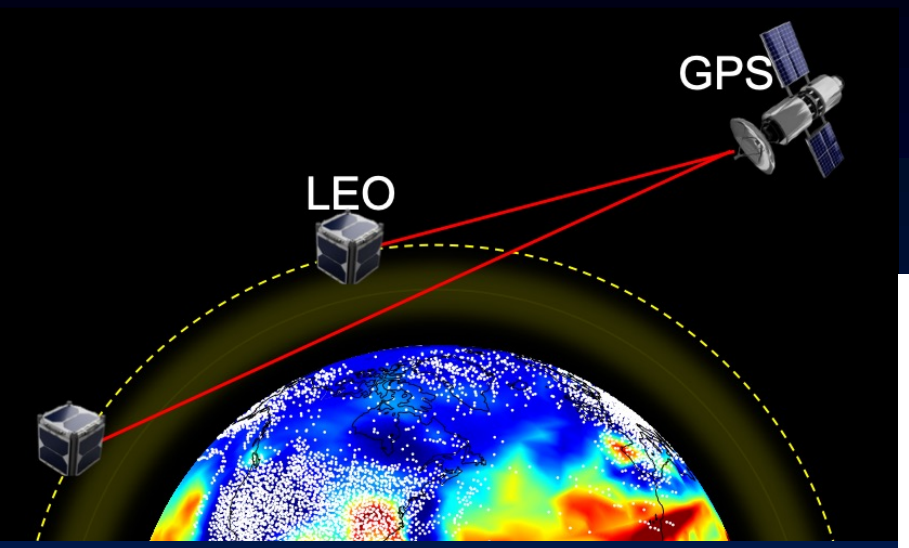
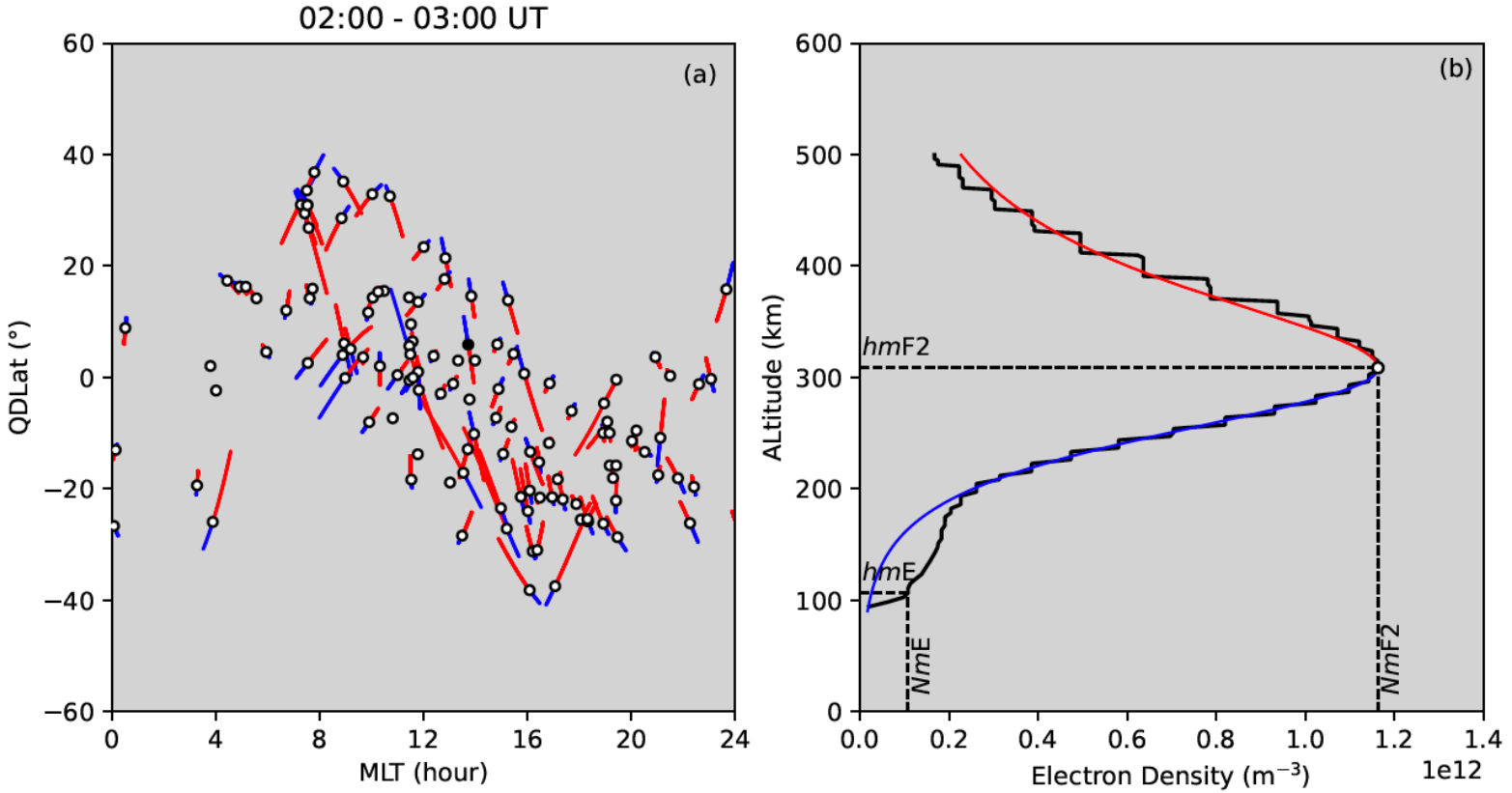
Observations $\vec{y}$



Anchor points are extracted from the data:

- Values and locations are collected for 5 anchor points



- Located at the F2 peak: $NmF2$, $hmF2$, B_{bot}^{F2}, B_{top}^{F2}
- Location of NmE anchor point will be slightly different.

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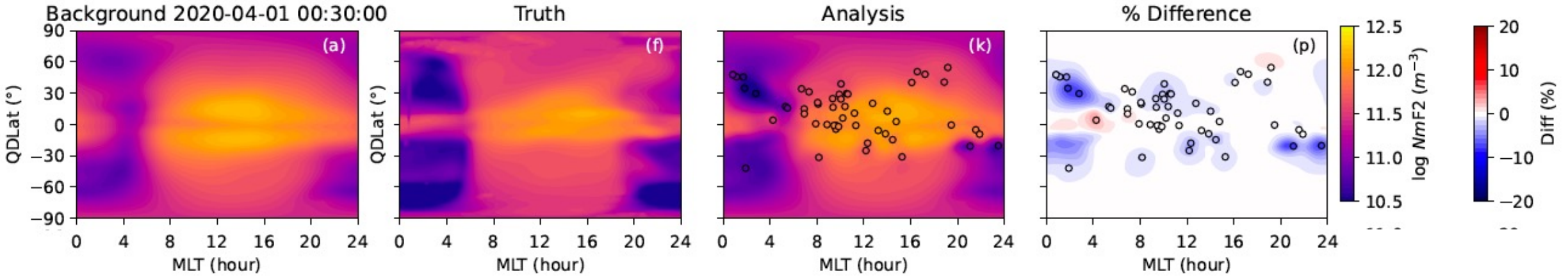
Analysis $\vec{x}_a$: *Nm*F2 Example



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

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

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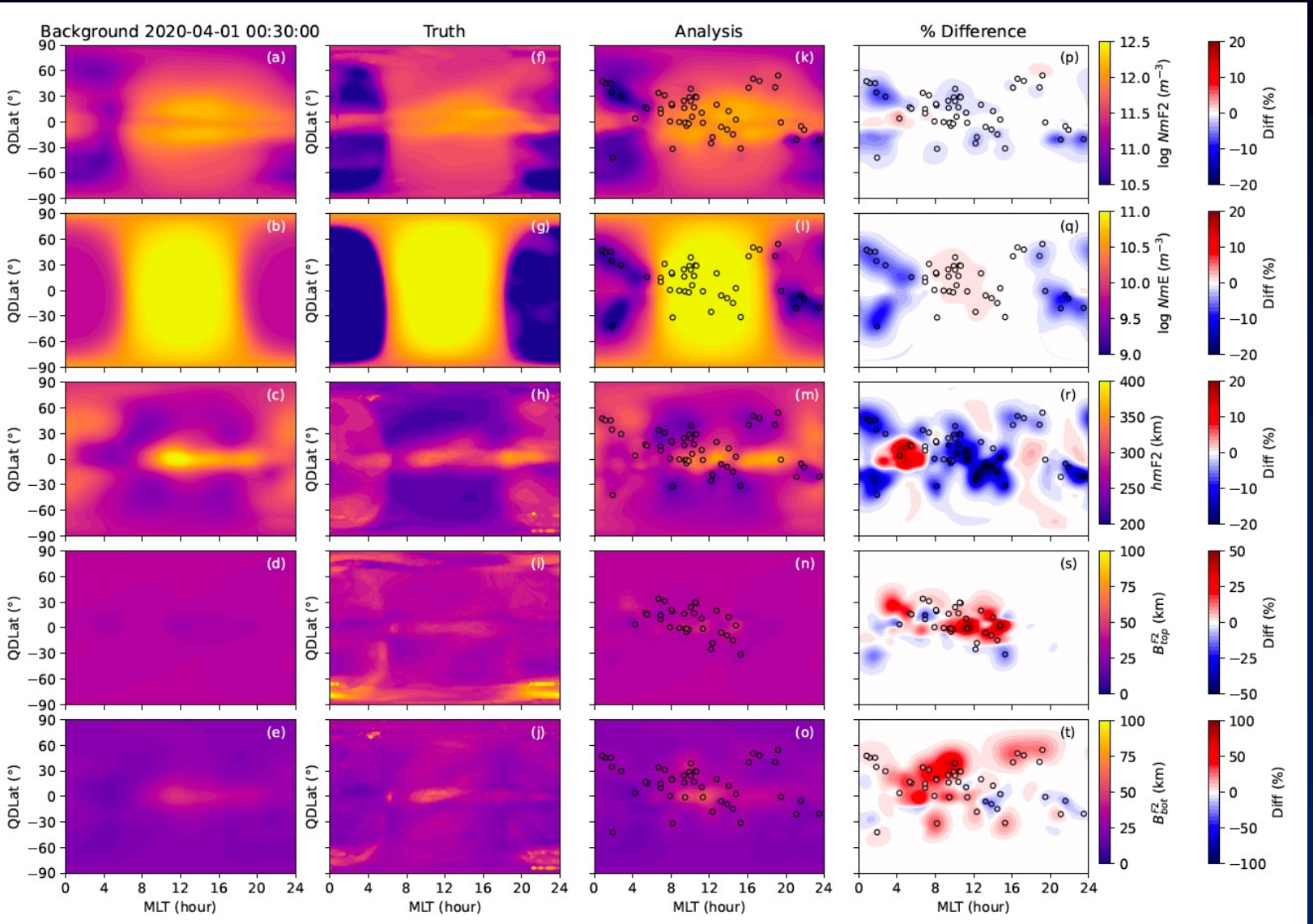
Analysis $\vec{x}_a$: All parameters



NmF2

NmE

hmF2

B top

B bot

- Assimilation is performed simultaneously for all parameters
- Parameters are treated as independent

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RMSEs

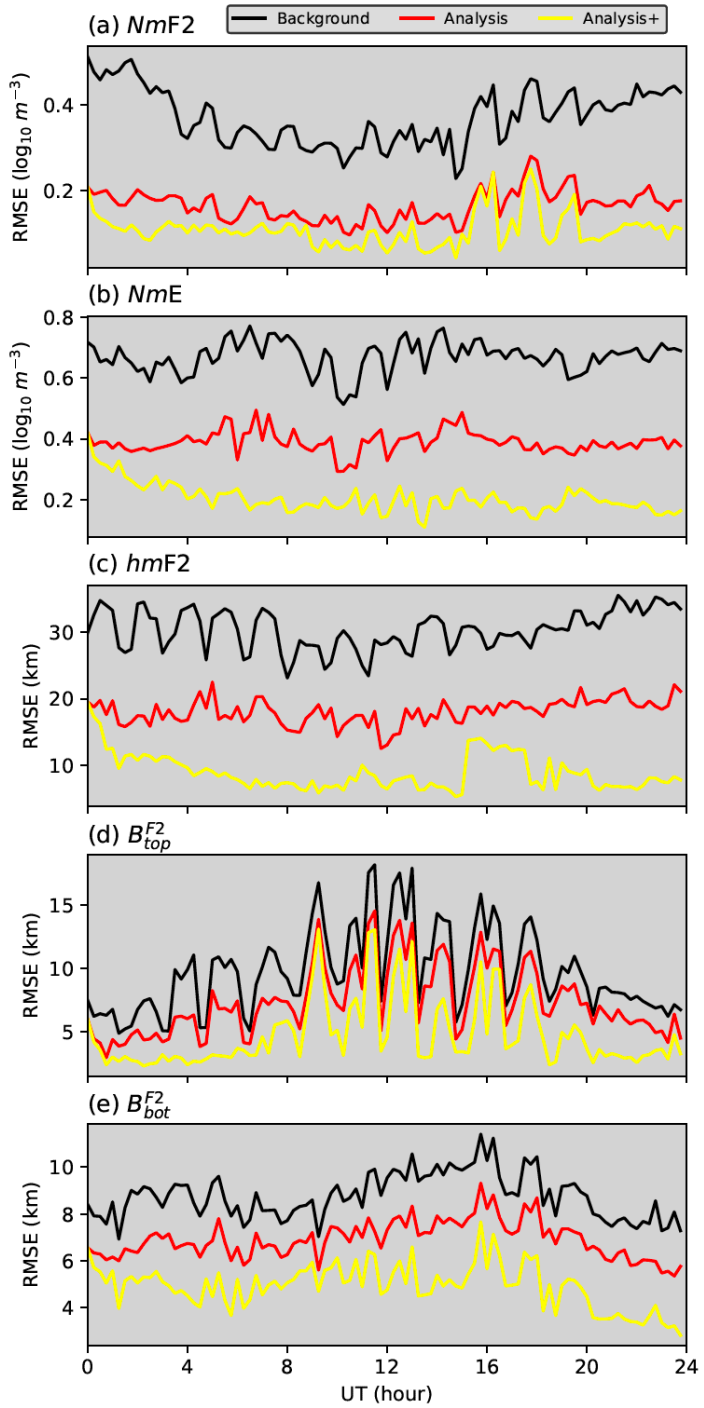
- The RMSEs are reduced for all parameters.
- The vertical structure of the ionosphere is preserved, because of the parametrization
- The DA takes only several minutes for the entire day, which includes data pre-processing, covariance calculation, etc.

ANCHOR: Global Parametrized Ionospheric Data Assimilation

ATMOSPHERIC SCIENCES | GEOPHYSICS

ANCHOR | IONOSPHERE | IONOSPHERIC DATA ASSIMILATION | KALMAN FILTER | PARAMETRIZATION | PYIRI

Victoriya Forsythe, Sarah E McDonald, Kenneth F. Dymond, Bruce Aaron Fritz, Angeline Gail Burrell, Katherine Anne Zawdie, Douglas Drob, Meghan Burleigh, Dustin A Hickey, Christopher Metzler, David Derieg Kuhl, Daniel Hodyss, Joseph Hughes



NmF2

NmE

hmF2

B top

B bot

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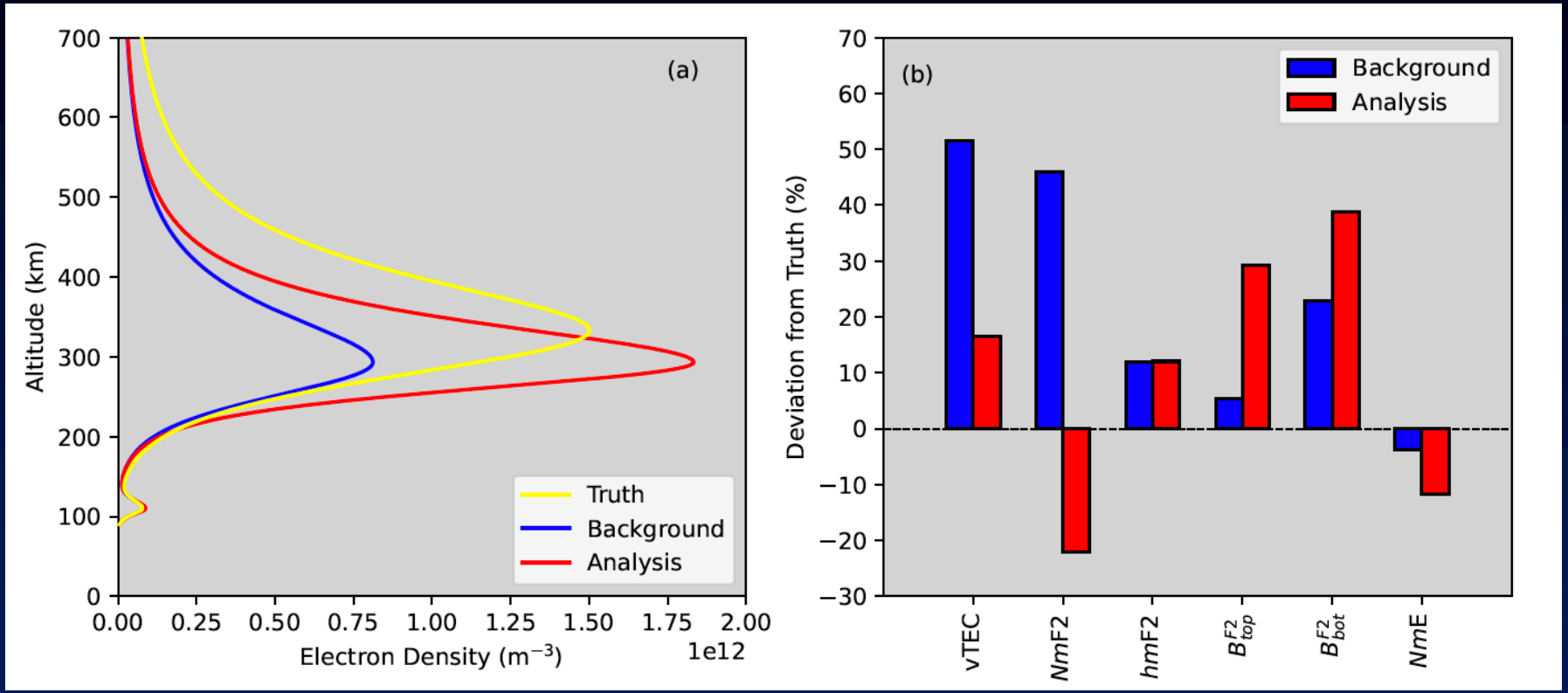
Ingestion of sTEC Data $\vec{y}$



- RO and Ionosonde measurements are local
- sTEC data are integral measurements
- Integral measurements are non-local
- If ingested in a traditional way, it can improve only $Nm\mathrm{F2}$
- Other parameters are unchanged ($hm\mathrm{F2}$) or become worse (B^{F2}_{bot}, B^{F2}_{top}, $Nm\mathrm{E}$)

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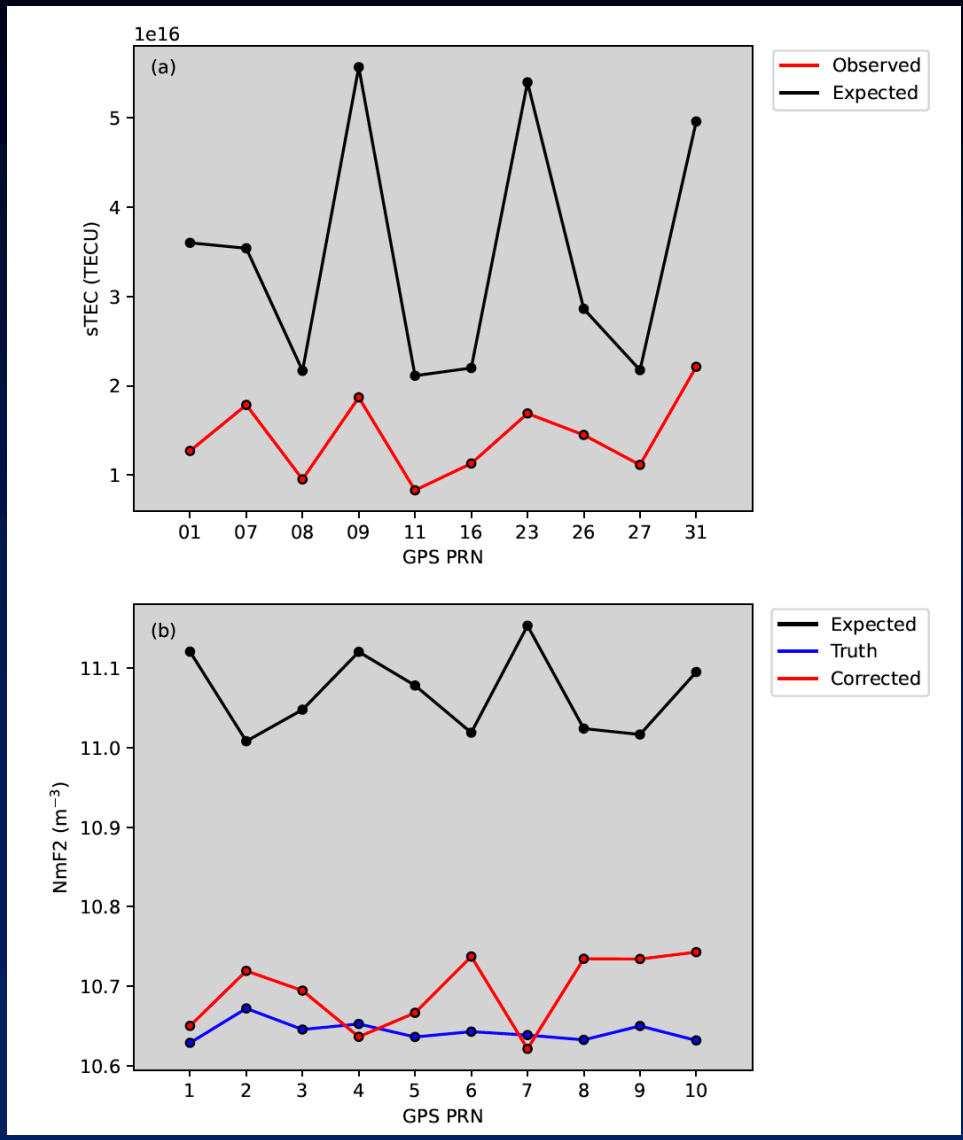
Ingestion of sTEC Data $\vec{y}$

- Since ANCHOR corrects other parameters with RO and ionosonde data, we focus only on NmF2
- According to PyIRI formalism:

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

- Each layer is expressed as Epstein function
- Only *F2* is a function of NmF2
- NmF2 correction can be analytically calculated from the observed sTEC
- Obtained NmF2 values are then ingested as point measurements into NmF2 background



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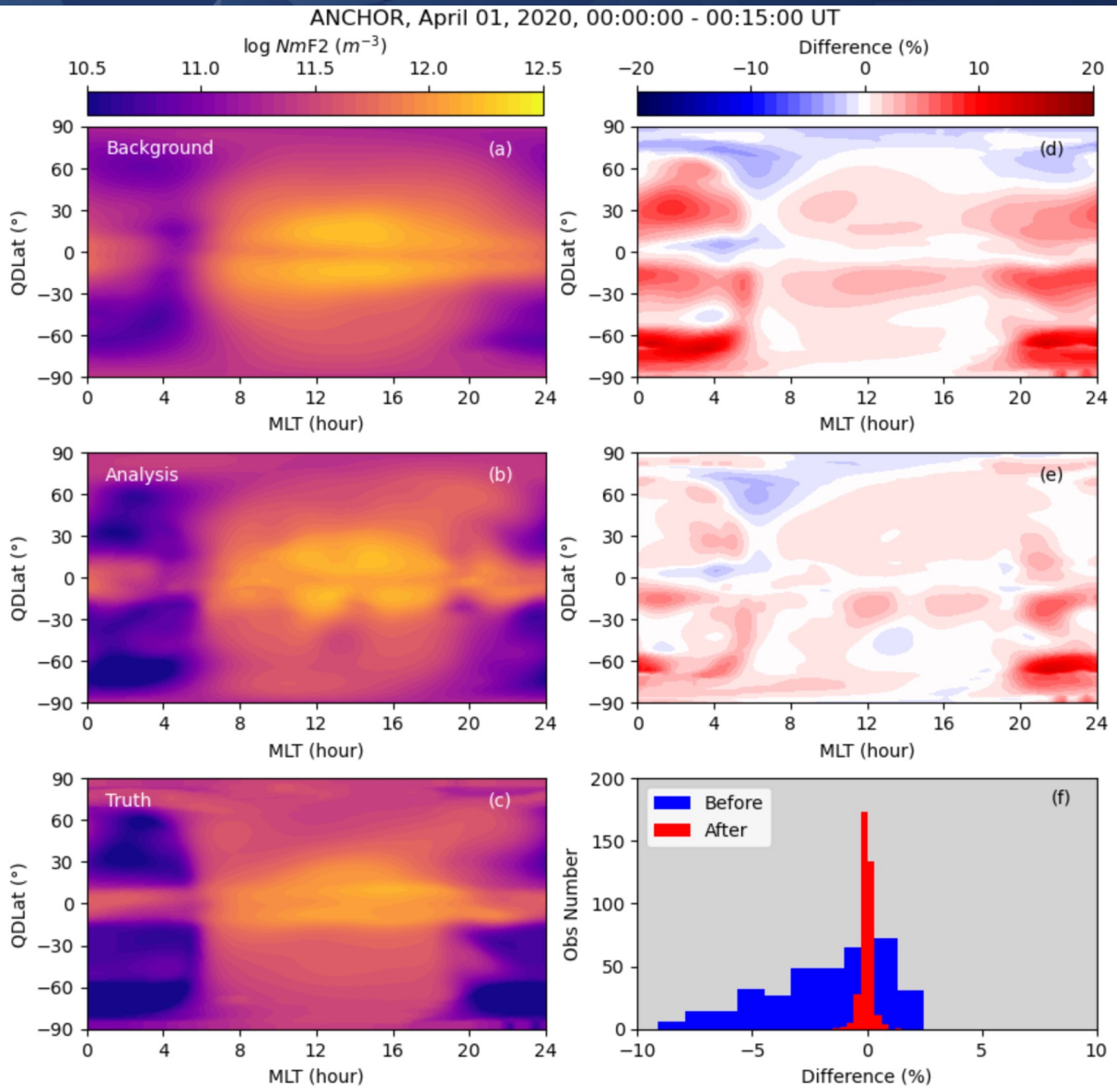
Analysis $\vec{x}_a$: with sTEC observations



- Obtained NmF2 values are ingested as point measurements into NmF2 background
- This significantly improves the NmF2 nowcasting
- To quantify the influence of sTEC data the runs with different data sets were completed

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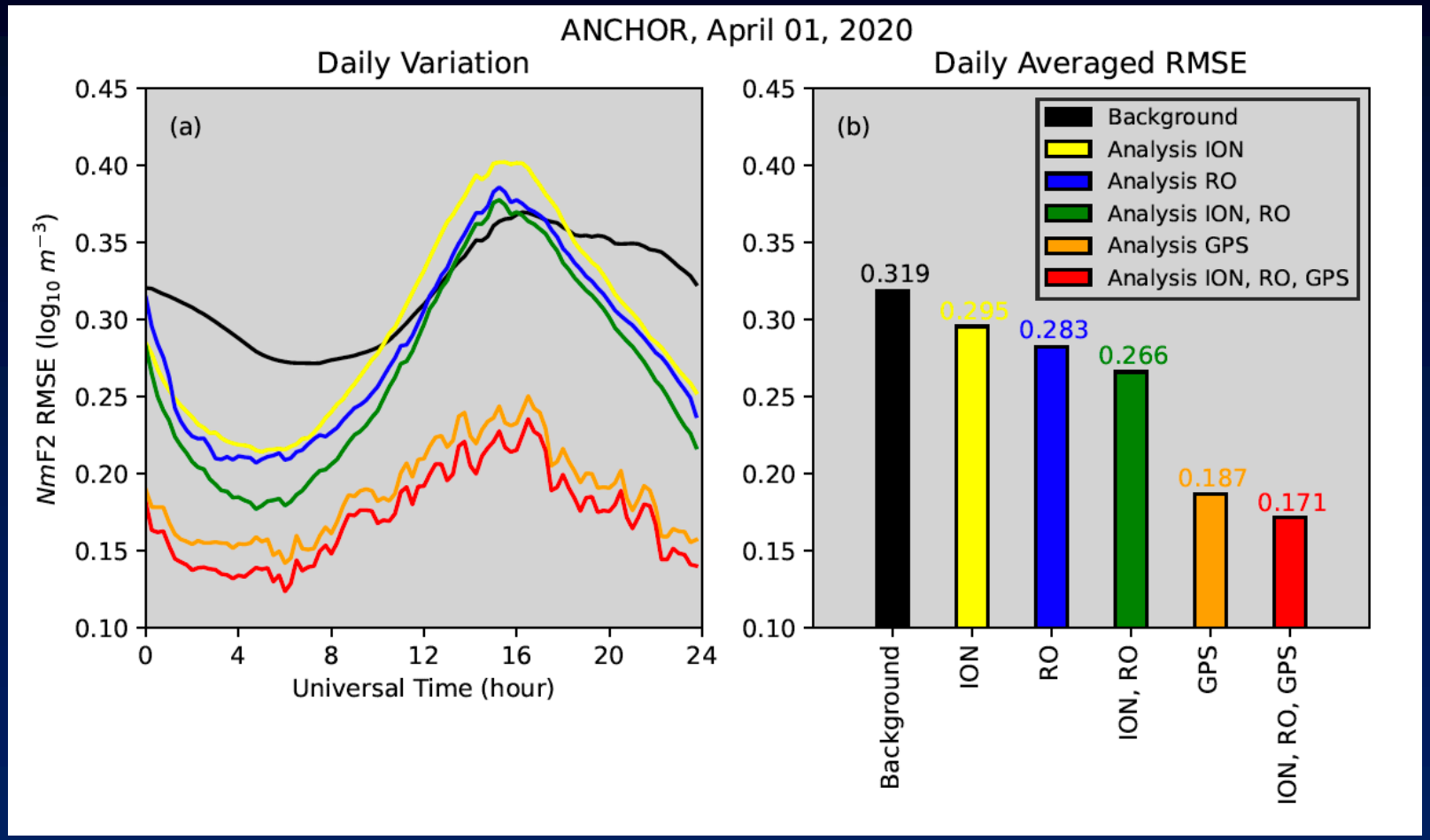
Analysis $\vec{x}_a$: RMSE Reduction



- The sTEC data reduces the daily averaged RMSEs by 41.6% (orange bar), when ingested alone, and by 46.4% (red bar) 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

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Tools For The Community

https://github.com/victoriyaforsythe/PyIRI

https://github.com/victoriyaforsythe/PyIRTAM

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