DATA - 15

Filtering/smoothing coupled technique implementation to the data assimilation algorithm

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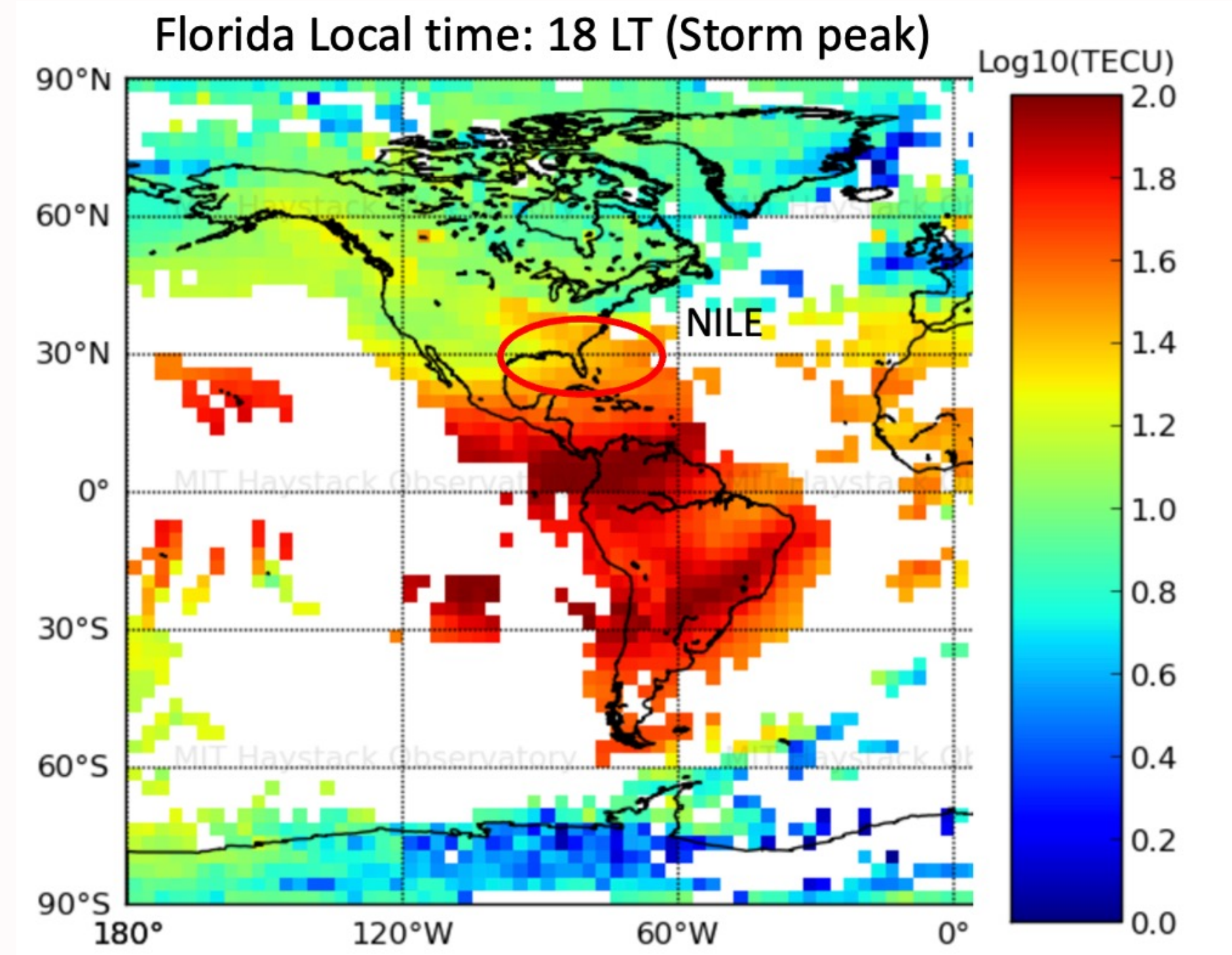
Motivation

- A storm-related phenomenon: **Nighttime Ionospheric Localized Enhancement** (NILE) [Datta-Barua, 2008]
  - Enhanced electron density was observed in the Florida region during the local nighttime



- Investigating the NILE mechanism via
  - Developing the data assimilation algorithm: **Estimating Model Parameter Ionospheric Reverse Engineering** (EMPIRE) [Datta-Barua et al., 2009]

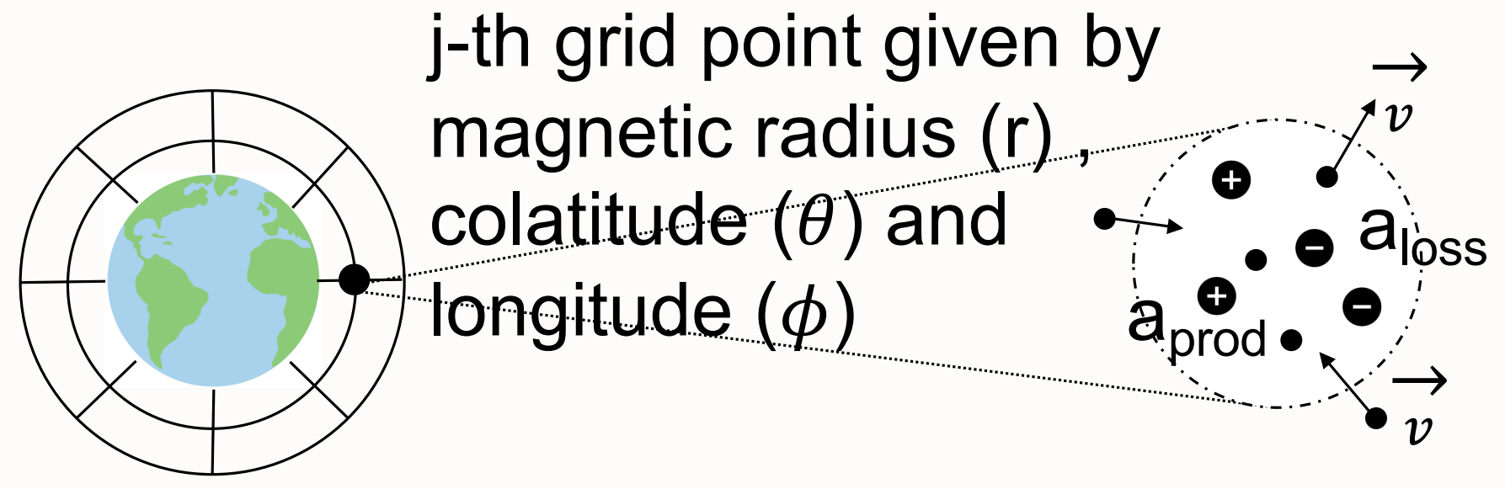
Fig. 1 GNSS total electron content map on log scale. Image credit: MIT Madrigal website

Objective

- To Implement the **coupled Kalman filter/smoother technique** to EMPIRE algorithm
- To inspect the performance at a period of quiet time for **validation and error analysis**

Background – EMPIRE algorithm

- **EMPIRE** algorithm: Reduce the gap between background model estimations and measurements [Miladinovich, 2018]
  - Analyze the ionospheric drivers with a **4D global grid map** governed by the **ion continuity equation**
    - **4D global grid map**



j-th grid point given by magnetic radius (r), colatitude (θ) and longitude (ϕ)

Fig. 2 Global grid map and representation of plasma flow in a constrained volume. Image credit: Aurora López-Rubio

- **Ion continuity equation**

$$\frac{\partial N}{\partial t} = \underbrace{\underbrace{s_{prod}}_{a_{prod,0}} + \underbrace{s_{loss}}_{a_{loss,0}} \underbrace{-\vec{\nabla}\cdot(N\vec{v}_{\perp})}_{a_{\perp}} \underbrace{-\vec{\nabla}\cdot(N\vec{v}_{\parallel})}_{a_{\parallel}}}_{a_0}$$

$a_{\perp,0} + \delta a_{\perp}$

$a_{u,0} + a_{grav,0} + a_{dfsn,0} + \delta a_u$

- Measurements: 4D global total electron content density rate [$\partial N/\partial t$]
- Background components [a_0]: Production rate [$a_{prod,0}$], loss rate [$a_{loss,0}$], Diffusive rate [$a_{dfsn,0}$], Gravitation effect [$a_{grav,0}$]
- **Ionospheric drivers to be estimated:**
  - **Neutral wind** [δa_u]: Parallel to the earth's magnetic field
  - **Ion drifts** [$\delta a_{\perp}$]: Perpendicular to the earth's magnetic field

New implementation – Kalman Smoother

- Kalman filter/smoother coupled technique conceptual flow

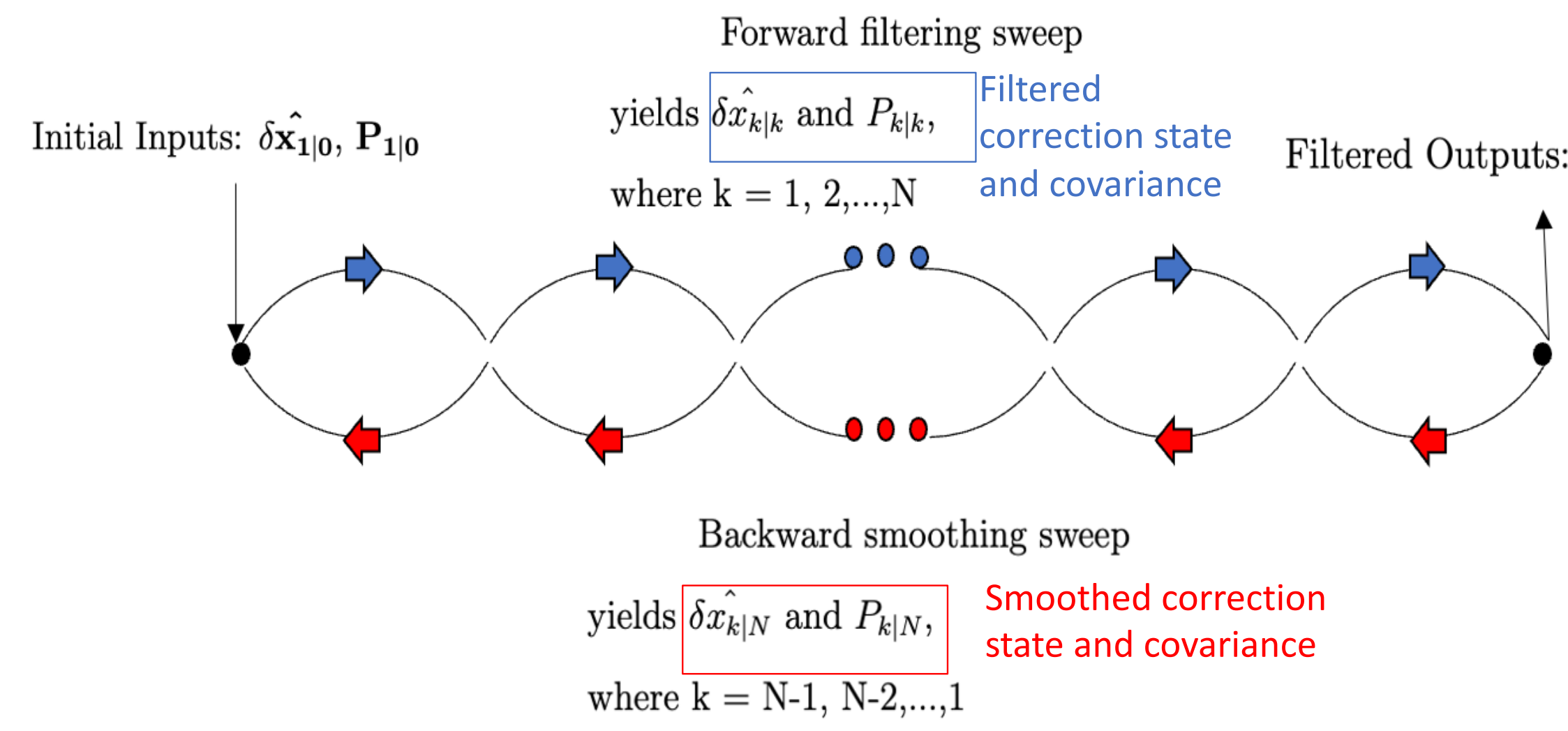
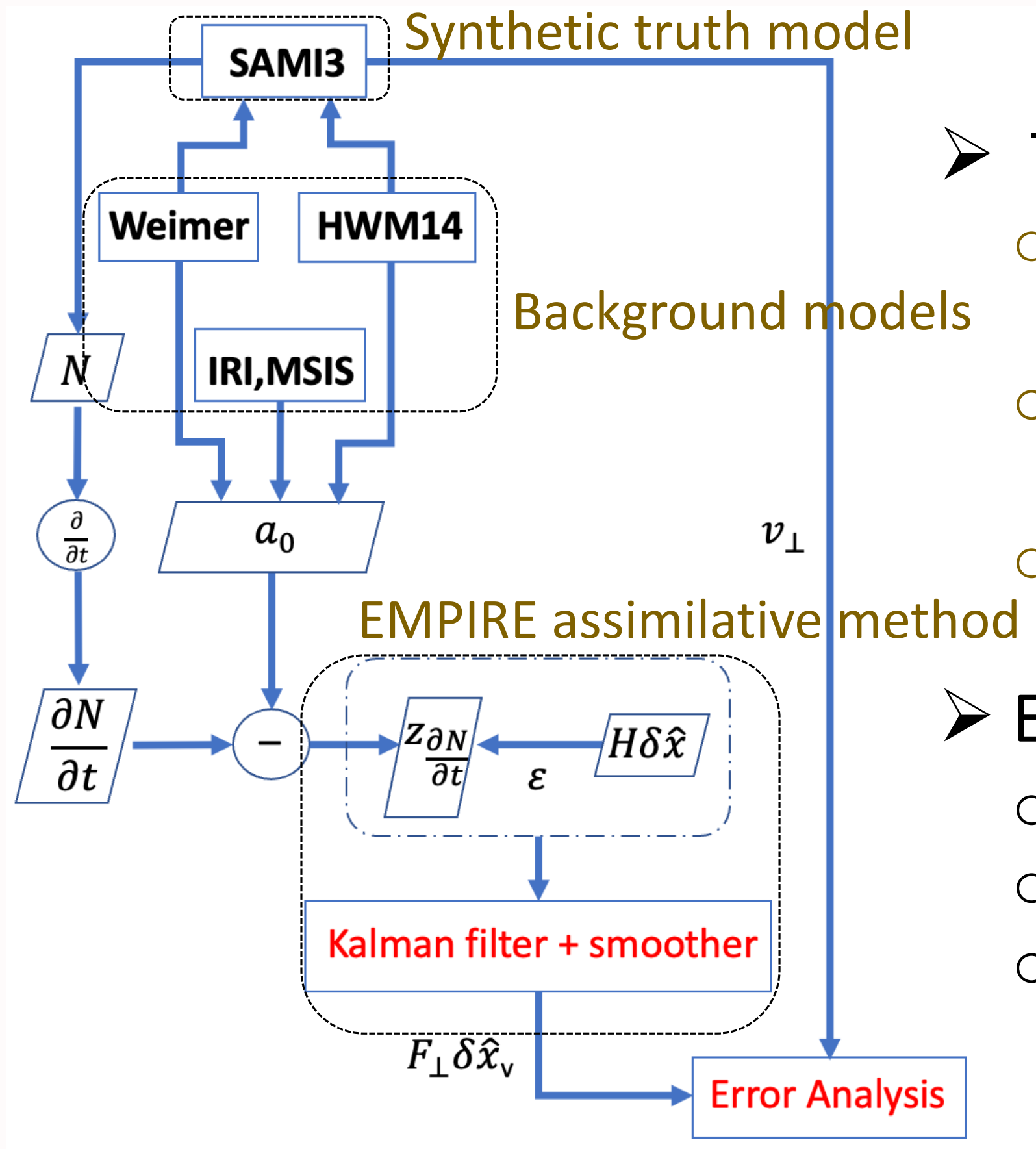


Fig. 3 Kalman filter/smoother coupled flowchart. Observations are assimilated into each time epoch. Kalman filter is a forward and recursive procedure represented by the top row. The bottom row shows the smoother as a backward and recursive process. [Robert Grover Brown & Patrick Y,C, Hwang, 1983]

- **Advantages** of adding Kalman smoother
  - Refine estimates of previous states with all provided measurements
  - Provides better analysis for a historical event (i.e., NILE)

Methodology



- To build the ingestion system:
  - The synthetic truth model provides electron density rates as measurements
  - Background models yield the background components
  - EMPIRE assimilative method is updated to the coupled Kalman filter/smoother technique
- EMPIRE configuration grid:
  - Colatitude: 3:6:177 [deg]
  - Longitude: -180:6:180 [deg]
  - Altitude: 200:50:500 [km]

Fig. 4 EMPIRE experiment setup. Red text indicates the new implementation and brown text is connected to the terms in the ion continuity equation. H is the mapping matrix that map the correction state $\delta\hat{x}$ to the observation gap, with error ε. $F_{\perp}$ is the mapping matrix map the correction state onto ion velocity space.

- Evaluation time period characterization

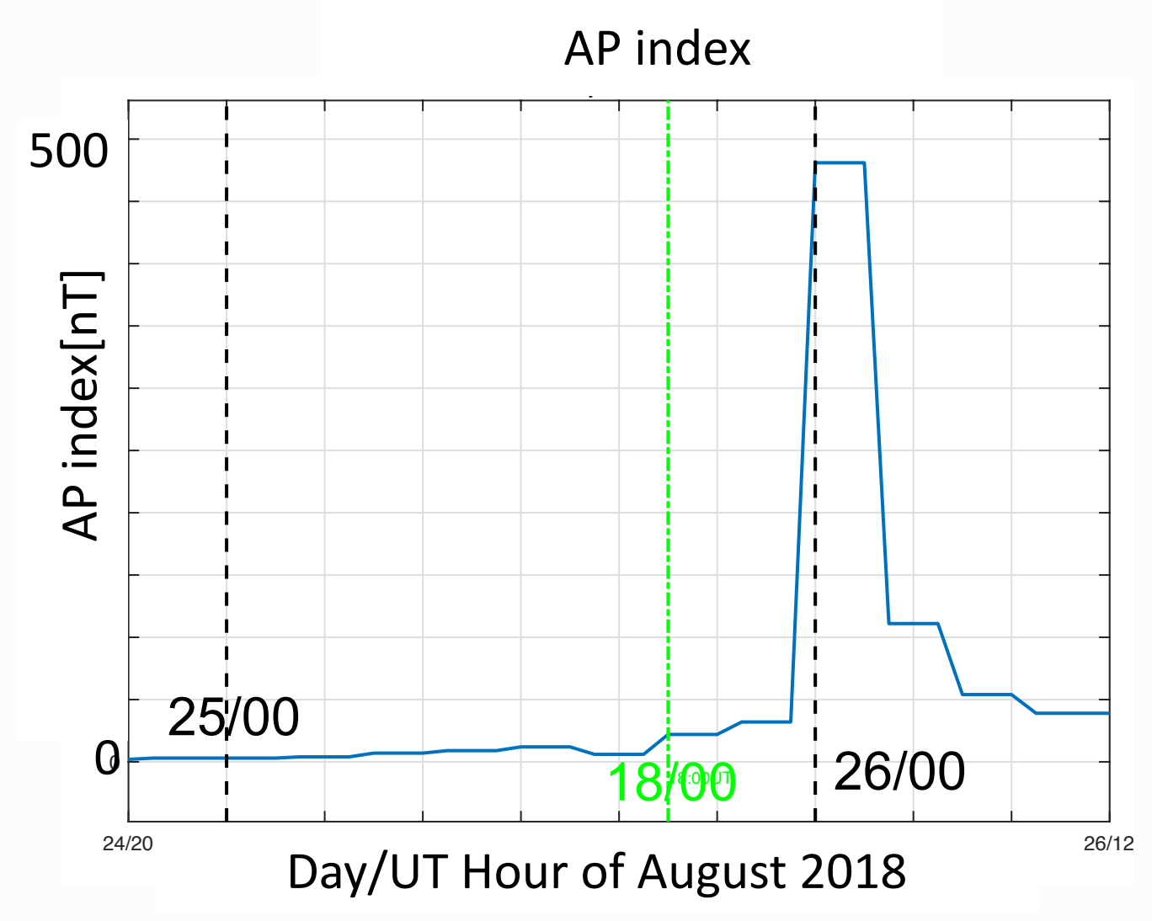


Fig. 5 Geomagnetic activity characterization for August 25th ,2018

- Error analysis $\epsilon_{vi} = v_{\perp} - (F_{\perp}\delta x_v + v_{\perp,0})$
  - Zonal averaged error

$$\bar{\epsilon}_{v_i}(\theta;t) = \frac{1}{n_\phi}\sum_{\phi=-180}^{\phi=180} \epsilon_{v_i}(\theta,\phi;t)$$

  - Time-averaged error

$$\mu_{\epsilon_{v_i}}(\theta) = \frac{1}{n_{qtimes}}\sum_{t=0UT}^{t=18T}\sum_{\phi=-180}^{\phi=180} \epsilon_{v_i}(\theta,\phi;t)$$

$$\sigma_{\epsilon_{v_i}}(\theta) = \left(\frac{1}{n_{qtimes}}\sum_{t=0UT}^{t=18UT}\sum_{\phi=-180}^{\phi=180} [\epsilon_{v_i}(\theta,\phi;t) - \mu_{\epsilon_{v_i}}]^2\right)^{1/2}$$

Result

- Zonal averaged ion drift error

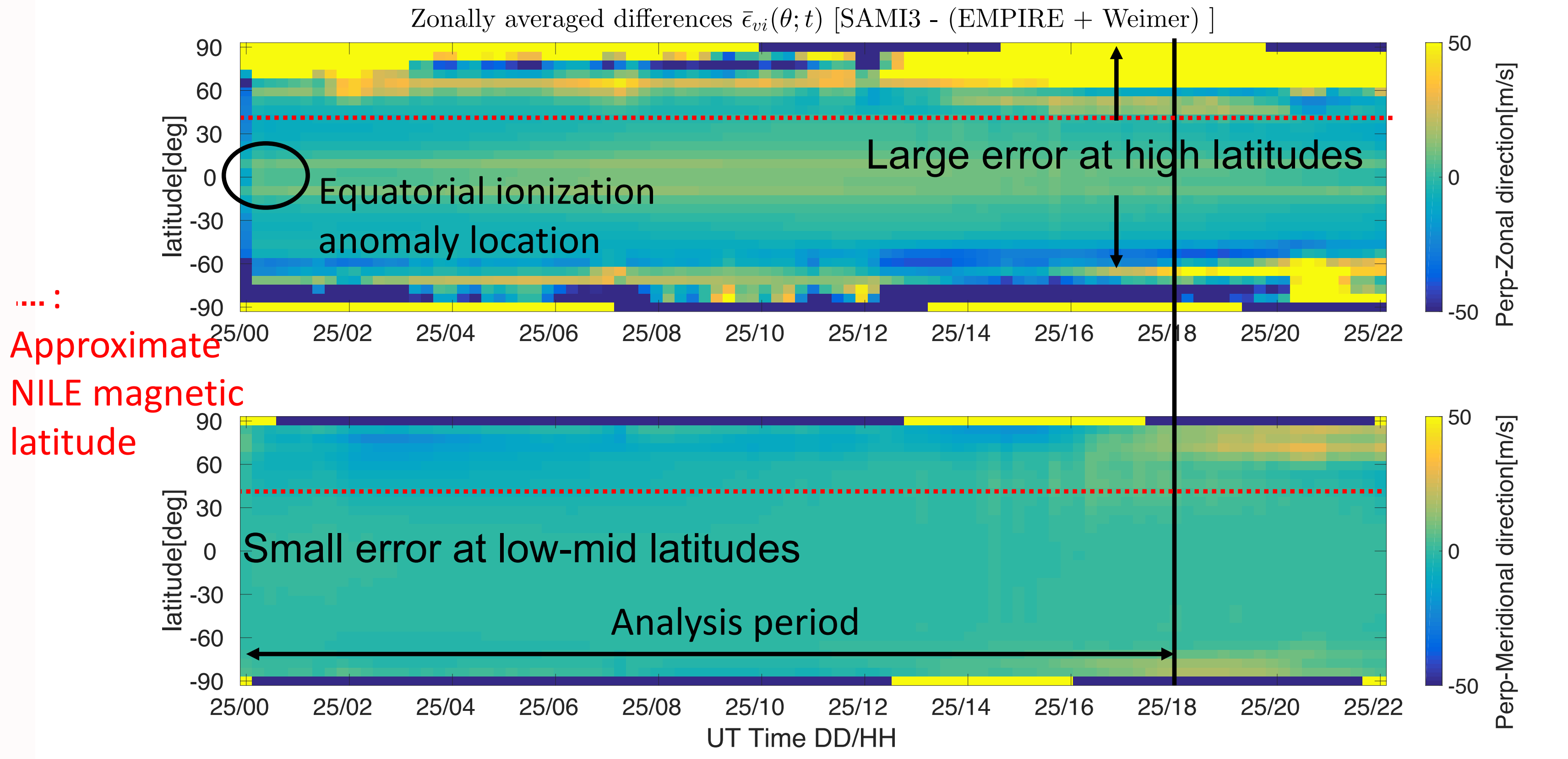


Fig. 6 Zonally averaged ion drift errors across evaluation time

- Time averaged error

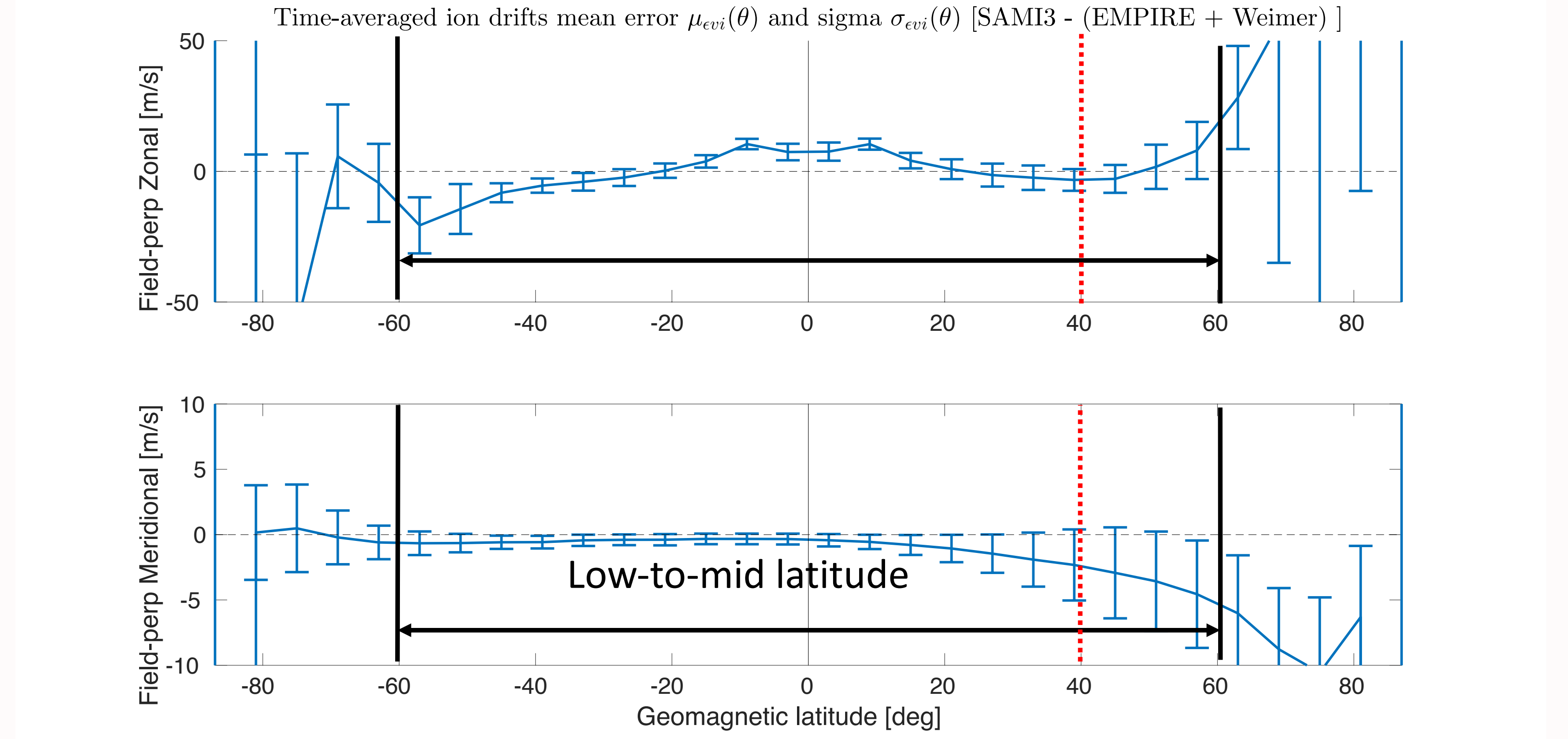


Fig. 7 Time-averaged ion drift mean errors and standard deviation

Conclusion & future work

- For the field-perp zonal direction ion drifts, significant errors are observed at high latitudes, with relatively large errors at the approximate equatorial ionization anomaly location (±25° latitude).
- At the low-to-mid latitude band (0° - ±60°), the time averaged error is bounded within ±5 [m/s] for field-perp meridional direction, ±25 [m/s] for Field-perp zonal direction
- **Future work**: Implement the Kalman filter/smoother coupled technique to storm time and investigate the NILE phenomenon with the current knowledge on the ion drift error during the quiet time

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