Severe Mid-Latitude GPS Scintillation and Position Errors During the Recent Major Storms

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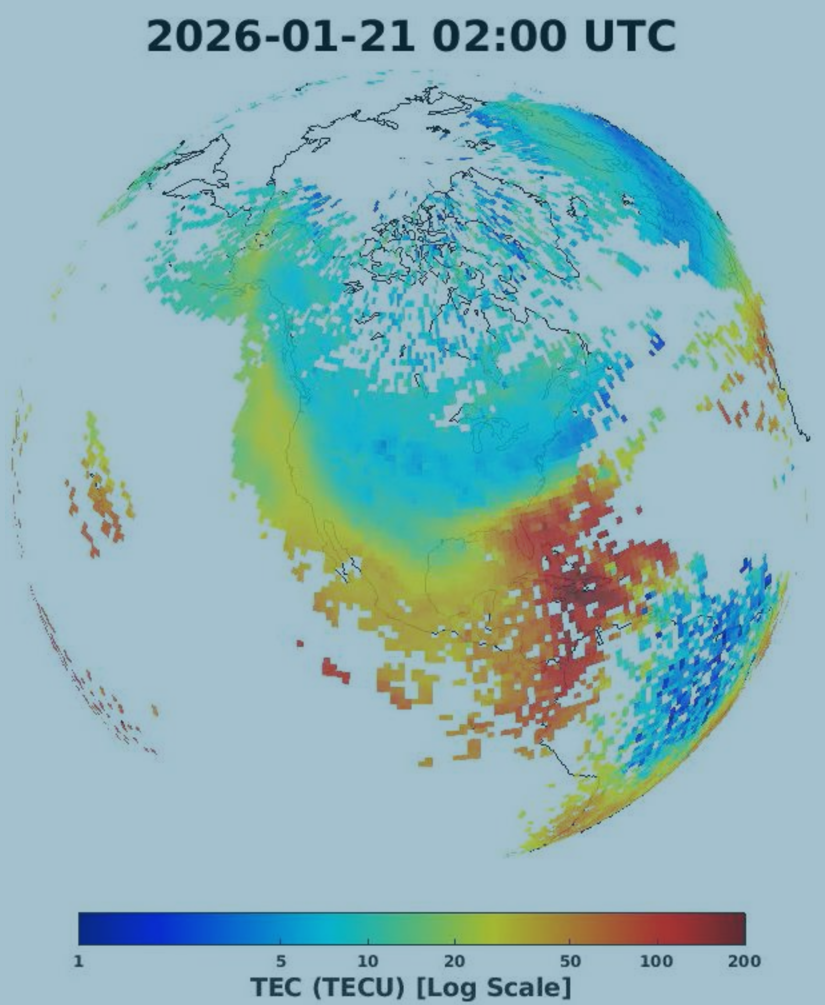

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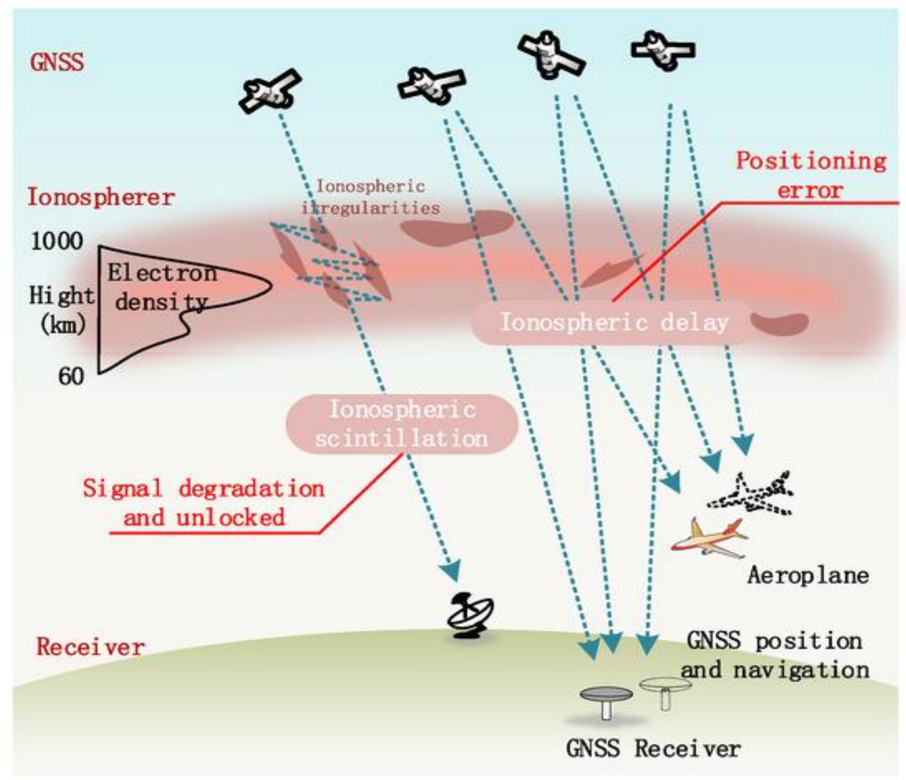
Precision and Continuity at Risk: Vulnerability of GNSS to Space Weather

- GPS signals are disturbed as they pass through the irregular ionosphere.
- Density irregularities cause scintillations.
- Large disturbances lead to cycle slips, loss of lock, and positioning error.
- 10-11 May 2024 storm caused large GPS disruption across USA.



Objectives

- Determine possible drivers of GPS disruptions in the US sector.
- Evaluate the spatio-temporal of evaluation of mid-latitude ionospheric irregularities and their impact on navigation signals.


The New York Times

Solar Storm Crashes GPS Systems Used by Some Farmers, Stalling Planting

The storm interfered with navigational systems used in tractors and other farming equipment, leaving some farmers temporarily unable to plant their crops.

Characterizing the Ionospheric Irregularities

Phase Fluctuations Index: The standard deviation of detrended phase.

$$\sigma_\phi = \sqrt{\langle(\Delta\phi)^2\rangle - \langle\Delta\phi\rangle^2}$$

Where *Δϕ* is detrended phase. <> correspond to averaging on 1 min interval.

Amplitude Fluctuation Index: The standard deviation of intensity.

$$S_4 = \sqrt{(\langle I^2\rangle - \langle I\rangle^2)/\langle I^2\rangle}$$

Where *I* is intensity of L1/L2 recorded at 1 Hz. <> correspond to averaging on 1 min interval.

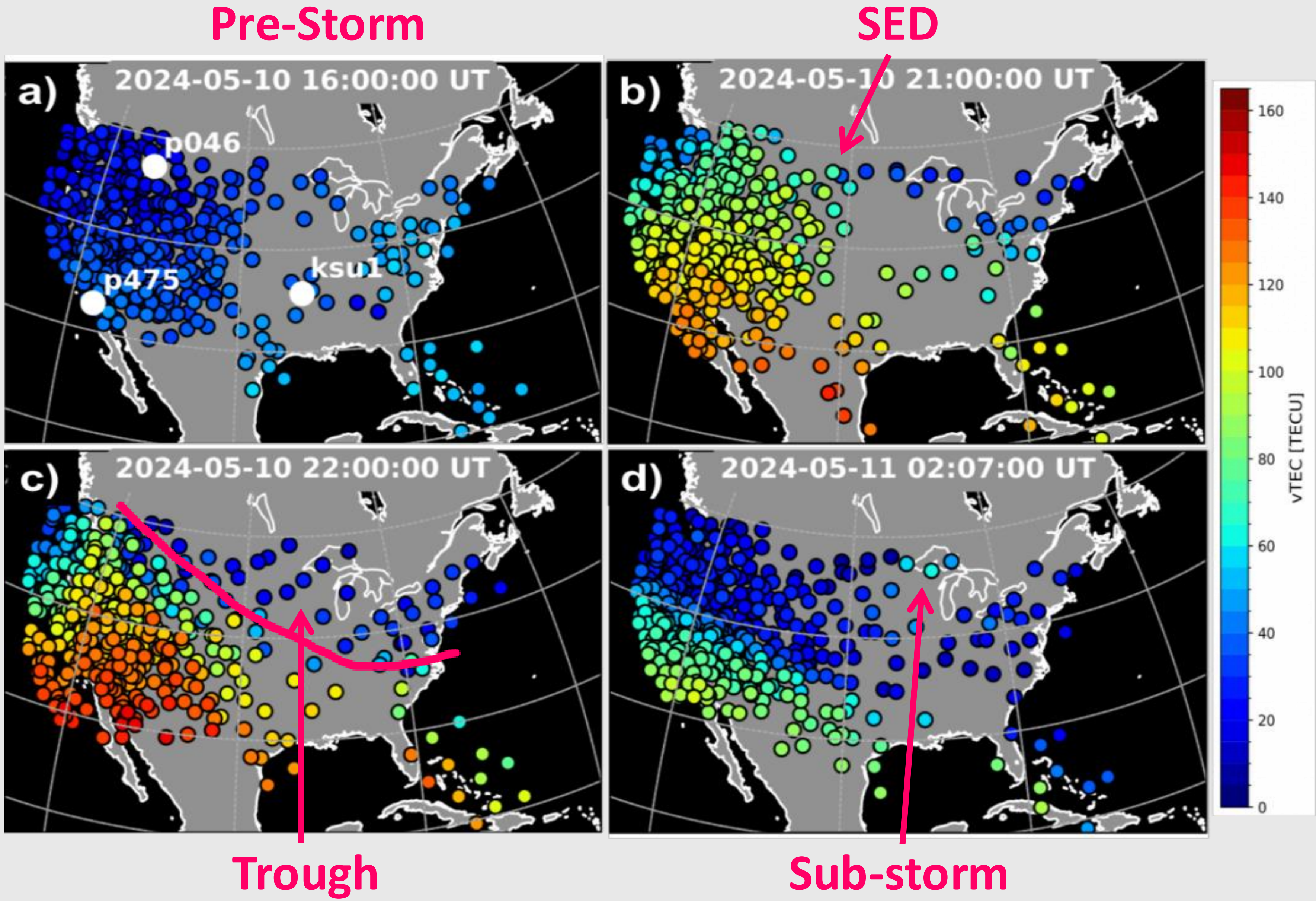
Total Electron Content (TEC): Total number of electrons in the cross section of m^2 from satellite to receiver.

$$sTEC = \frac{(f_1^2 * f_2^2)}{40.3(f_1^2 - f_2^2)}(P_2 - P_1)$$

Where f1 (P1) and f2 (P2) are frequency (pseudorange) of L1 and L2. sTEC is converted to vTEC by applying a mapping function. TEC further smoothed using carrier phase L1 and L2.

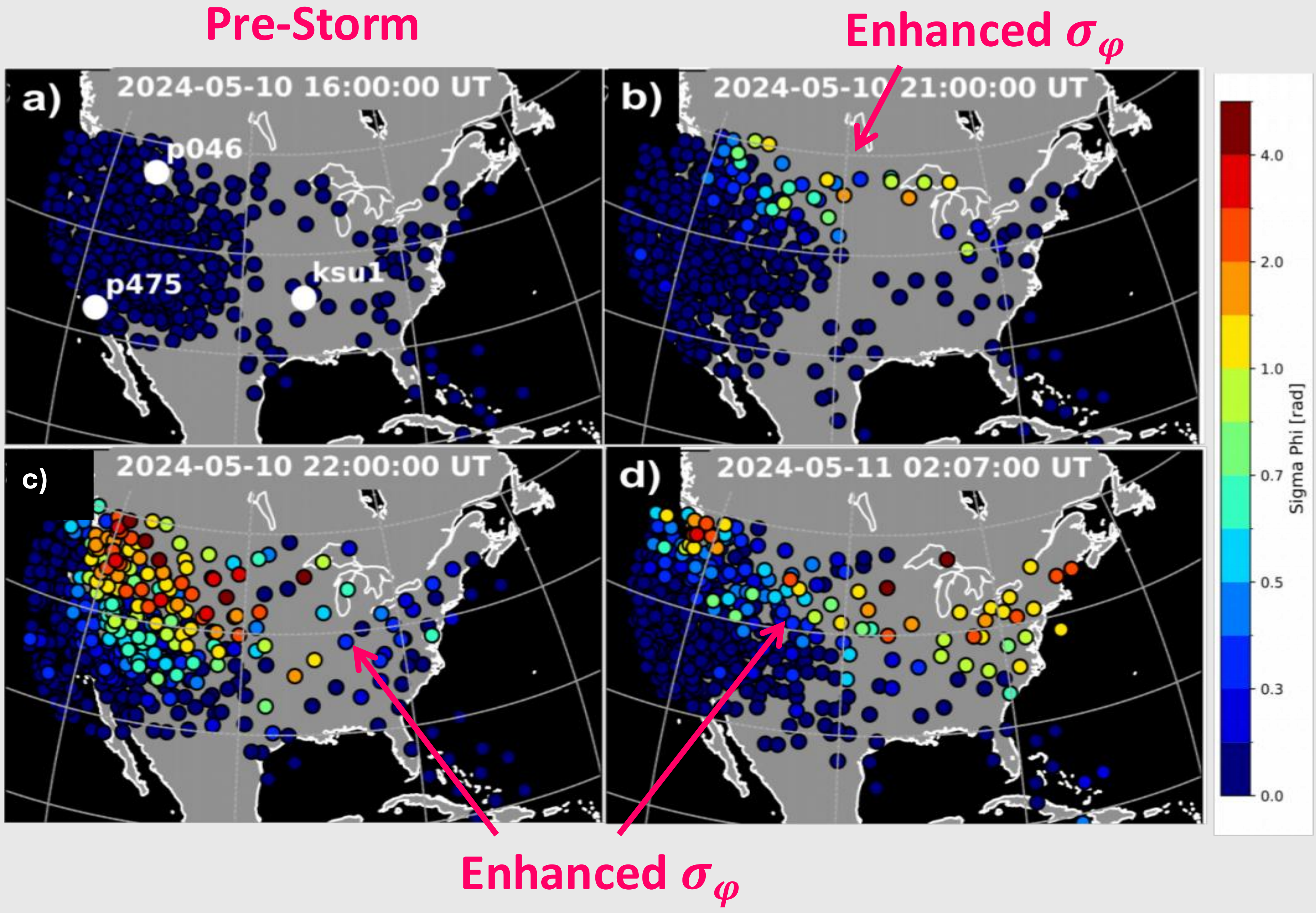
Total Electron Content (10-11 May 2024)

- **EIA/SED expands to mid latitudes.**
- **The trough propagates southwest.**
- **SED and Trough created steep plasma wall.**
- **Auroral precipitation caused TEC enhancement during dusk and night-time**



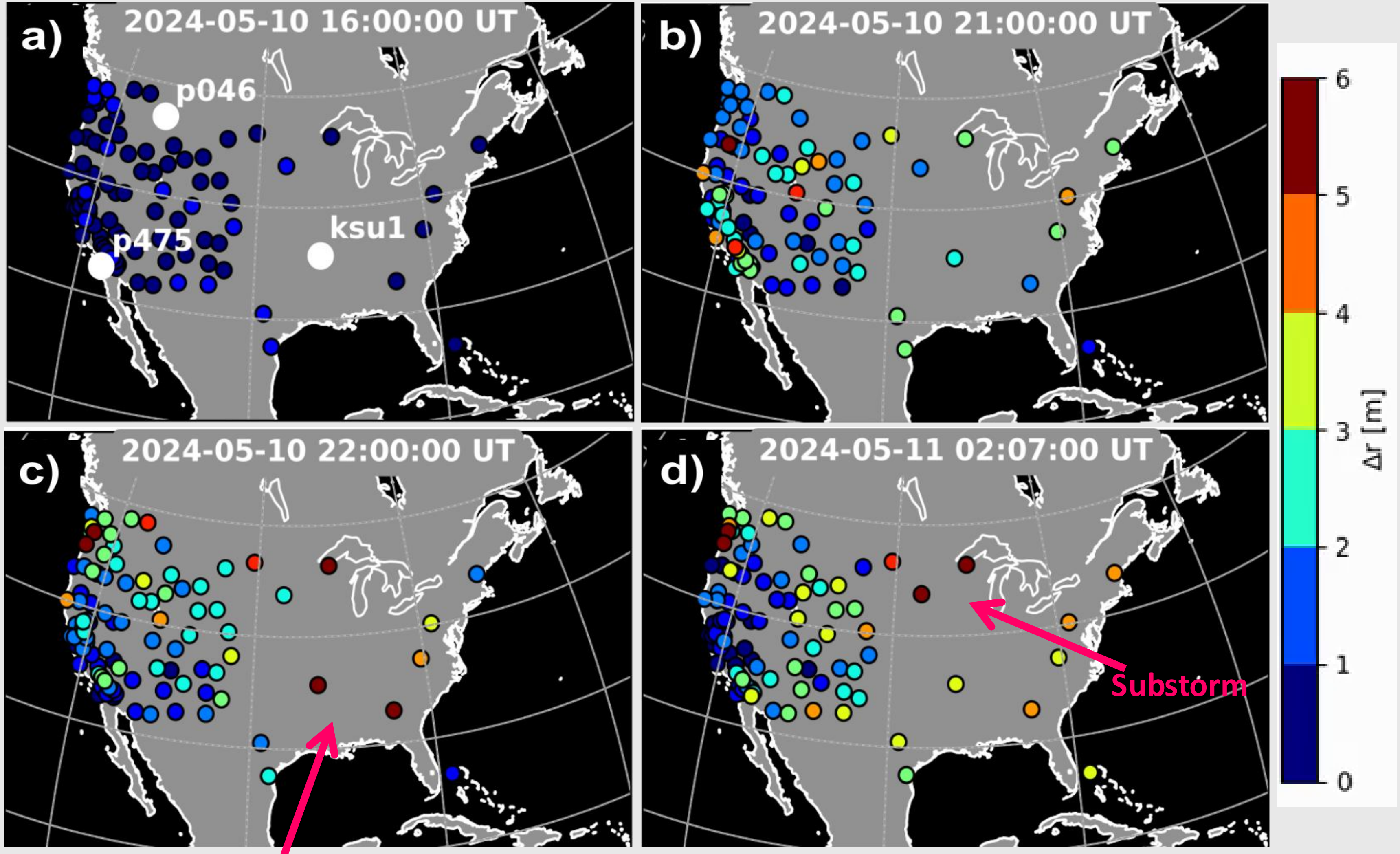
Phase Fluctuations (10-11 May 2024)

- Enhanced σ_φ poleward and equatorward of mid-latitude Trough. boundary.
- σ_φ propagate in southwest direction along trough.
- Substorm caused scintillation during local dusk and night side.



Position Errors (10-11 May 2024)

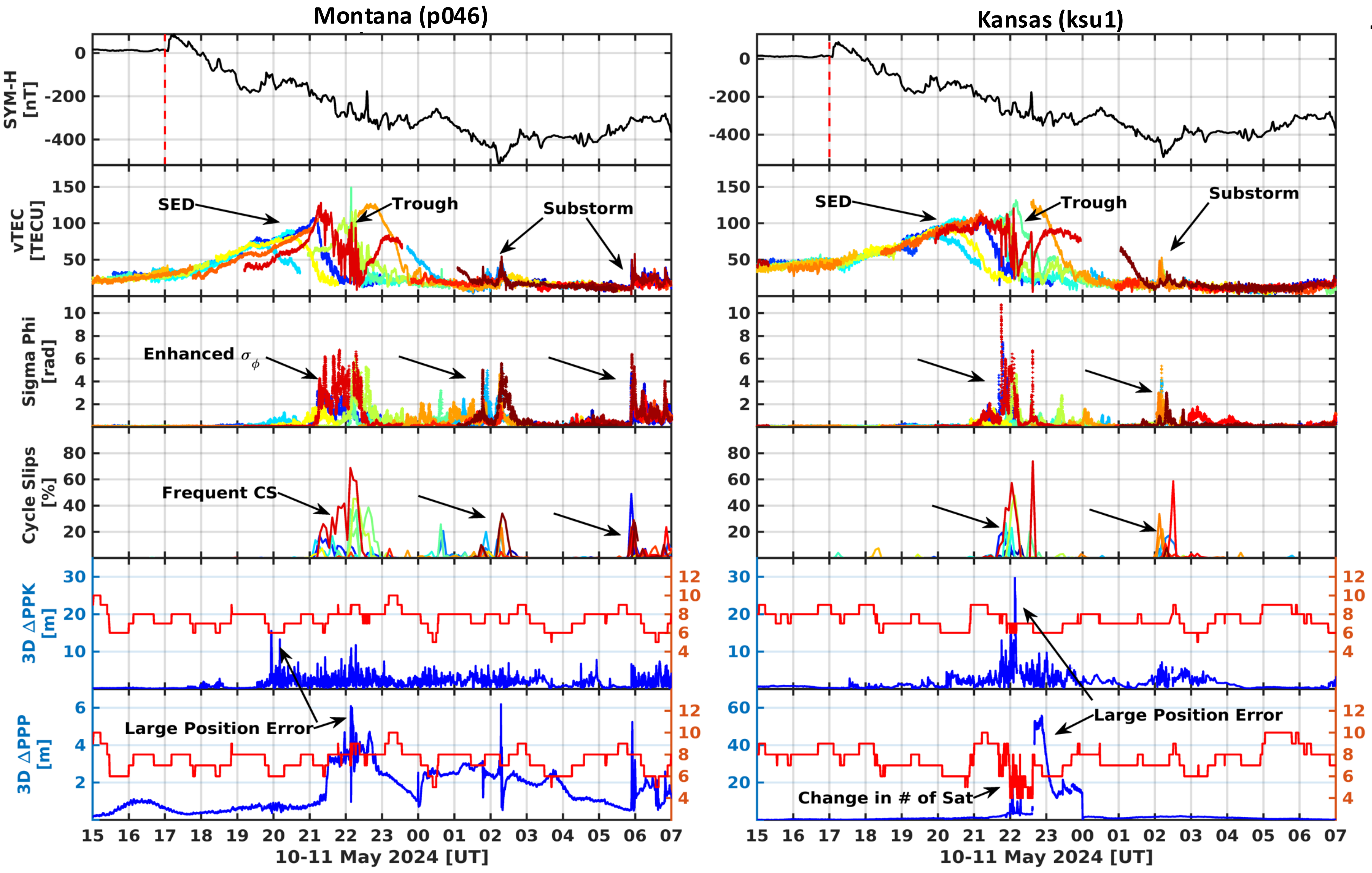
- **Position error increases as vertical ionosphere becomes non-uniform.**
- **Strong σ_φ along Trough boundary caused frequent cycle slips leading frequent outages and large errors.**
- **Substorms also caused position errors.**



Large position errors in regions where farmers reported disruptions

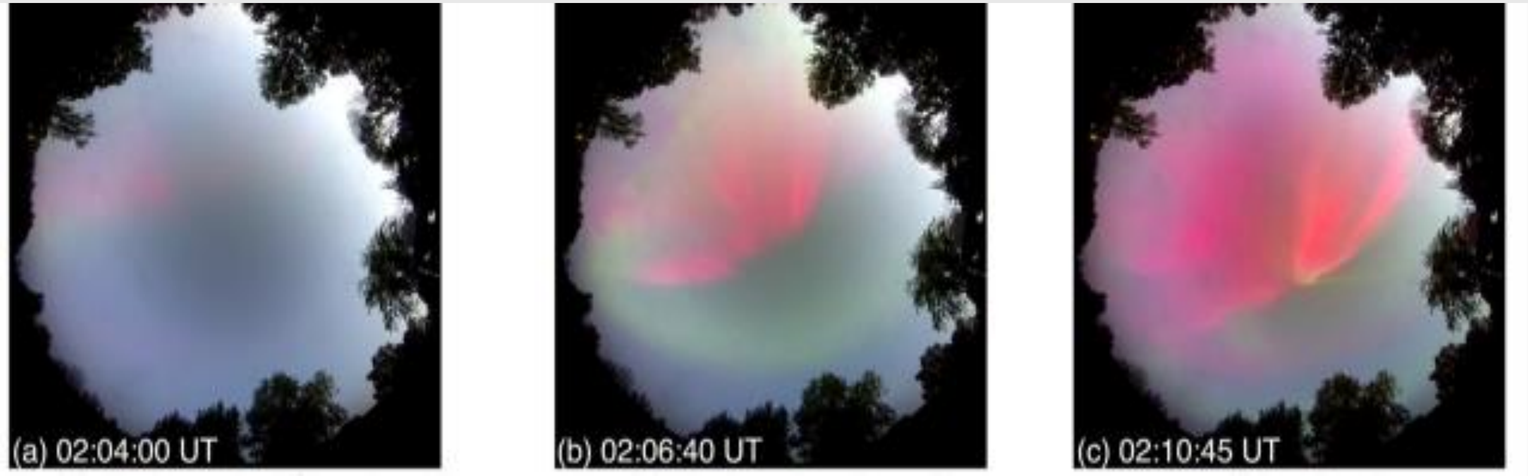
Spatio-Temporal Evolution of Scintillations (10-11 May 2024)

- **p046 show sharp TEC gradient around 21:30UT and σ_φ reached to 6 radian.**
- **ksu1 shows steep vTEC gradient around 22UT.**
- **Positioning error approaches 30m and 60m in PPK and PPP mode, respectively.**

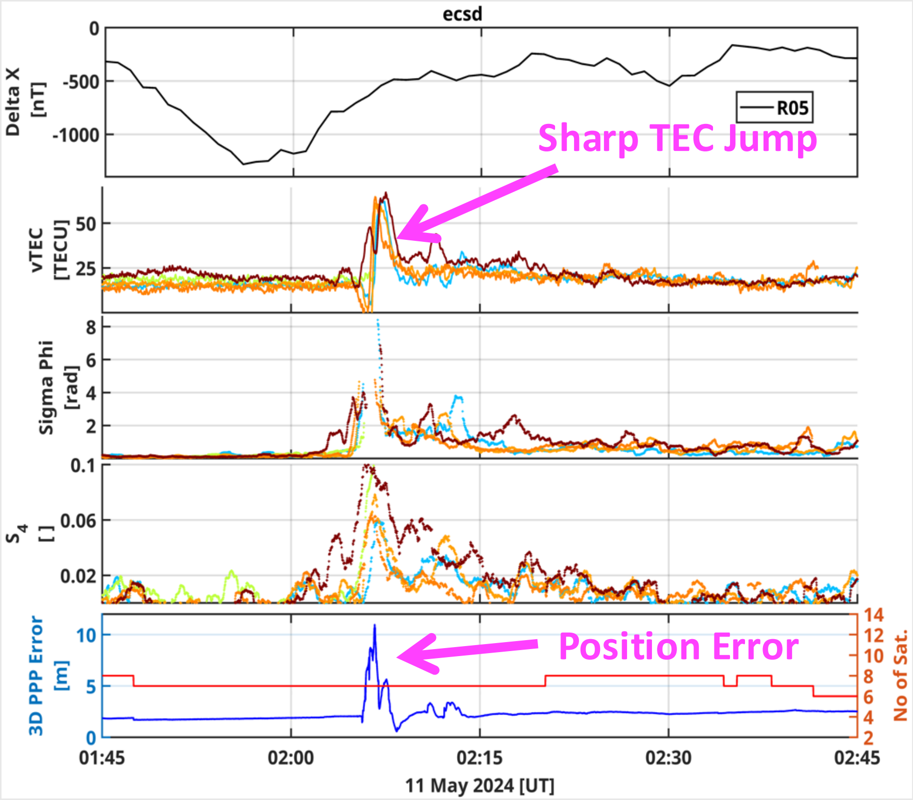


Position Error in the Vicinity of Extreme Aurora

All-sky Images at Missouri Skies Observatory



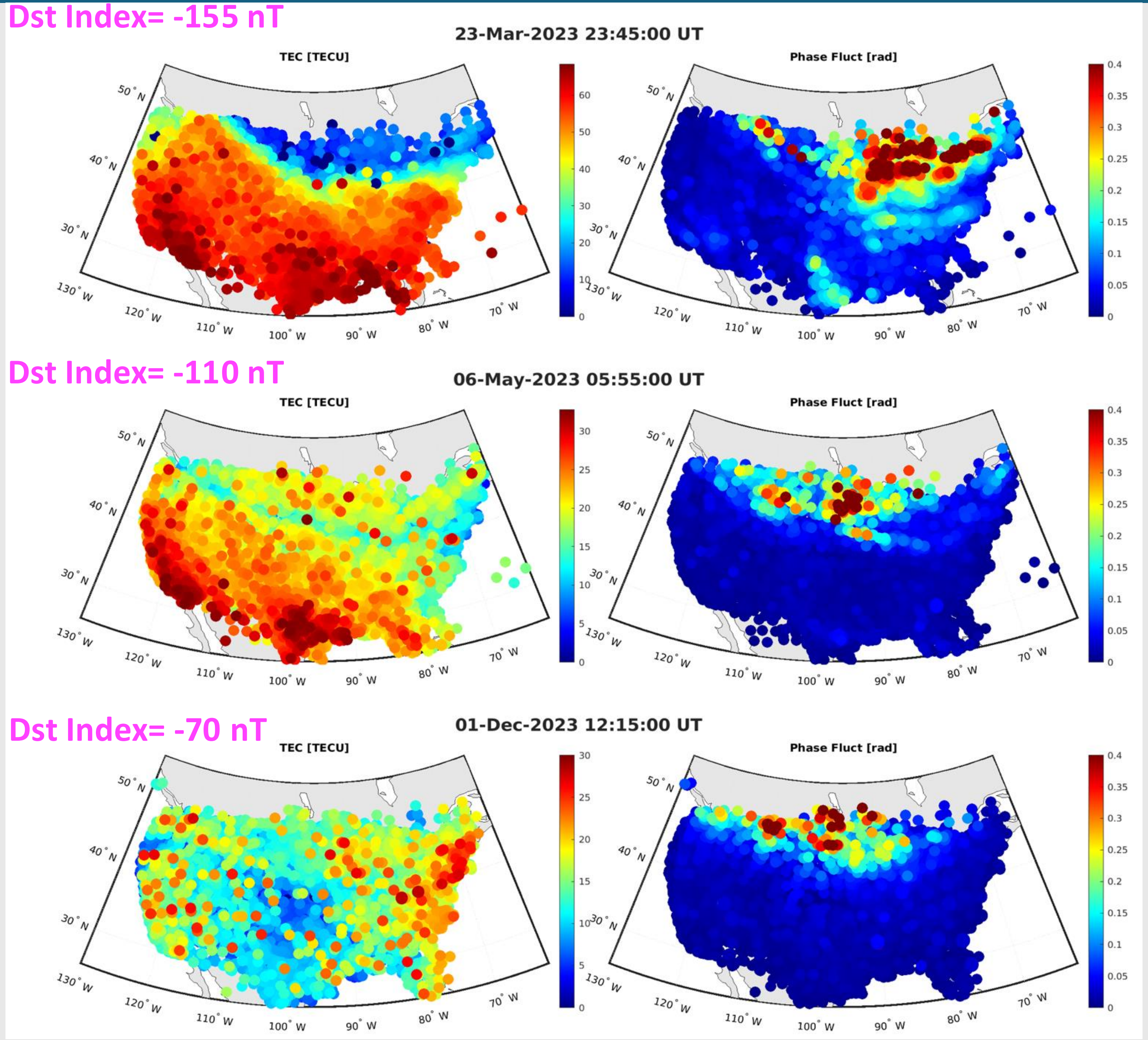
South Dakota



- **Auroral precipitation leads to sharp jump in TEC.**
- **Simultaneous σ_{φ} enhancement in all PRNs.**
- **Frequent cycle slips in all PRNs lead to sudden position error up to ~10 meters.**
- **Sudden and large positioning errors can compromise high-precision navigation systems, leading to a loss of integrity in safety-critical applications such as autonomous surveying and aviation.**

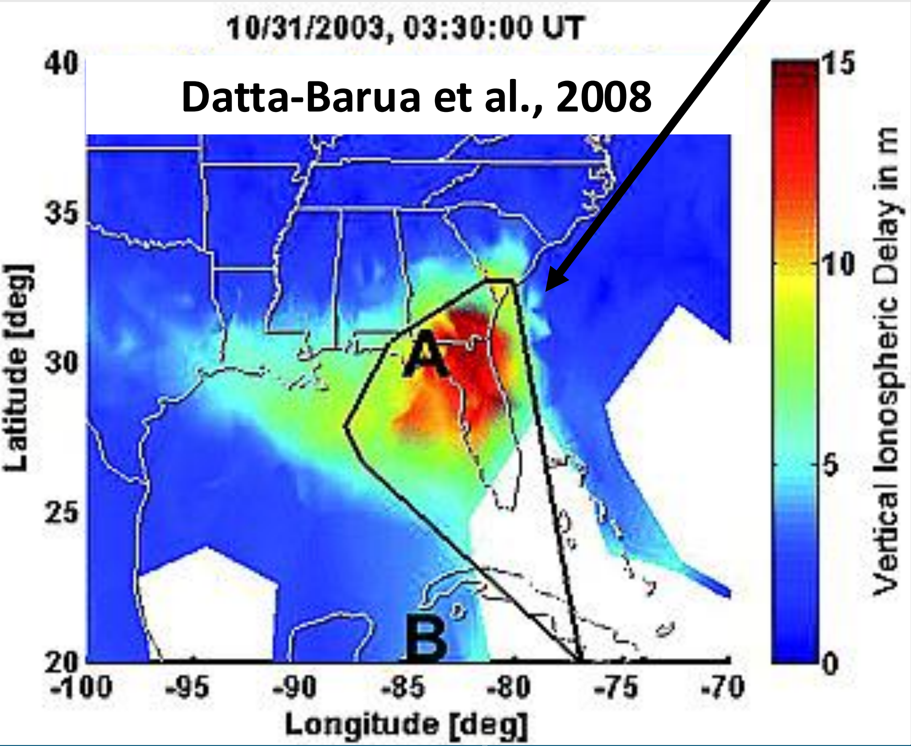
Mid-latitude GPS Disruptions during moderate storms

- **Large phase fluctuations also observed at mid-latitudes during the moderate and large storms.**
- **Phase fluctuations are enhanced along the trough, substorms surges and storm enhanced density regions.**
- **Latitudinal extension of GPS disruption may also depend on the arrival time of CME.**

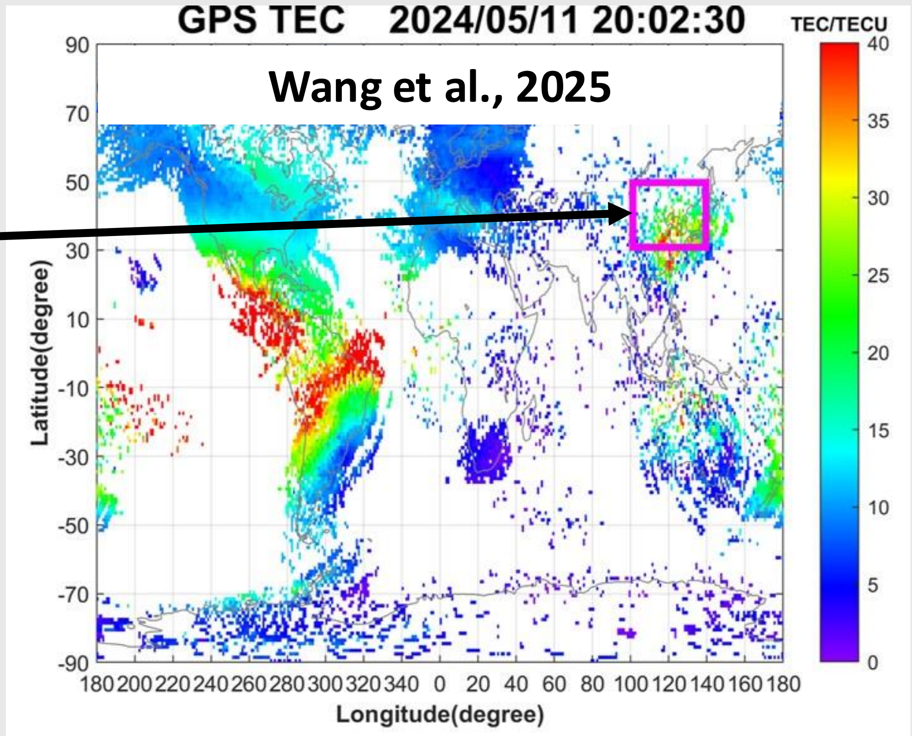


Night-time Ionospheric Enhancement (Florida effect)

- **Night-time ionospheric localized enhancements (NILE) have been observed at northern midlatitudes during the recovery phase of major storms and superstorms (Datta-Barua, 2004; Datta-Barua et al., 2008).**
- **The NILE constitutes a major enhancement of the ionosphere relative to the background night-time ionosphere, in a latitudinally narrow channel extending from the south-east to the northwest.**

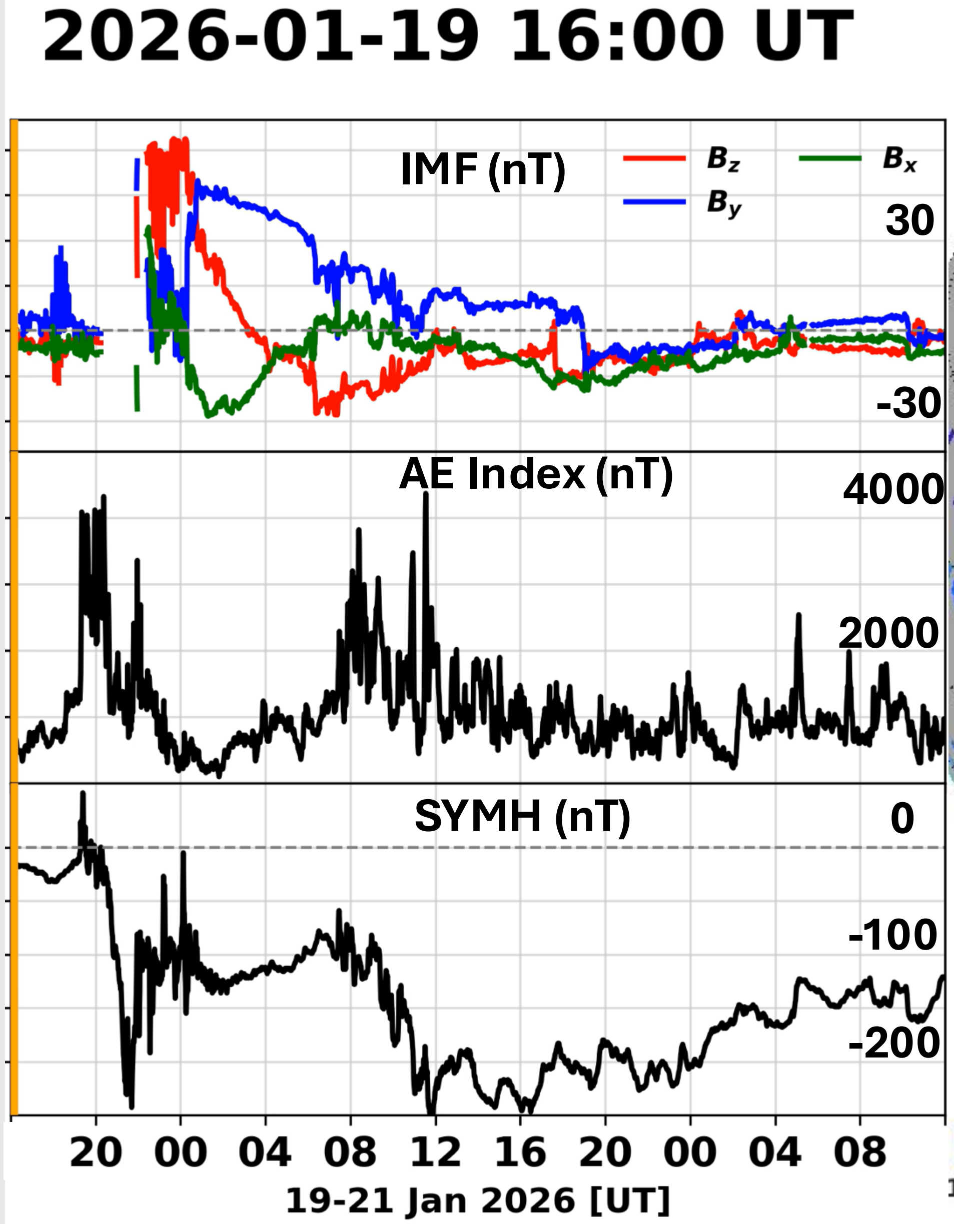


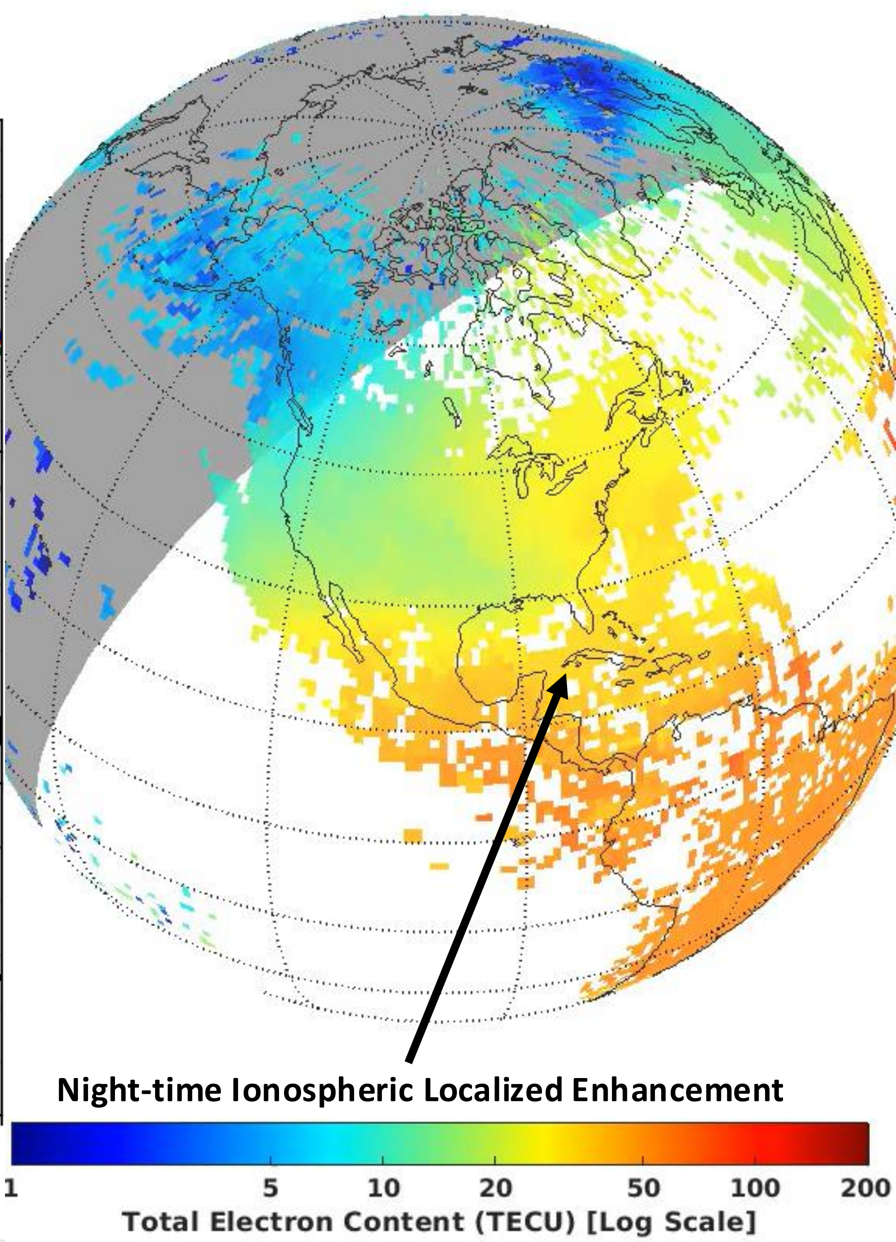
Wang et al. (2025) reported a similar event during the recovery phase of the May 2024 Superstorm over the Northeast Asian sector. Utilizing data from the Shandong Peninsula and global GPS TEC maps.



Space Weather Conditions During 19-21 Jan 2026

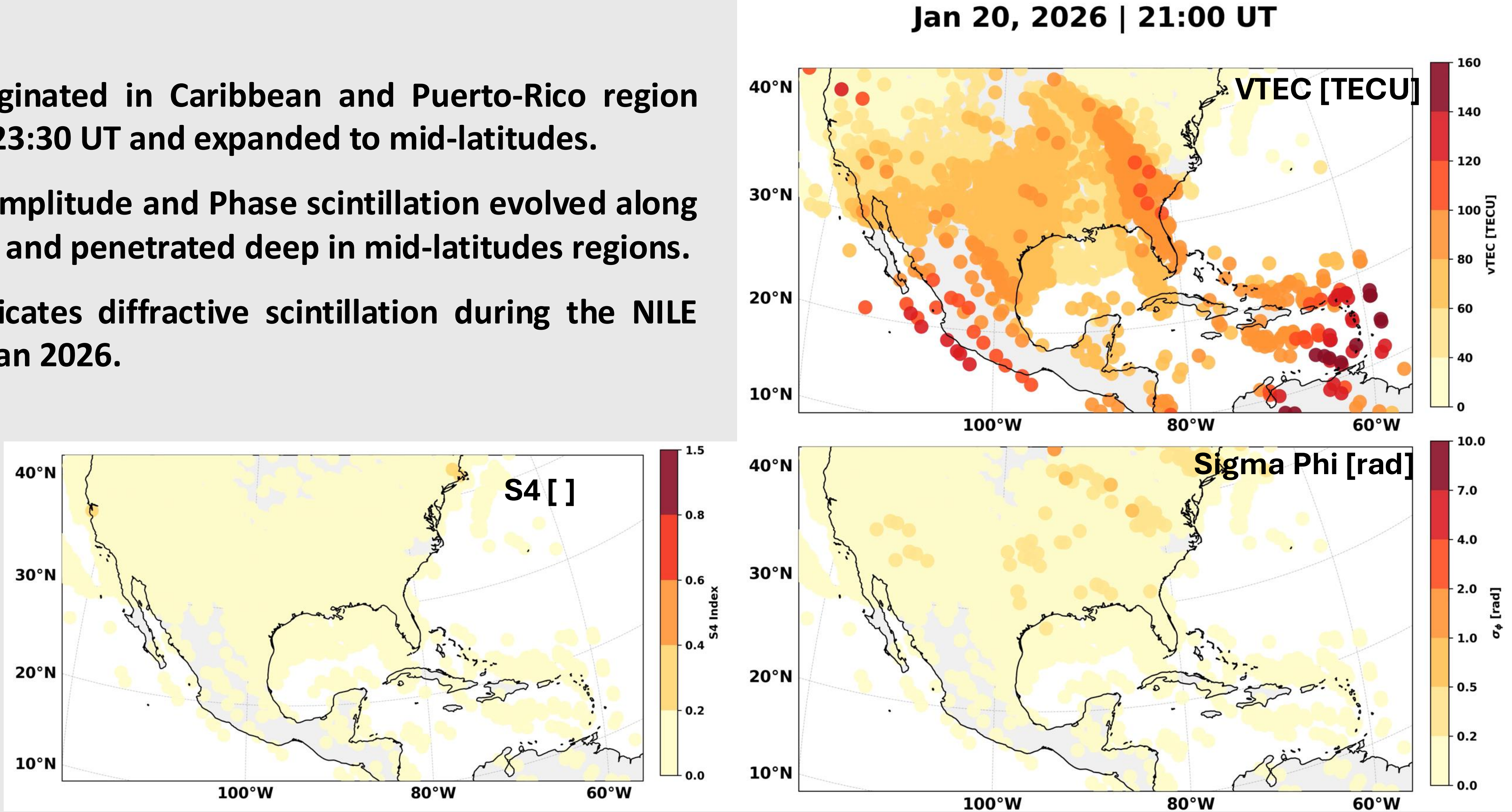
- **CME strikes on Jan 19th Jan 2026 19:10UT.**
- **It caused a severe geomagnetic storm with SYMH reaching ~-250 nT.**
- **NILE was observed late in recovery phase (21st Jan) and expanded to mid latitudes.**





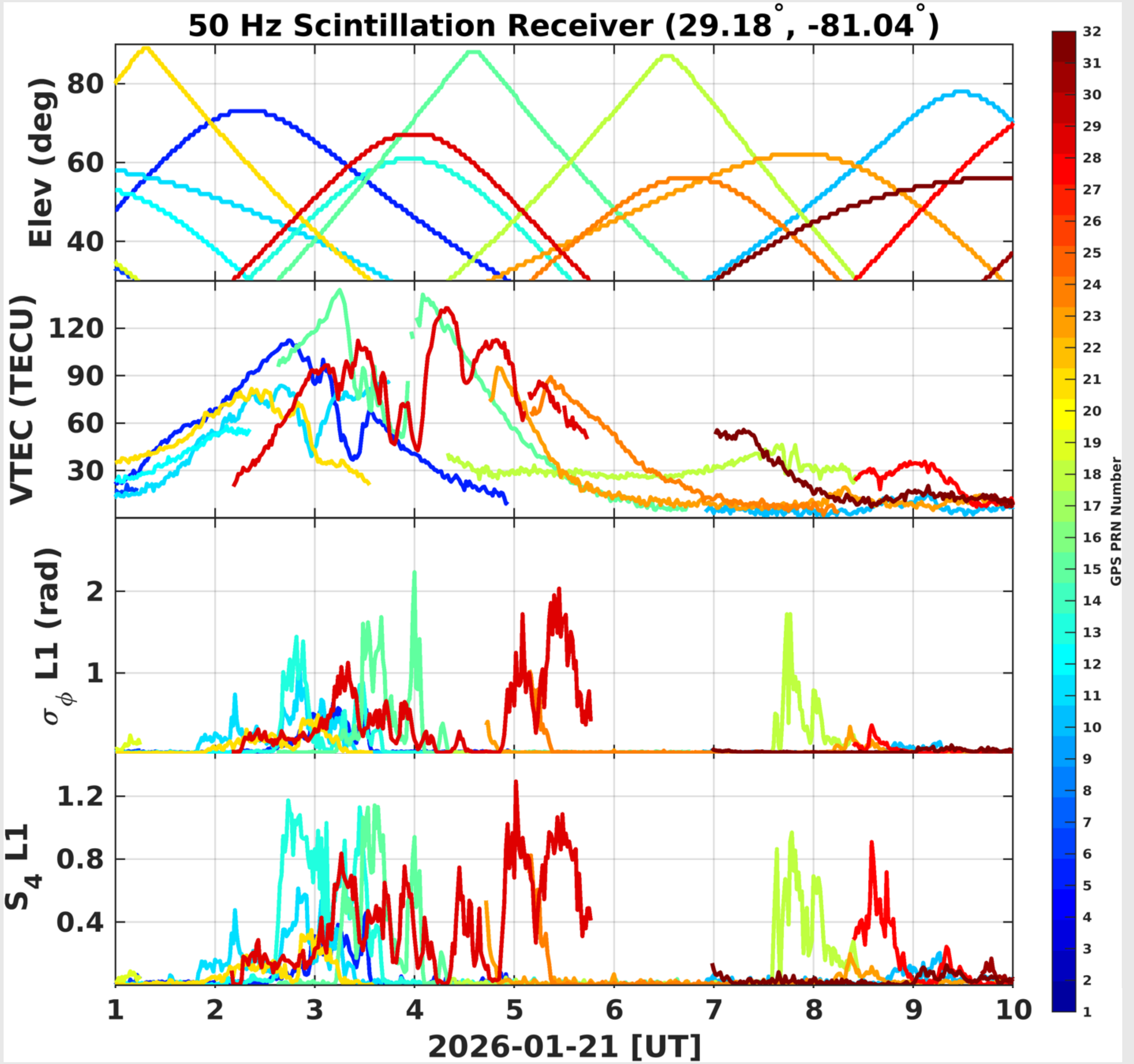
Spatio-Temporal Evolution of Scintillations

- **NILE originated in Caribbean and Puerto-Rico region around 23:30 UT and expanded to mid-latitudes.**
- **Strong amplitude and Phase scintillation evolved along the NILE and penetrated deep in mid-latitudes regions.**
- **This indicates diffractive scintillation during the NILE on 21st Jan 2026.**



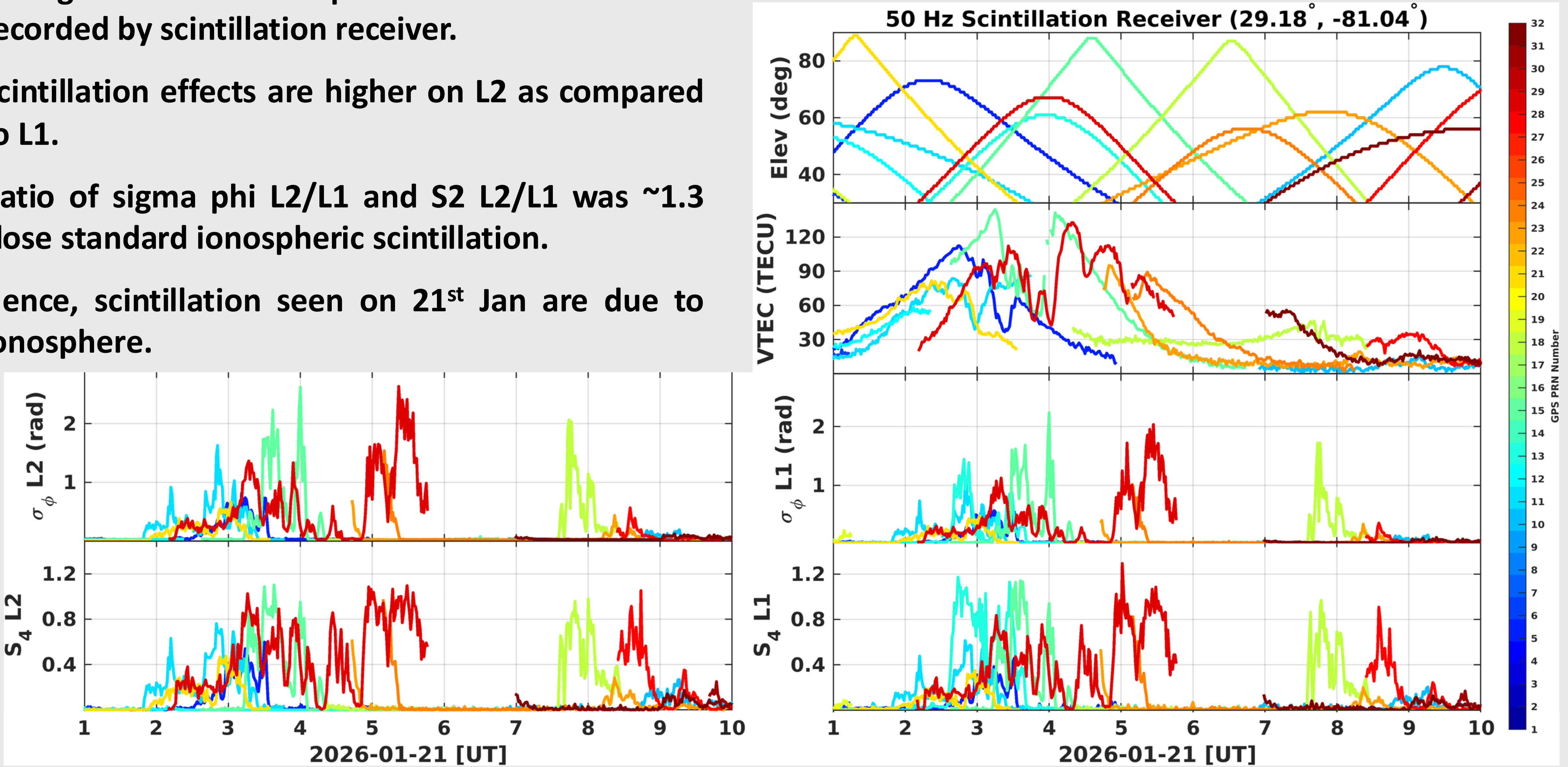
Is it Real Ionospheric Scintillation Event or RFI?

- Radio Frequency Interference (RFI) could also produce fake scintillations. It is important to confirm observed NILE is real ionospheric feature.
- RFI effects are generally more pronounced on L1 (high frequency) than L2 (Low frequency).
- Scintillation receiver at Embry-Riddle University (managed by Kshitija Deshpande) provides 50 Hz GNSS observations.
- Strong Phase and amplitude scintillation was recorded by scintillation receiver.



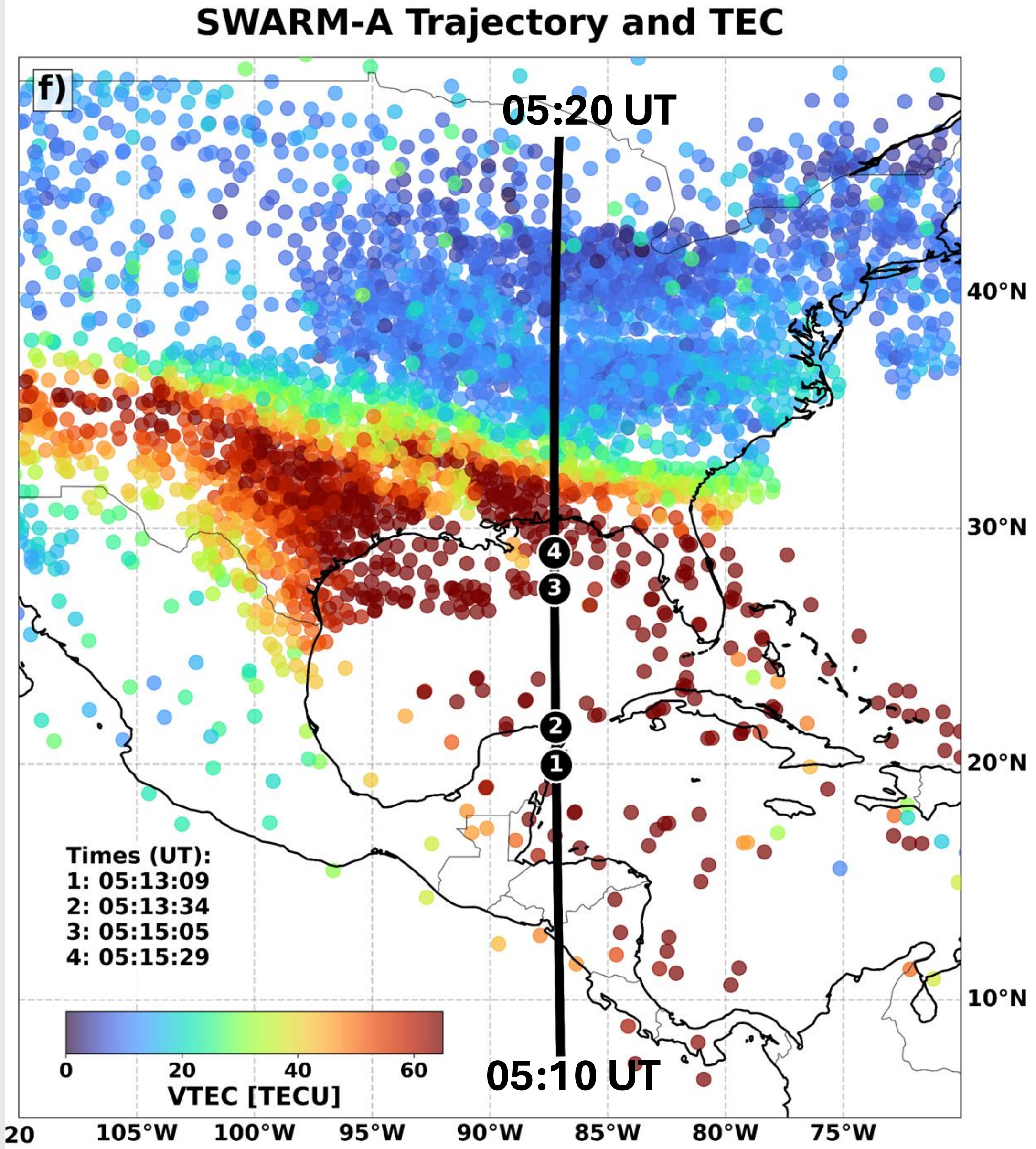
Is it Real Ionospheric Scintillation Event or RFI?

- **Strong Phase and amplitude scintillation was recorded by scintillation receiver.**
- **Scintillation effects are higher on L2 as compared to L1.**
- **Ratio of sigma phi L2/L1 and S2 L2/L1 was ~1.3 close standard ionospheric scintillation.**
- **Hence, scintillation seen on 21st Jan are due to Ionosphere.**



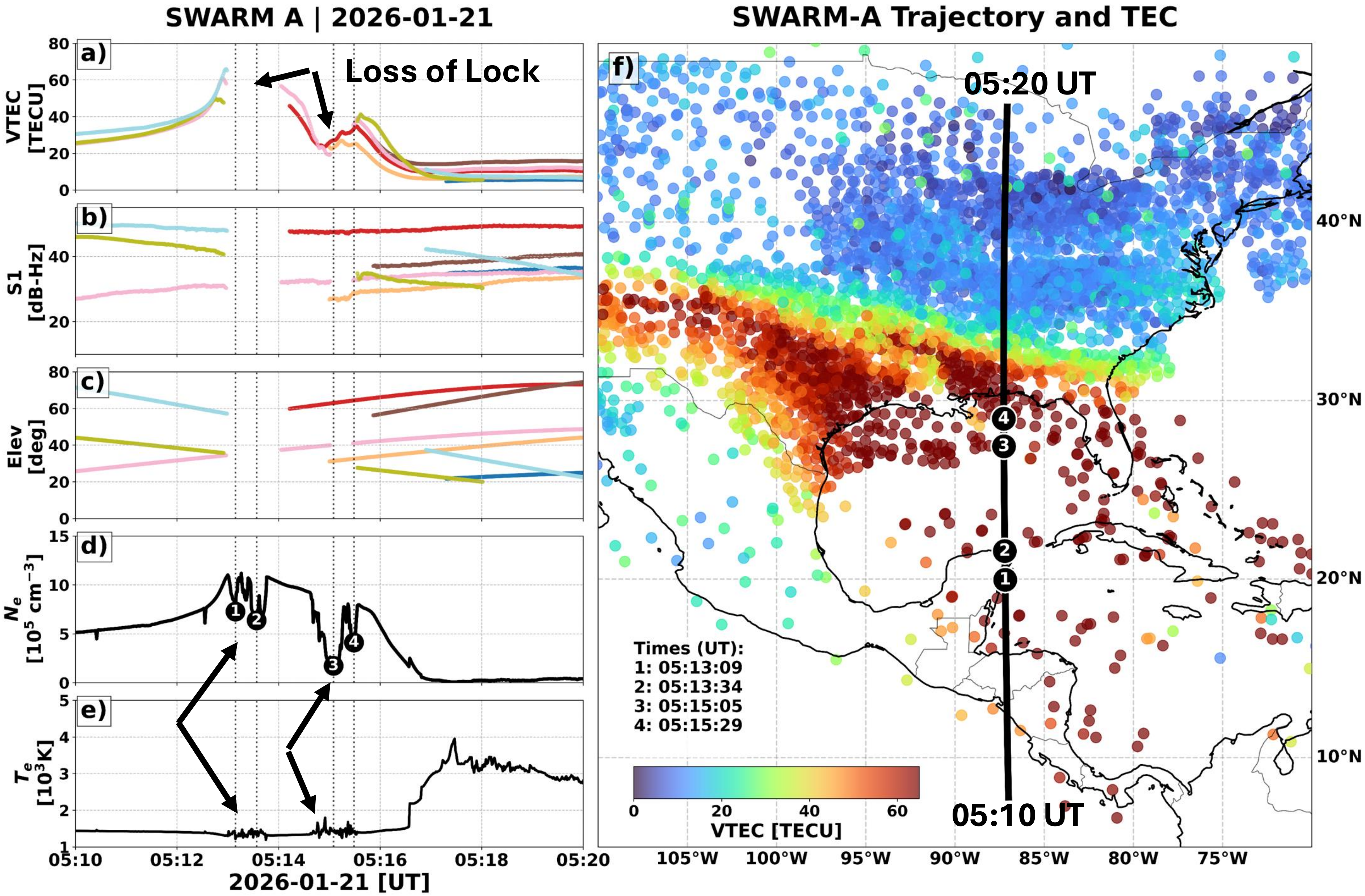
SWARM Passing Through Irregularities

- **SWARM-A passed through NILE around 05:10 to 05:20 UT.**
- **TEC at 05:05 UT is shown in background.**



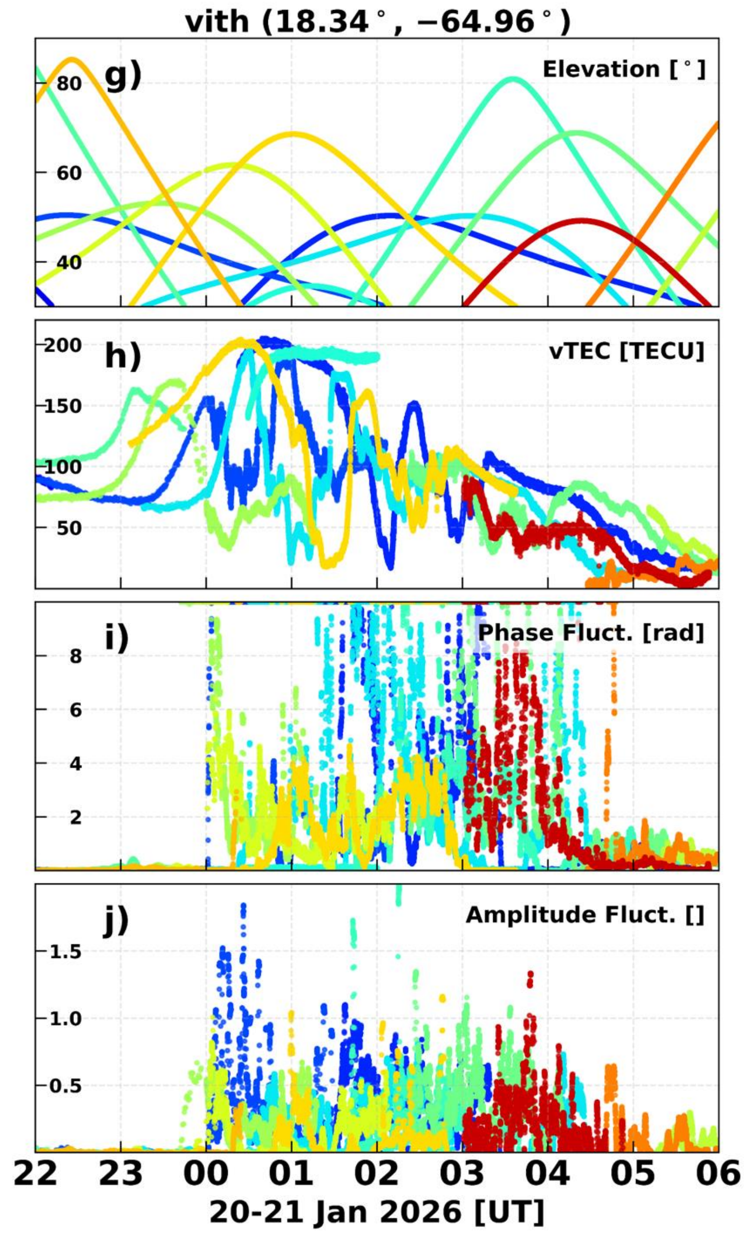
SWARM Passing Through Irregularities

- **GPS receiver on board SWARM loss lock while passing through NILE.**
- **In-Situ plasma density shows localized depletions within large scale enhancement.**
- **Electron temperature also shows rapid fluctuations.**
- **These are potential signatures of equatorial plasma bubbles.**



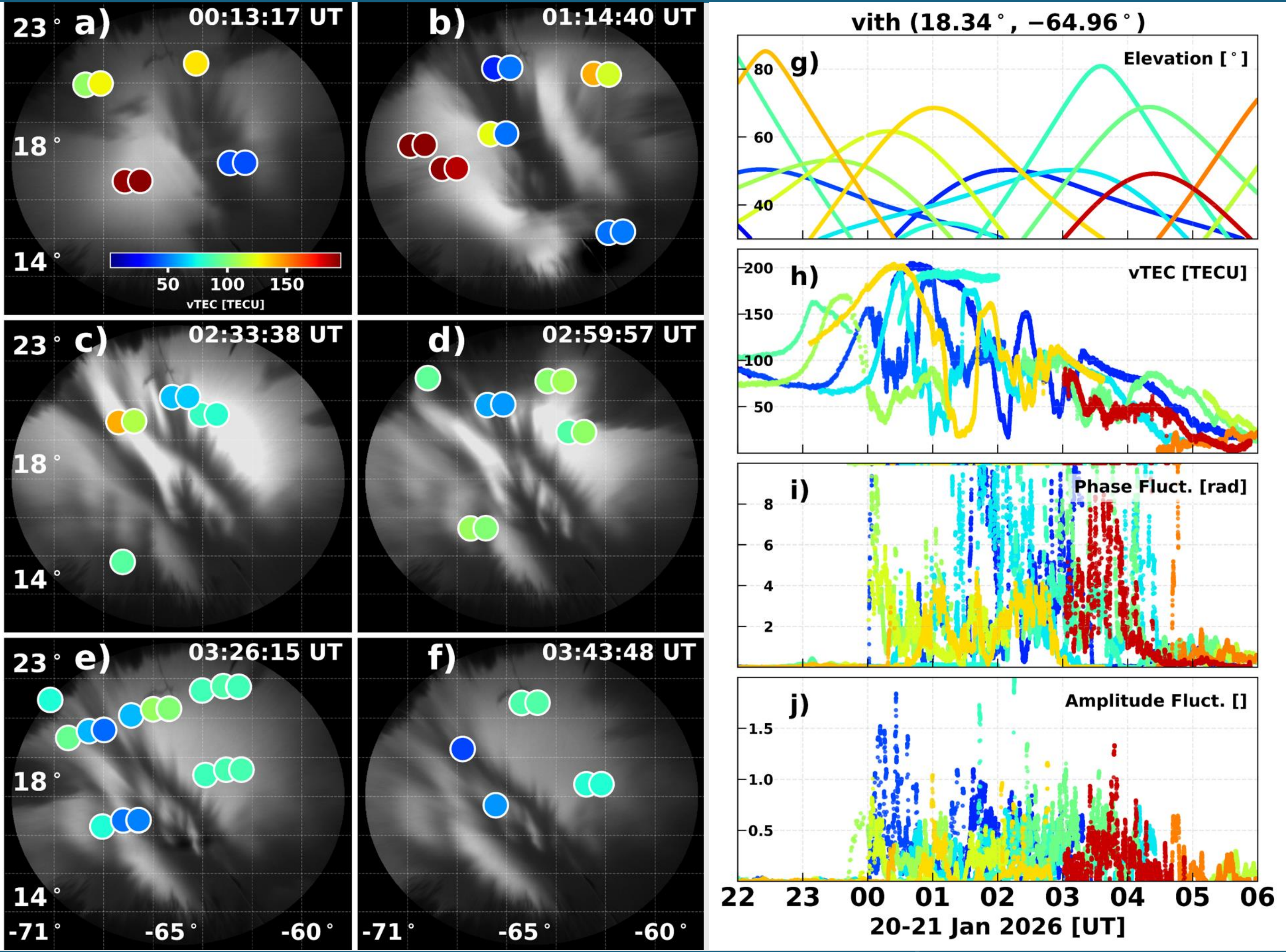
Comparison with All Sky Imager Airglow in Puerto Rico

- **GPS receiver (vith) in Puerto Rico show dramatic TEC variations.**
- **TEC from some PRNs was about 200 TECU while at the time others showing as low 20 TECU.**
- **Since there strong scintillation at the same time which makes the precision of TEC questionable.**
- **6300A Air glow emissions provides another independent way verify the such extreme gradients.**



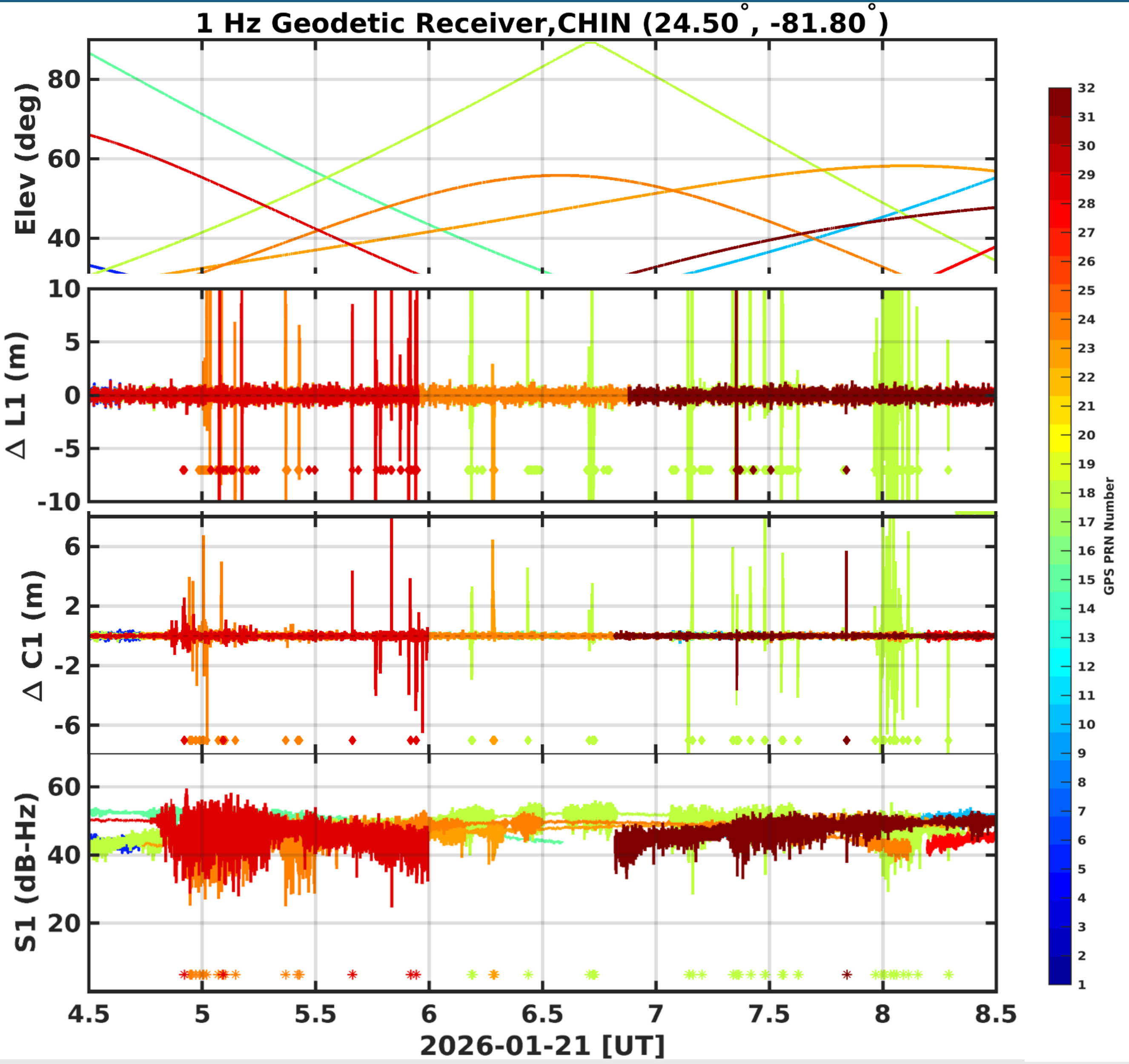
Comparison with All Sky Imager Airglow in Puerto Rico

- **ASI emissions are superimposed with TEC at IPP.**
- **ASI emissions shows strong density depletions and enhancements.**
- **Superimposed TEC shows very good correlation with airglow emissions.**
- **Hence, ASI confirms the Ionospheric structures observed through ground GPS receivers.**



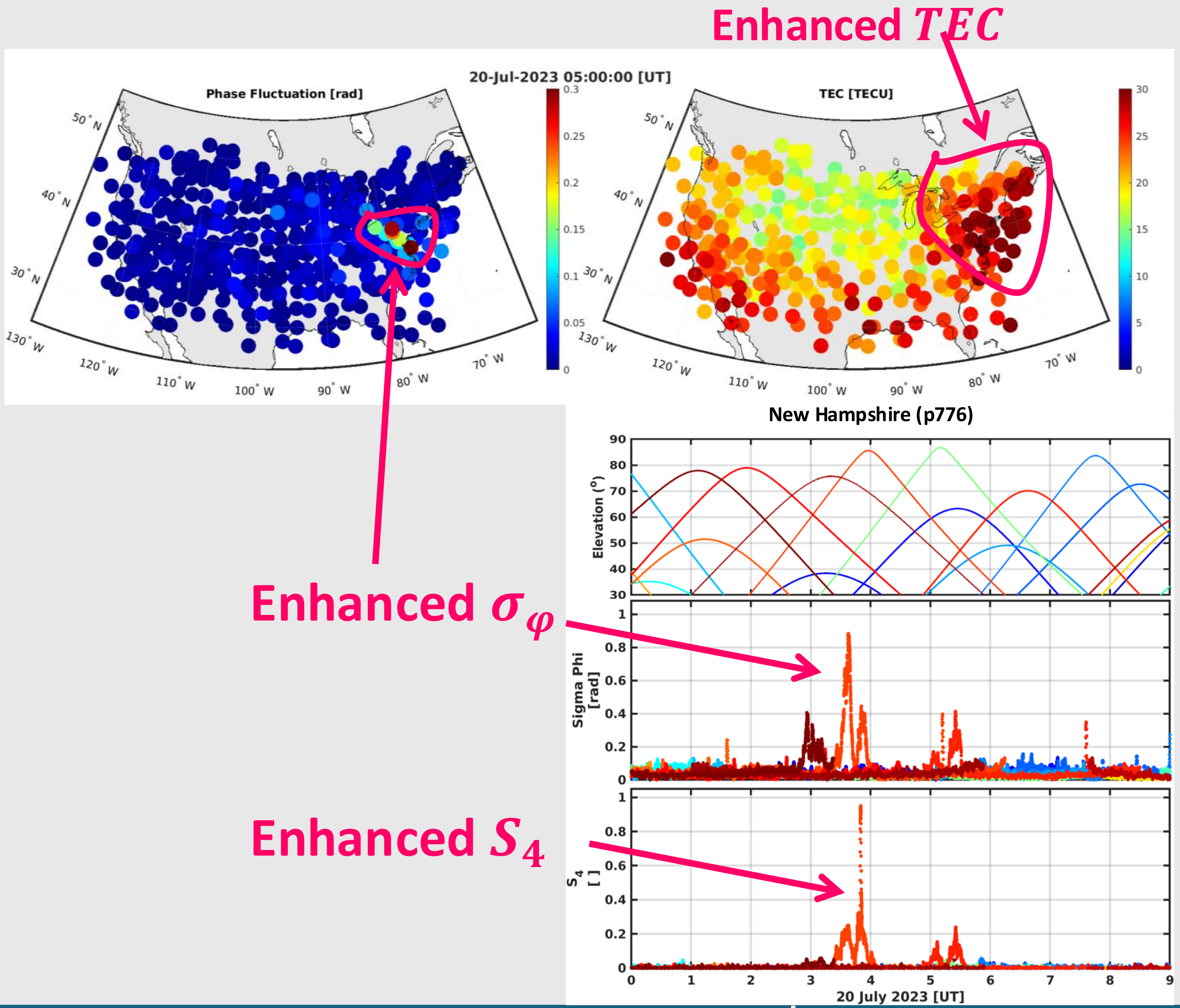
Performance Evaluation of Carrier Phase (L) and code (C) Signals

- **GPS tracks carrier phase and code pseudo range through phase lock loop (PLL) and delay lock loop (DLL).**
- **Code pseudo-range estimate the approximate satellite receiver distance while carrier phase precisely measures up to fraction of phase of signal with some ambiguity.**
- **Comparison of detrended L1 and C1 shows more outages and spikes in carrier phase signals than code pseudo-range.**
- **This shows fragility of PLL which could fail more often such extreme scintillation environment.**
- **Levelling TEC to carrier phase could introduce artifact and unrealistic values due to frequent cycle slips.**



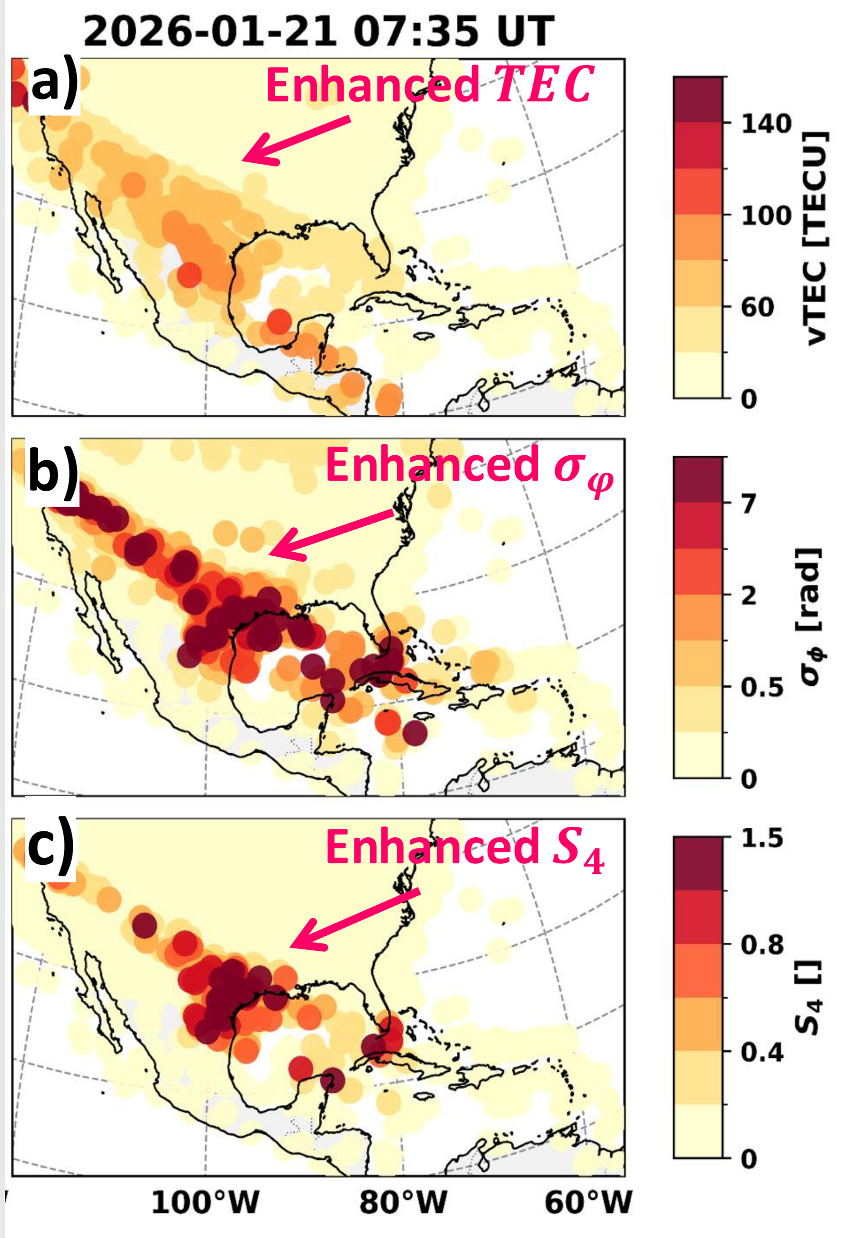
Mysterious Mid-Latitude GPS Scintillation During Quiet Days

- Strong enhancement in σ_{φ} and S_4 is observed on 20 July 2023 during the 03-04 UT by 1Hz receiver (p776).
- Phase fluctuations are detected at the many receivers drifting to southwest.
- There are about 30 such event detected during different seasons.
- What are possible mechanisms for such irregularities: Either forcing from below or something else?



Summary

- We identify rapid TEC fluctuations, phase scintillation as key contributors to positioning errors over the U.S. on May 10–11.
- Large position error were observed along the trough boundary and substorm surges and SED.
- GPS disruptions at mid-latitude are not exclusive to superstorm. While large to moderate storm can also caused significant phase fluctuations. Night-time Ionospheric enhancement could also transport severe scintillation and disruption from low to mid latitudes.
- Unusual scintillation events are observed at mid-latitude during the geomagnetic quiet days which need further investigation.



This work was supported by the NASA Jack Eddy Fellowship.

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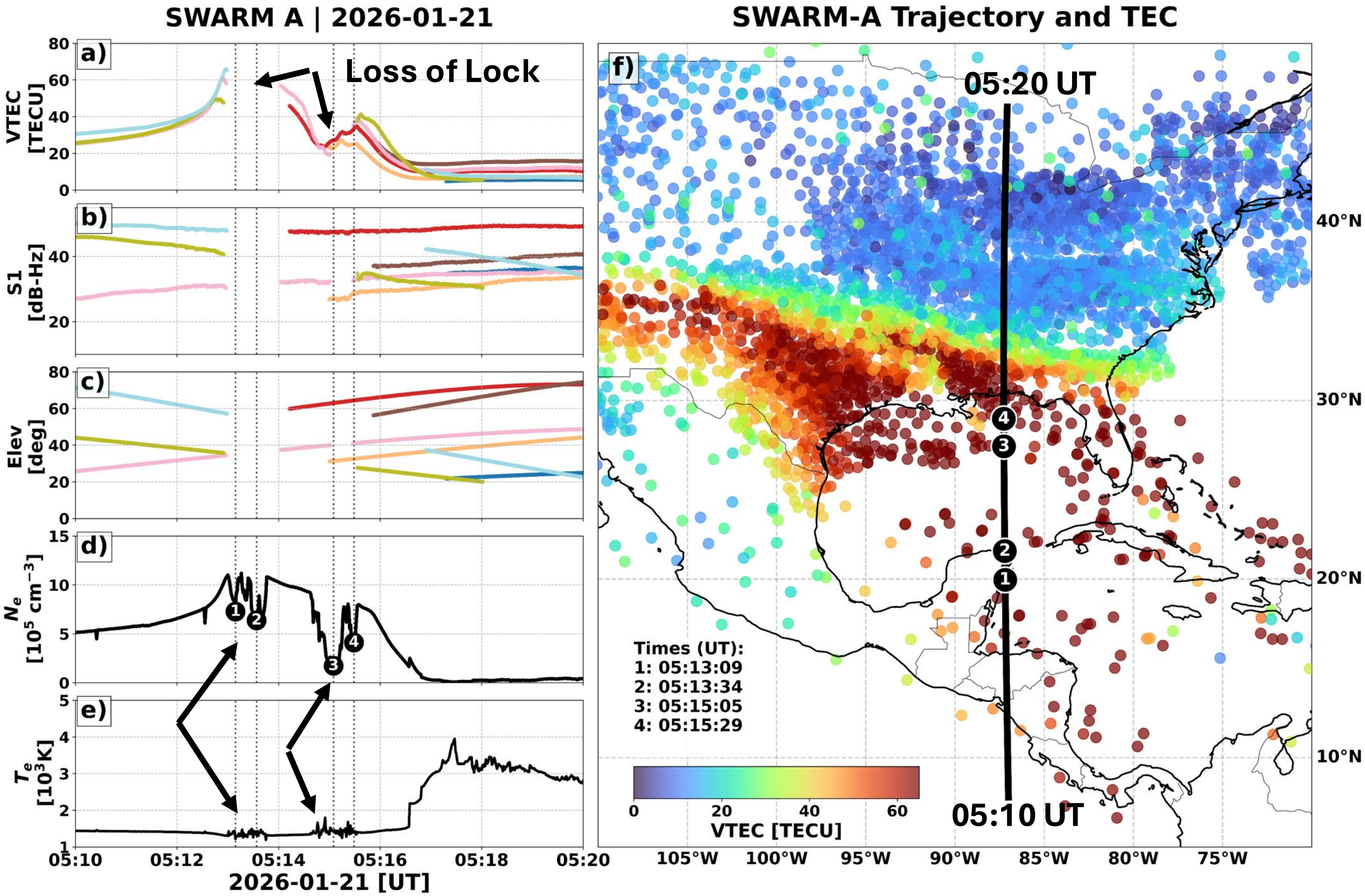

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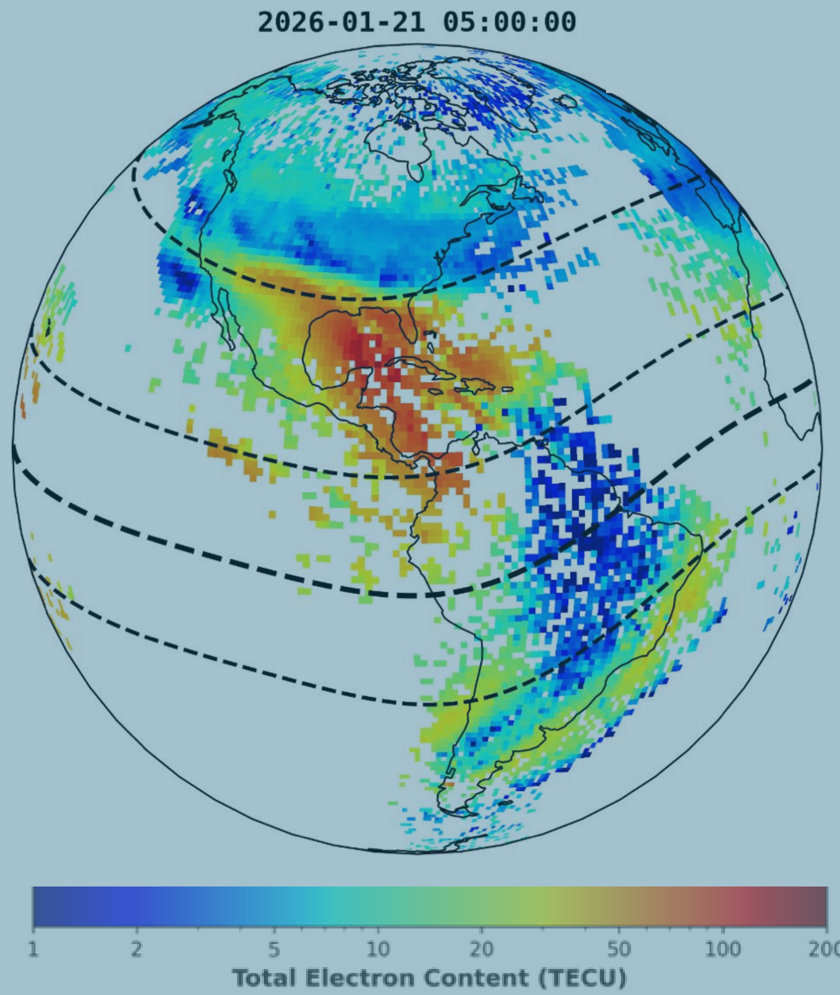

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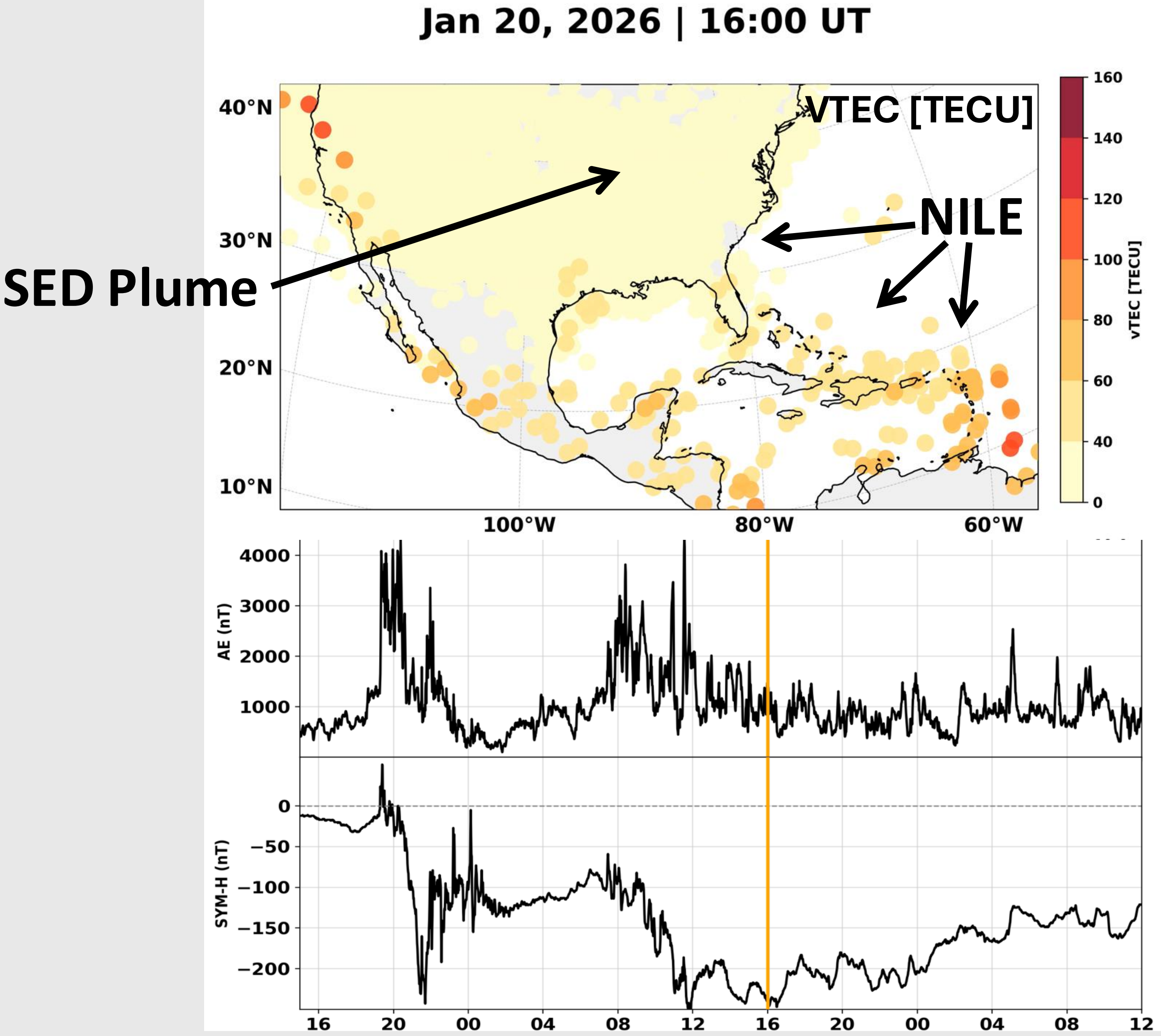
Spatio-Temporal Evolution of TEC

- **VTEC computed from high-rate (1 Hz) ground GNSS receivers in North America using code-pseudorange observations (C1/C2).**
- **Day-side SED plume was observed over North-America around 19:00 UT which drifted westward.**
- **NILE originated in Caribbean and Puerto-Rico region around 23:30 UT and expanded to mid-latitudes.**
- **NILE stretched in North-West to South-East band and spans over 12 hours.**



Spatio-Temporal Evolution of Scintillations

- **Phase scintillation (sigma phi) is standard deviation of detrended phase.**
- **Sigma-Phi computed using the 1 Hz GPS data and integration time of 1 minute.**
- **No significant phase scintillation caused by day-side SED plume.**
- **Strong phase scintillation was observed with NILE.**
- **Phase scintillation evolved along the NILE and penetrated deep in mid-latitudes regions.**