NASA 5th Eddy Cross-Disciplinary Symposium

LONGITUDINAL VARIATION OF IONOSPHERIC IRREGULARITIES

Valence Habyarimana

05/05/2026

UNIVERSITY OF MICHIGAN

MBARARA UNIVERSITY OF SCIENCE AND TECHNOLOGY
SUCCEED WE MUST

Schmidt Sciences

About me

vhabyari@umich.edu

Valence Habyarimana *(He/Him/His)*
Schmidt African Faculty Fellow
PhD in Space Physics at MUST

Research Interests:

- ✓ Ionospheric modeling.
- ✓ AI/ML.
- ✓ Foundation models.
- ✓ Data clustering.

Teaching Experience:

- ✓ Physics and Mathematics.
- ✓ Since 2003 to date.
- ✓ Secondary schools 2003-2011.
- ✓ University 2011 to date.
- ✓ Part-timer to Lecturer.

Longitudinal variation of ionospheric irregularities and response of the ionosphere during May and October 2024 geomagnetic storms

Valence Habyarimana[1,2,*], Mark B. Moldwin[2], John Bosco Habarulema[3,4,5], Sharon Aol[1], Jean Claude Uwamahoro[6,7], Teshome Dugassa[8], Daniel Okoh[9], and Solomon Otoo Lomotey[10]

Geomagnetic storms

- ✓ The temporary disturbance in the Earth’s magnetic field as a result of a space weather phenomenon such as coronal mass ejection (CME), corotating interaction region (CIR) or solar flare is referred to as a geomagnetic storm (Dessler and Parker, 1959).

- ✓ The Earth’s ionosphere responds to both solar and geomagnetic disturbances in a complex way spatially and temporally due to its dynamic nature (Kelley, 2009).

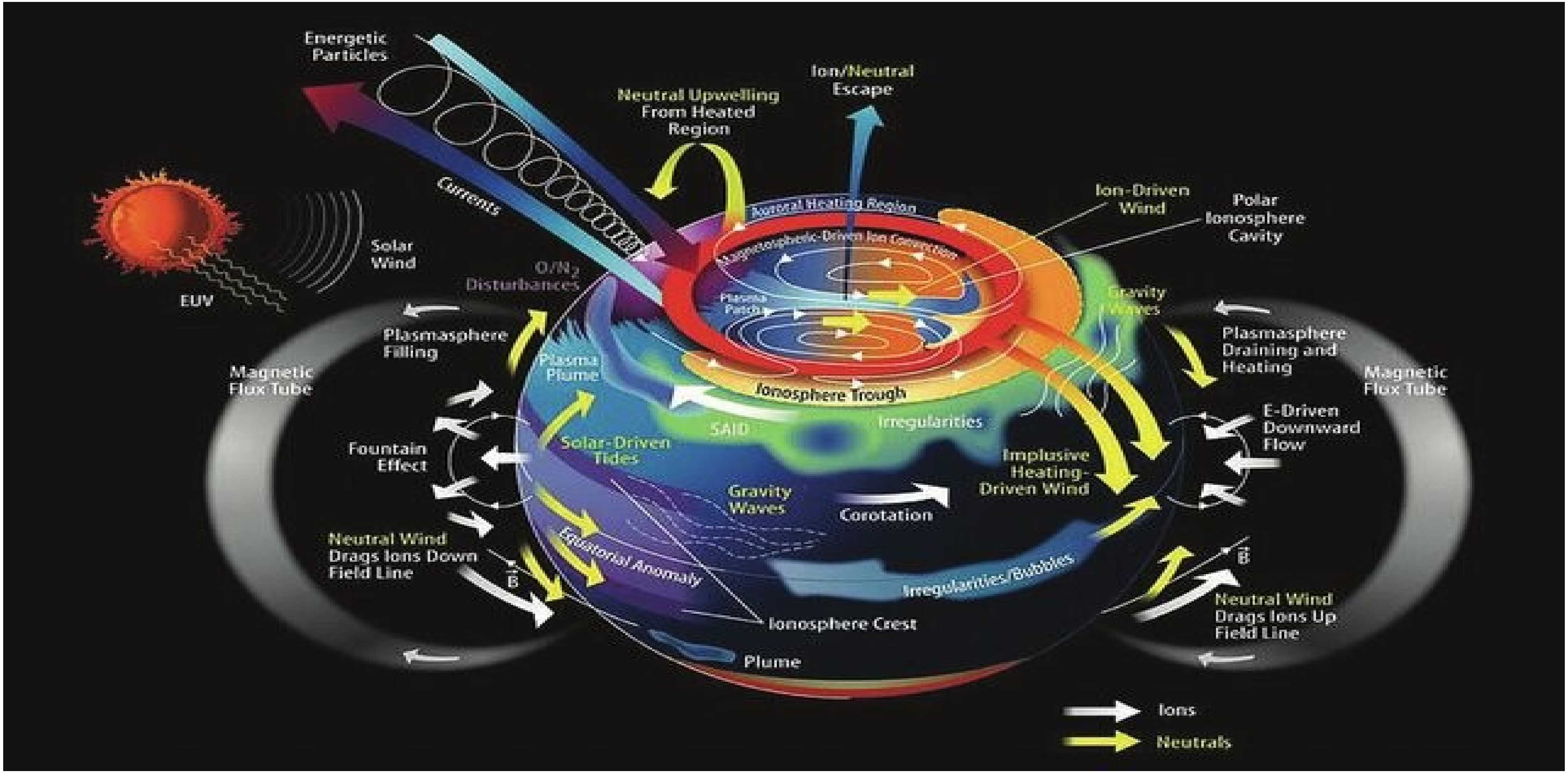


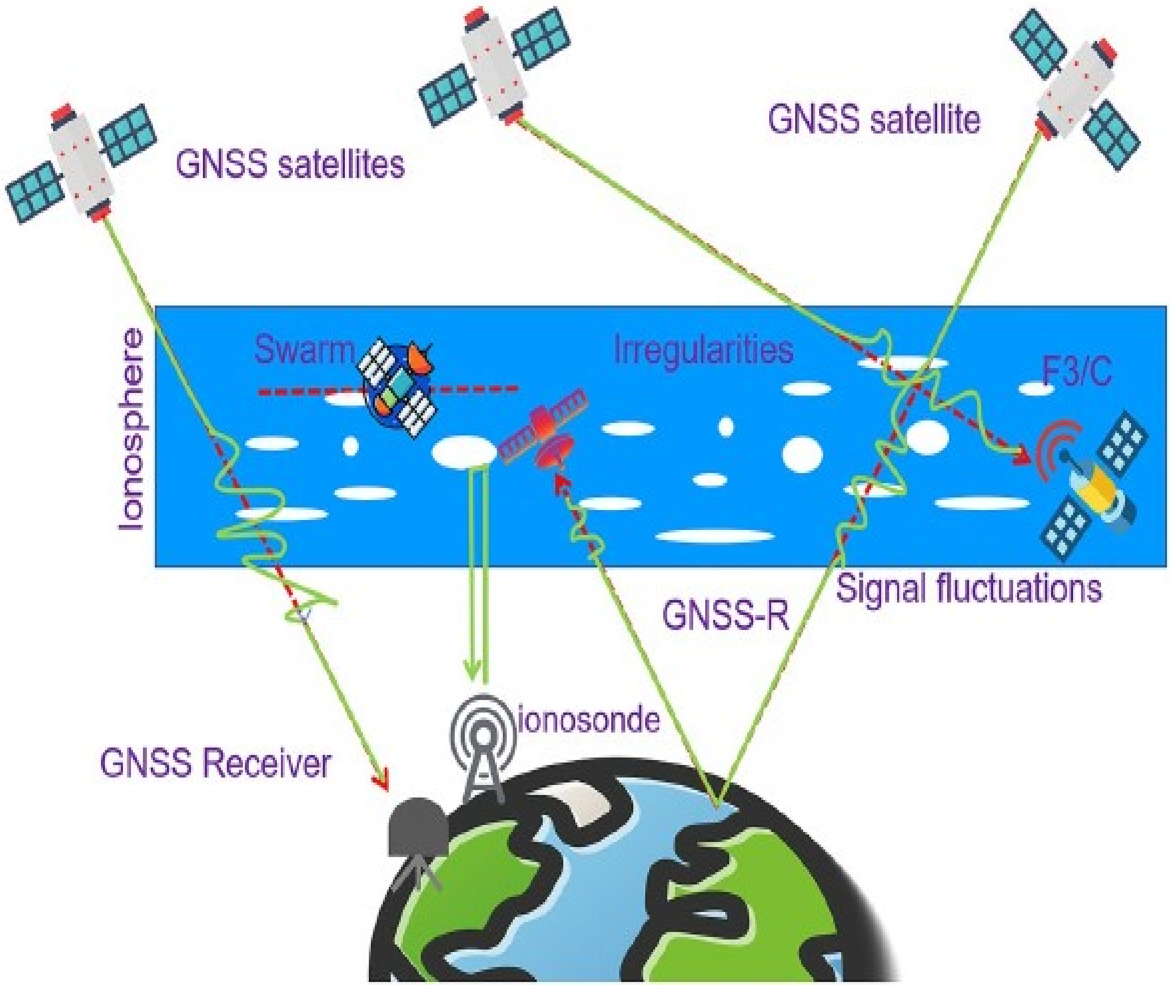
Figure 1: The Earth's ionosphere and corresponding processes (Grebowsky and Aikin, 2009)

- ✓ Geomagnetic storms, which result from enhanced solar wind-magnetosphere interactions, can significantly impact ionospheric plasma, leading to irregularities that disrupt radio communications, navigation systems, and space based technologies (Kintner et al., 2007; Moldwin, 2008).

- ✓ These storm-induced electric field perturbations redistribute ionospheric plasma, leading to the formation of plasma density irregularities, especially in equatorial and low-latitude regions (Bagiya et al., 2011; Remya et al., 2025).

- ✓ Ionospheric irregularities are often observed as plasma depletions along satellite tracks, scintillations, traveling ionospheric disturbances (TIDs) and variations in the Rate of change of Total Electron Content Index (ROTI) (Burke et al., 2004; Aol et al., 2020; Ondede et al., 2022).

Ionospheric irregularities



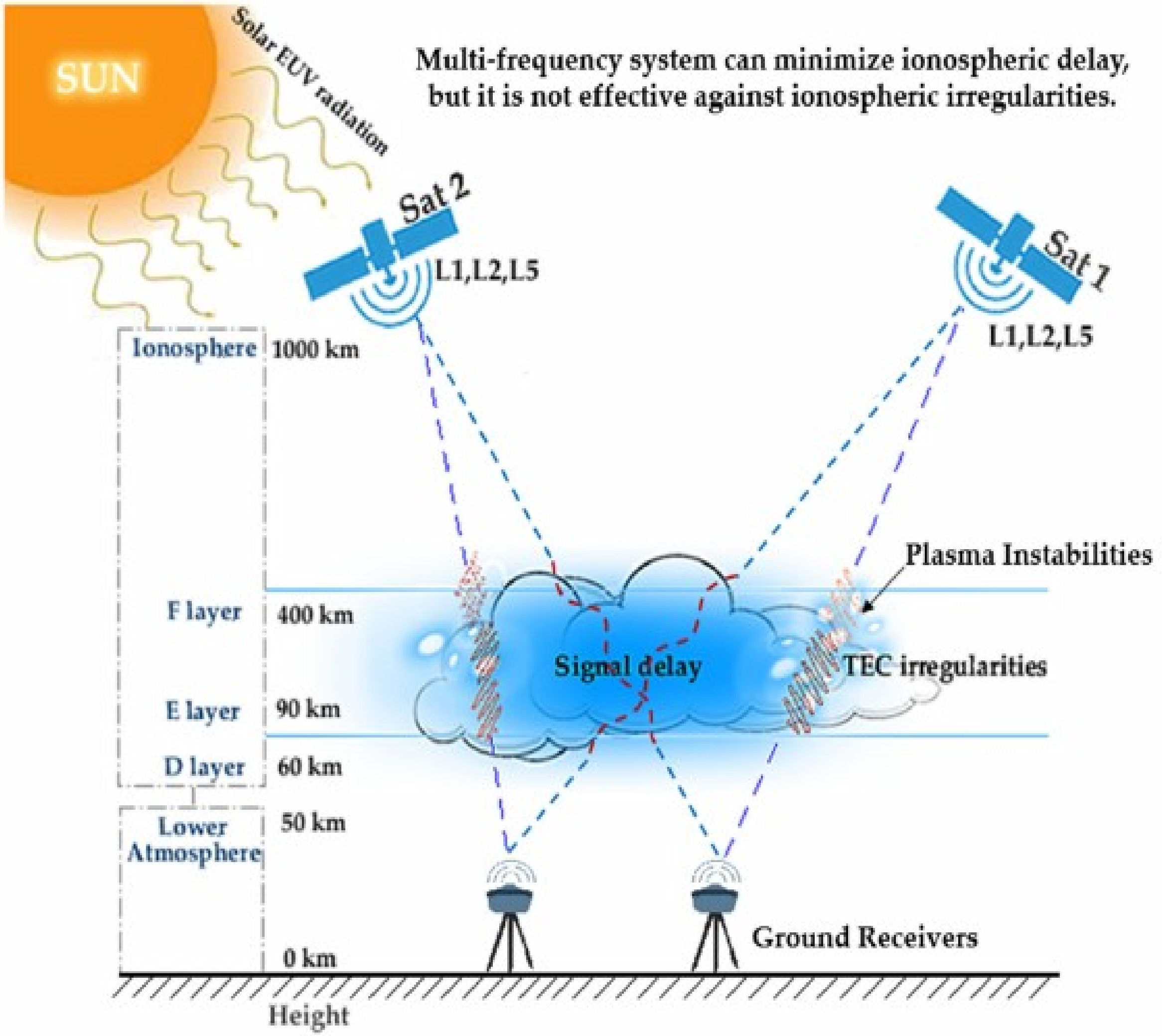


Figure 2: Ren et al. (2022). Leveraging the CYGNSS spaceborne GNSS-R observations to detect ionospheric irregularities over the oceans: Method and verification. Space Weather, 20, e2022SW003141. https://doi.org/10.1029/2022SW003141.

- Ionospheric irregularities exhibit strong longitudinal and latitudinal dependencies due to geomagnetic field geometry, thermospheric winds, and electrodynamic processes (Yizengaw and Groves, 2018).

- The knowledge of longitudinal dependence of ionospheric irregularities plays a pivotal role in space weather research since it is necessary for assessing their impacts on satellite communications, Global Navigation Satellite System (GNSS) accuracy, and in identifying the longitudinal input during ionospheric modeling.

- ✓This is because even at the same latitude, the ionosphere behaves differently at different longitudes as a result of non-uniform geomagnetic field, zonal electric fields, thermospheric winds, and solar terminator effects.

- ✓The temporal dependence of GNSS cycle slip is related to ionospheric irregularities over the global low latitude region (e.g., Li et al., 2025).

- ✓Therefore, it is important to study the characteristics and evolution of ionospheric irregularities especially during geomagnetic storms.

May and October 2024 Geomagnetic storms

- ✓ The two recent severe geomagnetic storms that occurred on 10-13 May 2024 and 10-13 October 2024 were among the greatest geomagnetic storms since 1957 when Disturbance storm time (Dst) index, an index used to measure the severity of a geomagnetic storm, was first estimated (Campbell, 1996; Paul et al., 2025a).

- ✓ Not only did the two geomagnetic storms cause an impact on the Earth's ionosphere that led to adverse effects on the technological systems but also led to the visibility of some beautiful auroras extending to low latitudes.

Data used

- ✓ In this study, data from selected GNSS receivers (https://cddis.nasa.gov/archive/gnss/data/daily/2024/) and Swarm-A satellite observations (https://vires.services/) were used.

- ✓ We analyzed the response of the ionosphere and characterized the spatial distribution and evolution of ionospheric irregularities across the three longitude sectors of American, African, and Asian.

- ✓ GNSS receivers Saõ LuÍs, SALU (2.59°S, 44.2°W geographic, and 0.25°S geomagnetic), Addis Ababa, ADIS (9.04°N, 38.8°E geographic, and 0.18°N geomagnetic), and Guam island, GUUG (13.43°N, 144.8°E geographic, and 5.66°N geomagnetic) represent American, African and Asian sectors, respectively.

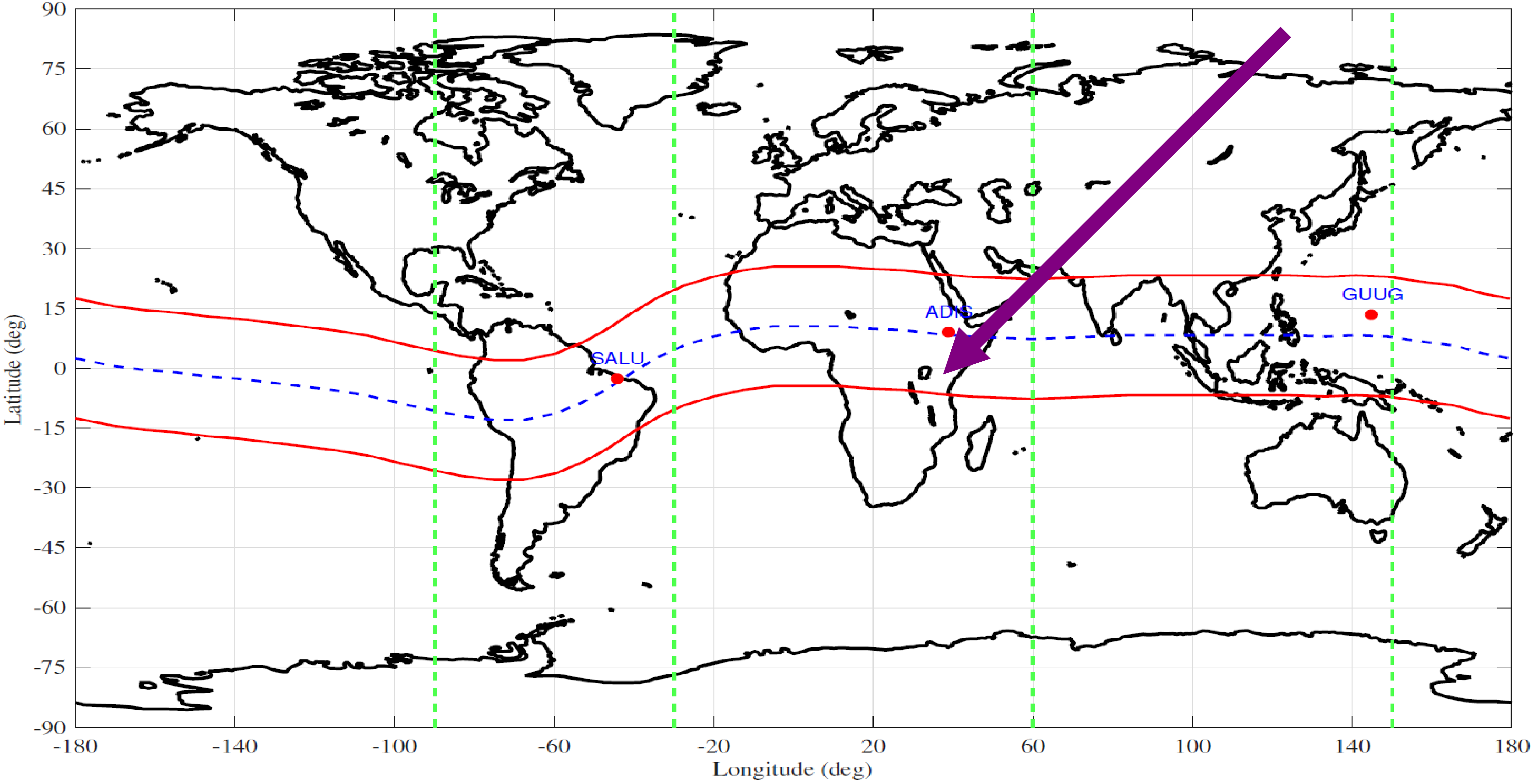


Figure 3: Map showing the stations of IGS receivers used in this study

Swarm Satellites

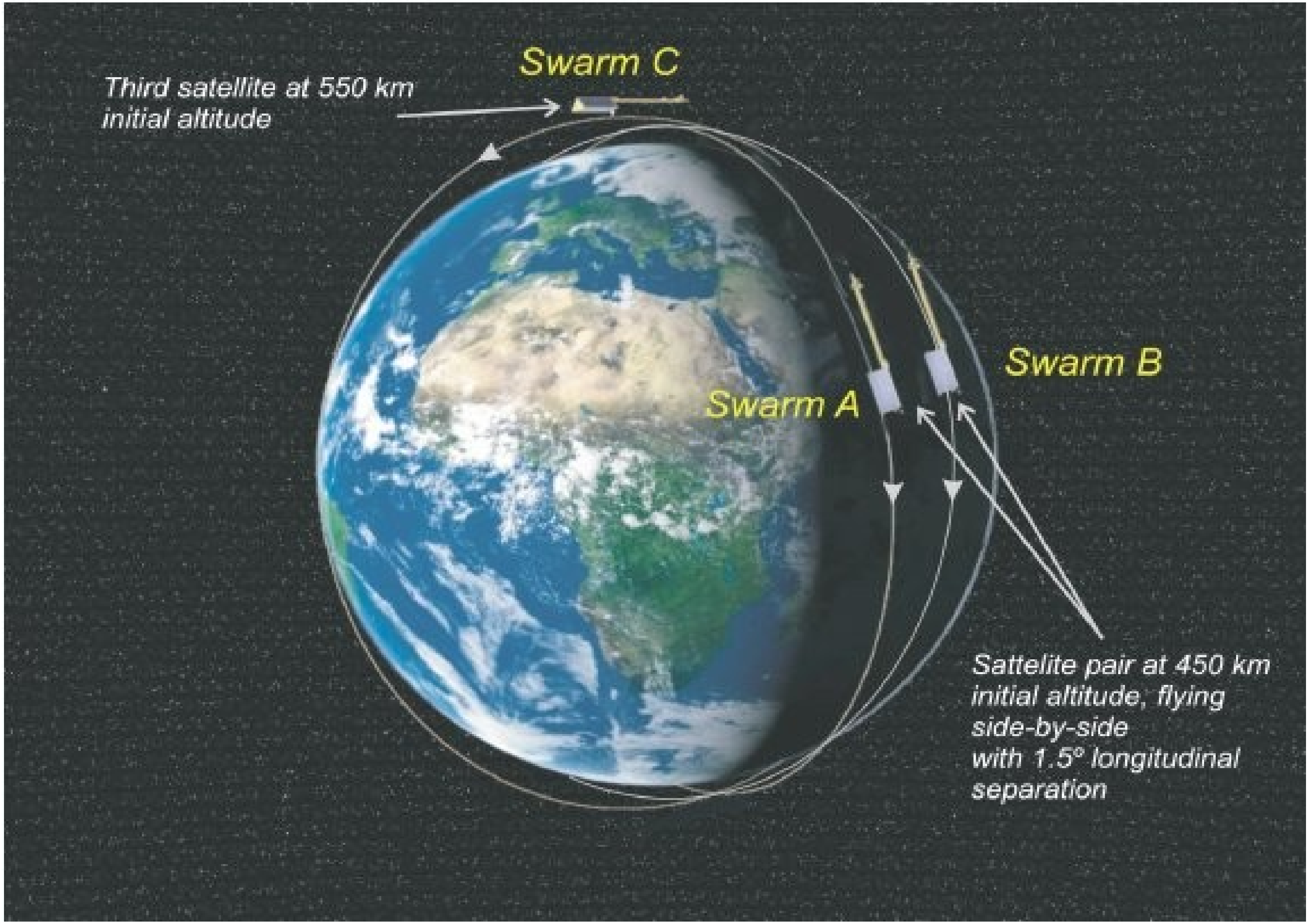


Figure 4: Swarm A and C (lower pair, flying side-by-side).

Swarm B (higher satellite).

Swarm satellites

- The Swarm mission comprises three satellites, Swarm Alpha (A), Swarm Beta (B), and Swarm Charlie (C), designed to study Earth's magnetic field, ionosphere, and space weather.
- These satellites orbit at altitudes of 450 km (Swarm A and C) and 530 km (Swarm B), with inclinations of 87.4^{o} and 87.5^{o}, respectively.
- Equipped with GPS receivers, the satellites measure Electron density and Total Electron Content (TEC) at a frequency of 1 Hz.
- TEC data represents the number of electrons along the signal path between the satellite and the GPS receiver.

Data processing

- ✓ We took into account data from the American, African, and Asian longitude sectors that ranged between -90 to -30, -30 to 60, and 60 to 150 degrees, respectively, for the Swarm satellite products.

- ✓ The GNSS data files were downloaded in Receiver Independent EXchange (RINEX) format.

- ✓ The RINEX data were extracted into readable files using the GPS-TEC analysis software developed at Boston College (Seemala and Valladares, 2011; Seemala, 2023) with vertical TEC (VTEC) and slant TEC (STEC) among the output parameters.

- ✓ An elevation cutoff of 30^{o} was used to minimize multipath effects (Habyarimana et al., 2023).

- ✓The VTEC was used to compute its percentage deviation from the background (taken as the mean VTEC of the five international quietest days at a particular station in a particular month).
- ✓The five international quietest days were downloaded from the International Service of Geomagnetic Indices (ISGI) website (https://isgi.unistra.fr/data_download.php).
- ✓This was then used to reveal the occurrence of positive or negative ionospheric storms during the geomagnetic storms under this study.
- ✓The percentage deviation in VTEC can fairly approximate the departure of disturbed time TEC values from quiet mean values.

✓The percentage deviation was computed using the equation:

$$\Delta TEC = \frac{TEC_{ob} - TEC_q}{TEC_q} \times 100\%,$$

where TEC_q is mean of the five international quietest days in a month and TEC_{ob} is the VTEC value during the geomagnetic storm day.

✓The STEC was used to compute Rate of change of TEC (ROT) using the equation (Pi et al., 1997):

$$ROT(t) = \frac{STEC(t+dt) - STEC(t)}{\Delta t},$$

where Δt is the difference between two successive time epochs, usually 30 s for GNSS receivers.

✓The ROTI is derived from the variance of ROT by finding its standard deviation over a 5-minute interval, to quantify the intensity of ionospheric irregularities.

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}.$$

- ✓ The Swarm satellite in situ electron density data were also used to infer ionospheric irregularities.

- ✓ Rate of change of electron density index (RODI) measures the fluctuations in electron density (Ne) and is defined in a way similar to ROTI with Ne in the place of TEC, and taken as the standard deviation of ROD with a running window of 10 s, or 20 s (Zakharenkova et al., 2016; Jin et al., 2022; Dugassa et al., 2023; Dugassa and Habyarimana, 2025).

- ✓ We used RODI computed using a standard deviation of 10 s so as to capture small scale fluctuations in Ne.

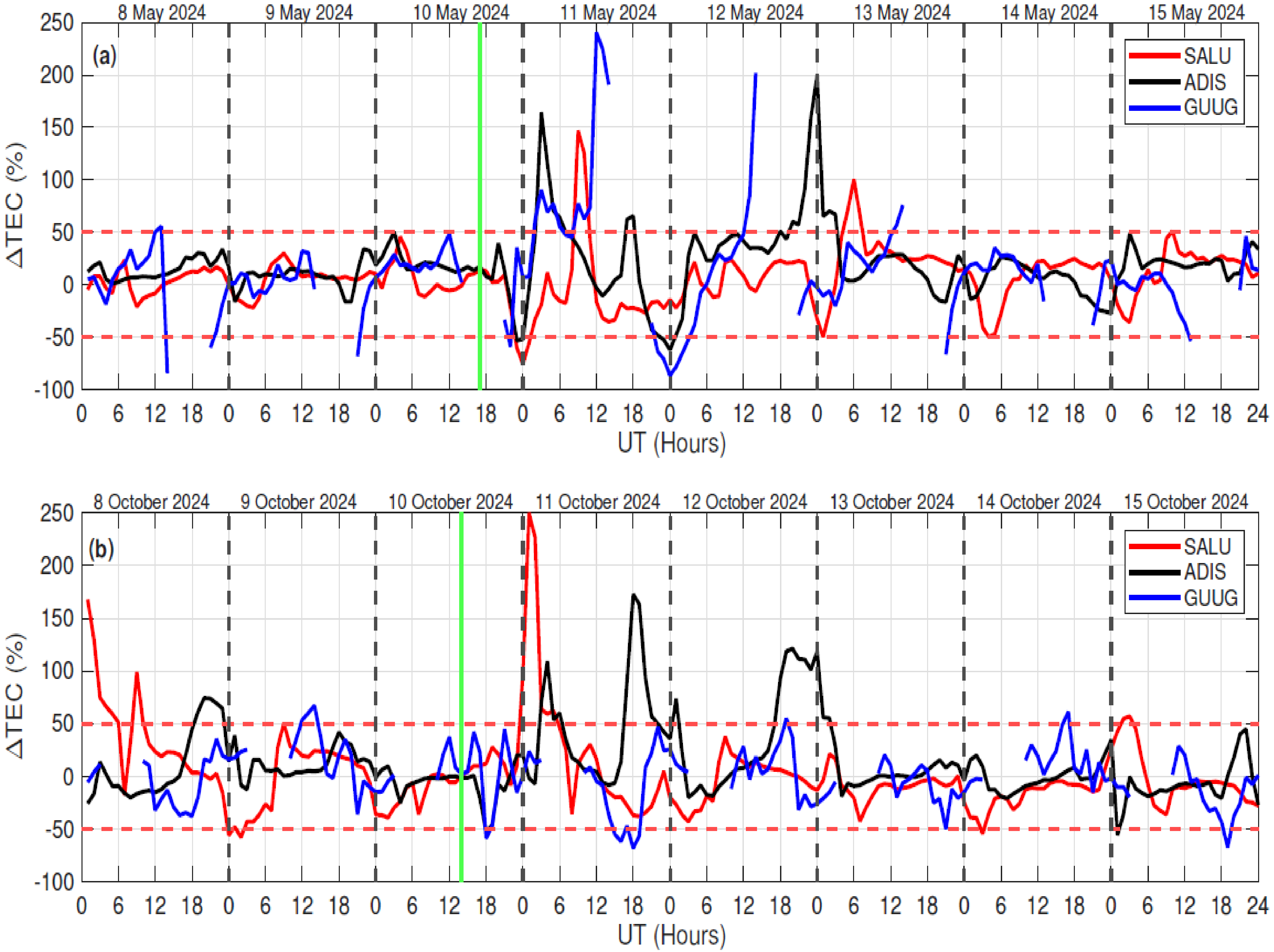


Figure 5: The response of the ionosphere to the two geomagnetic storms

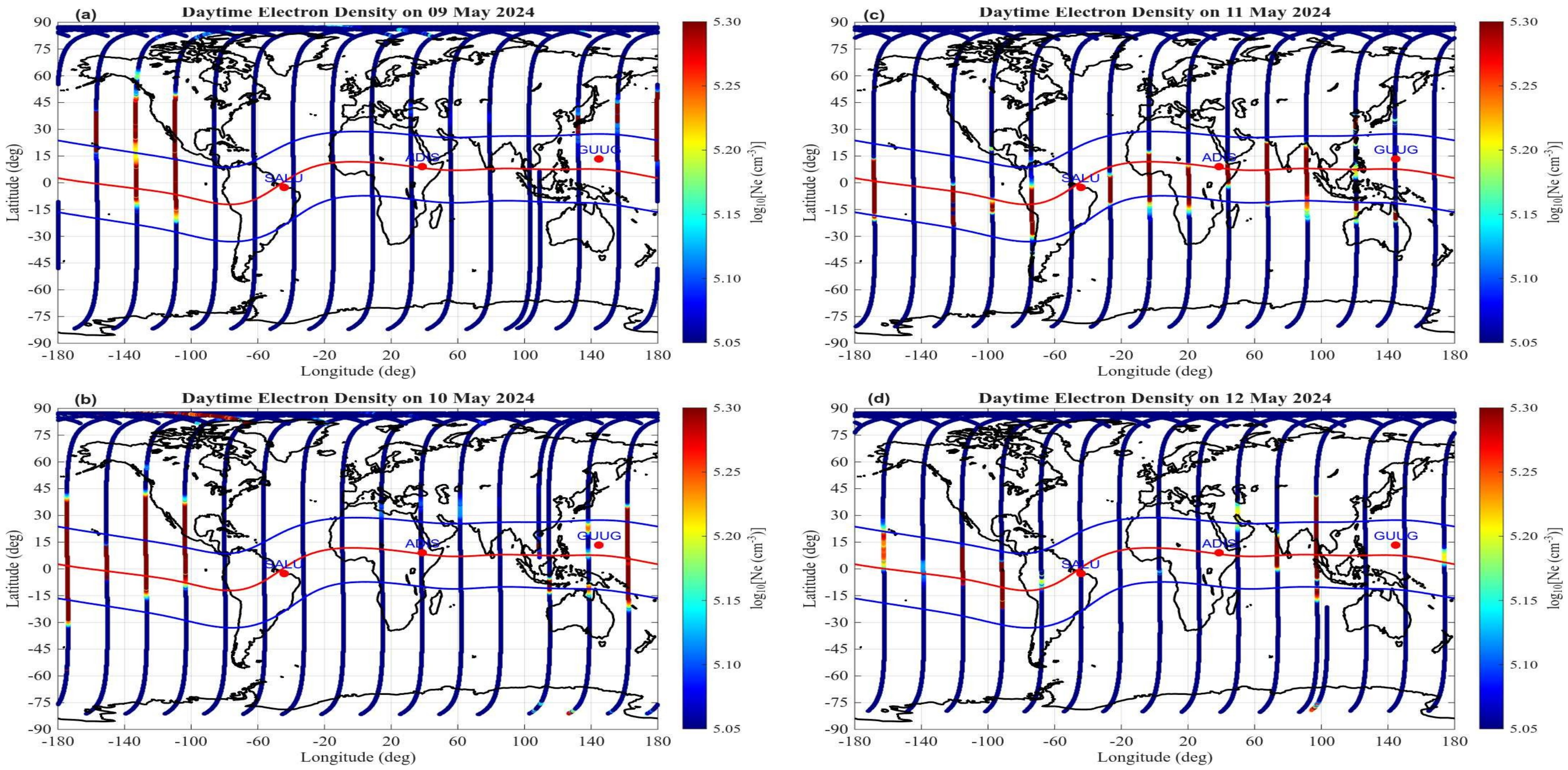


Figure 6: Swarm satellite data for electron density between 9-12 May 2024.

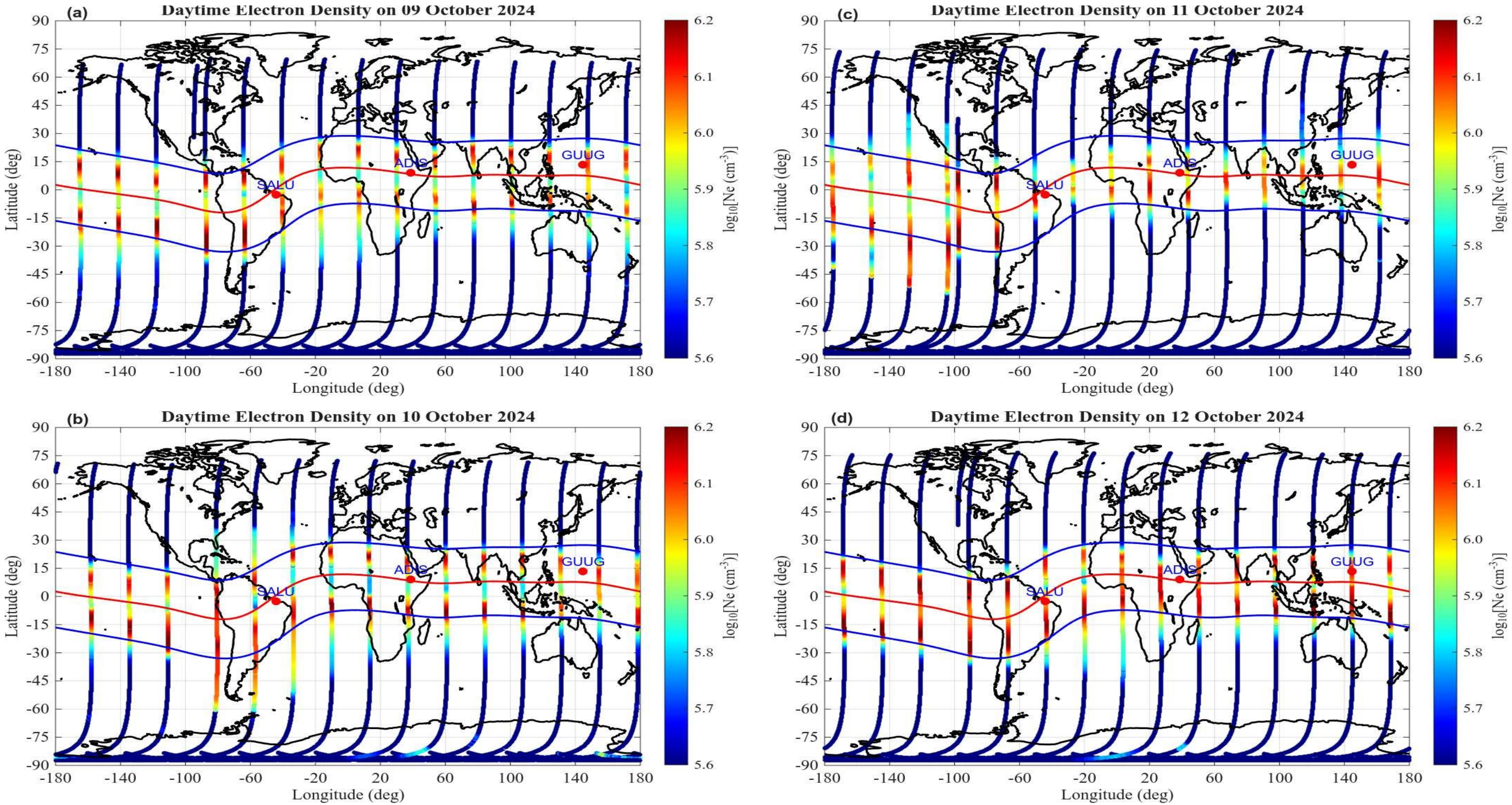


Figure 7: Swarm satellite data for electron density between 9-12 October 2024.

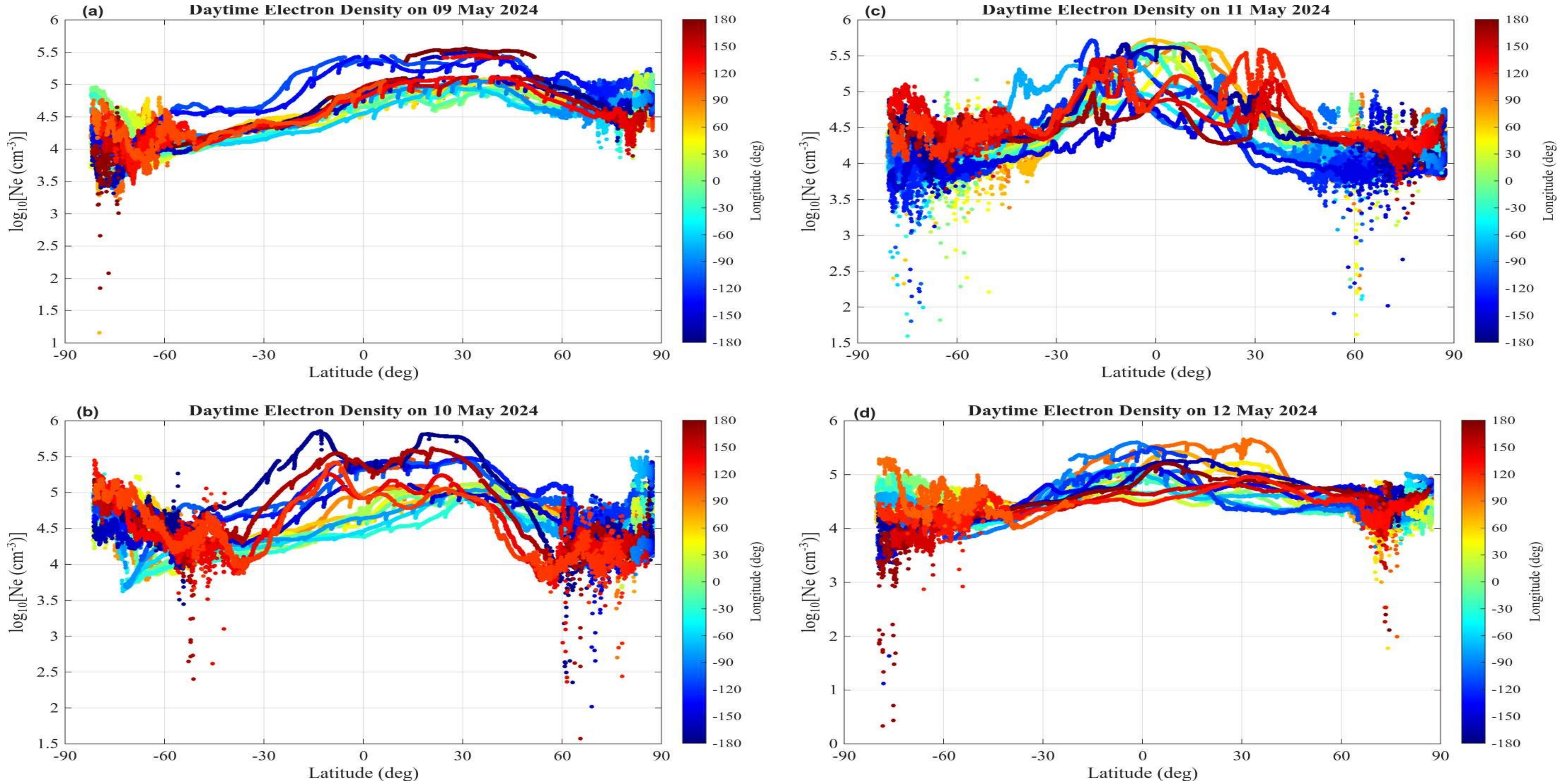


Figure 8: Swarm-A latitudinal profiles between 9-12 May 2024.

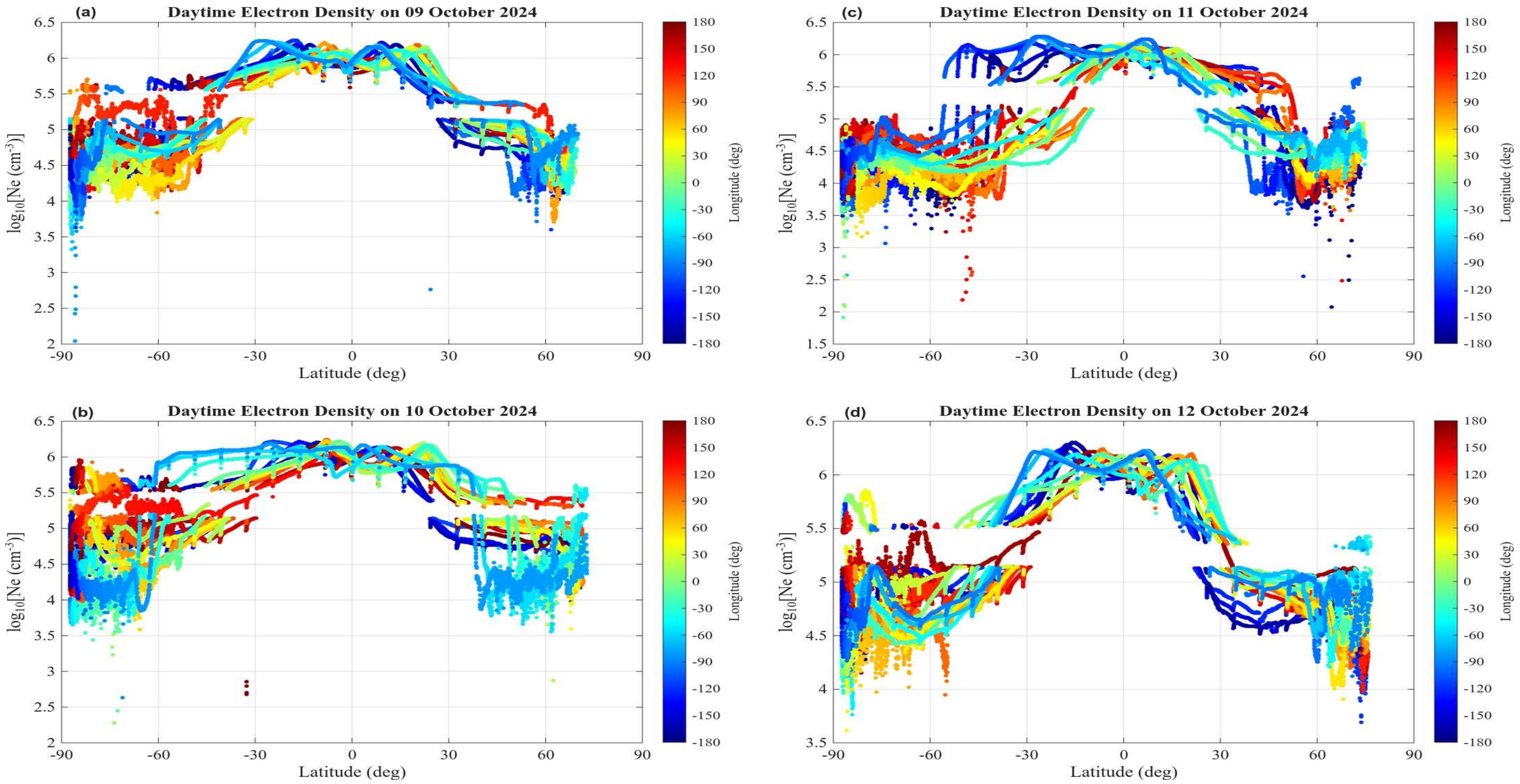


Figure 9: Swarm-A latitudinal profiles between 9-12 October 2024.

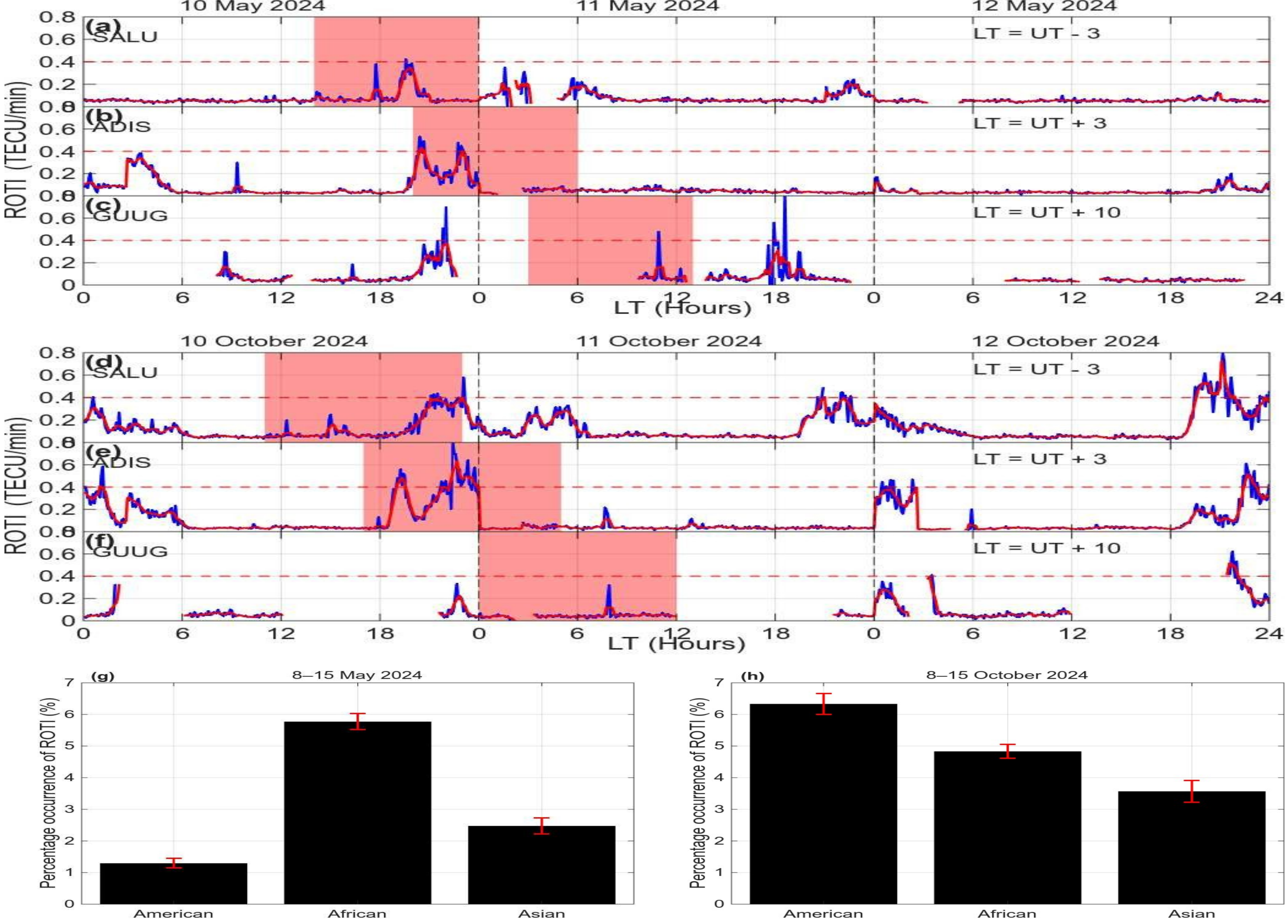


Figure 10: IGS Longitudinal variation and the time of occurrence of ionospheric irregularities

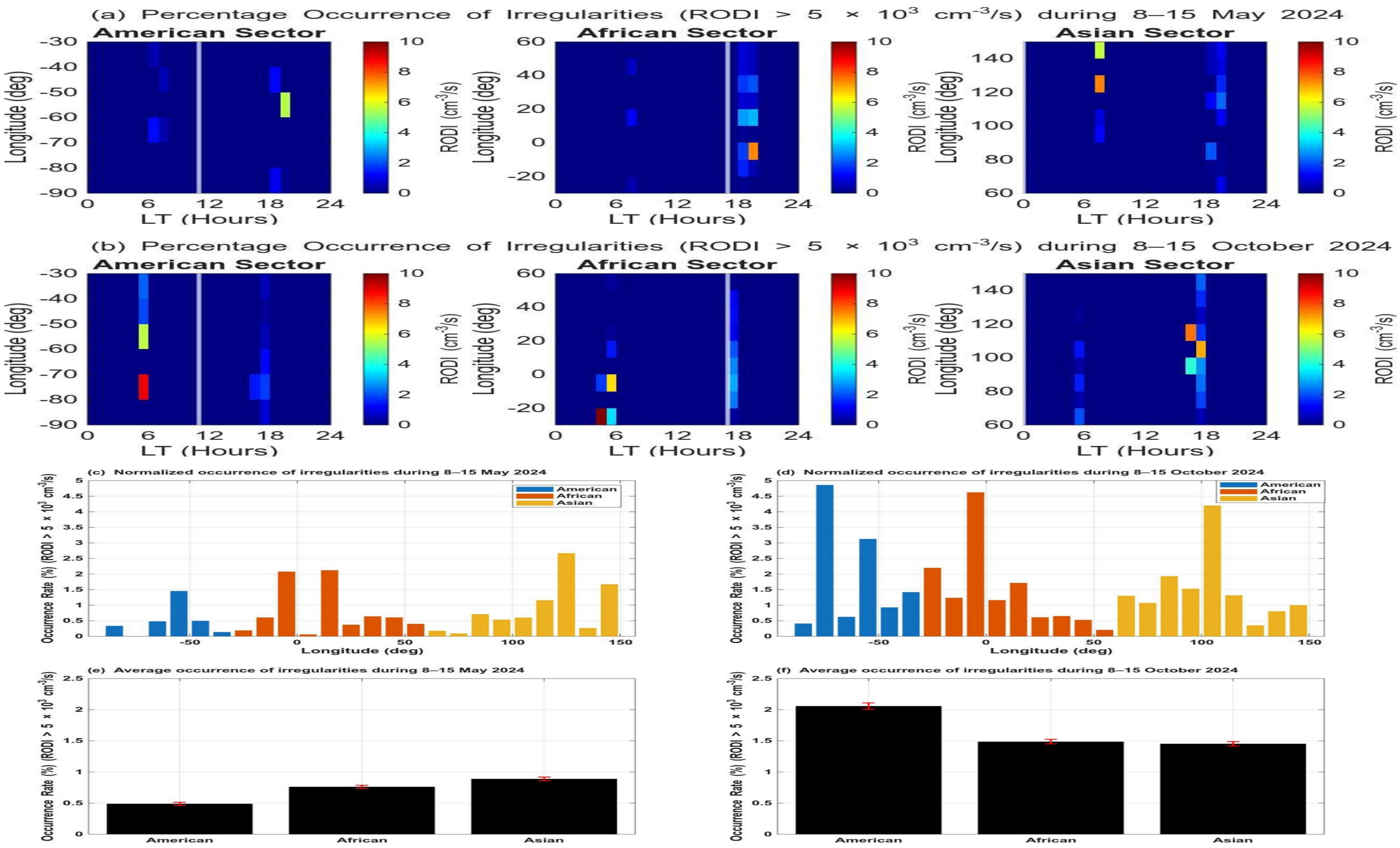


Figure 11: Swarm-A Longitudinal variation and the time of occurrence of ionospheric irregularities

Conclusions

- The TEC and electron density values were higher for the storm of October 2024 than the May 2024.
- The two geomagnetic storms triggered and inhibited the occurrence of ionospheric irregularities during the storms' main phase.
- There was a reverse longitudinal trend in the percentage occurrence rate of ionospheric irregularities during the two geomagnetic storms.