Investigation of The Main Ionospheric Trough with GNSS and DMSP Data

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Abstract

This study presents a visual and statistical analysis of the main ionospheric trough (MIT) during geomagnetically active dates in 2013 and 2014. The MIT is visualized using total electron content (TEC) values from the CEDAR Madrigal database, which provides a variety of data from ground based GNSS receivers, and data from the Defense Meteorological Satellite Program (DMSP). The MIT can be calculated as regions of low TEC, typically less than 50% below the background electron content. Observations thus far have shown a hemispherical asymmetry in trough occurrence near solstices and magnetospheric data alignment in the Northern hemisphere primarily on the dusk side. Based on our visualizations of the MIT, we observe gaps typically occurring near dusk. We hypothesize that there may exist a connection between this structure and sub-auroral polarization streams (SAPS). Our goal is to visualize and analyze behavior of the ionospheric trough and verify our results using other studies and data. Our analysis is compared with previous work done by Liu et al. (2020) and Liu and Xiong (2020) and offers reasonable and similar results. Along with the MIT itself, we plot Poynting flux (PF), ion drift velocity (VF), and electric field (EF) vectors from DMSP over these maps. Since PF is derived from magnetic field perturbation, electric field, and ion drift observations, strong flows are a good indication of SAPS. The EF and VF vectors offer verification that the ions are flowing in the expected direction for SAPS (along a poleward EF). We find correlation between trough gaps and PF on the dusk side with similar behavior on the dawn side of the Earth (typically in the Southern hemisphere), however it is unclear if these may be due to poor data coverage. Statistical analysis on both trough characteristics and the observed data alignment will be presented to demonstrate how this behavior depends on latitude, MLT, and its potential connection to SAPS. This analysis gives us insight to the precise latitudes and MLT occurrences of both trough gaps and Poynting flux to see how closely these values are aligned. This work opens the door to further investigation of dawnside and Southern hemisphere ionospheric behavior.

Methods

Detection Algorithm

- The Python algorithm for detecting the MIT was developed by Greg Starr [3]
- GNSS total electron content data used to determine drops in electron density
- TEC values are averaged over an hour and interpolated to improve data coverage

Steps for data processing:

- Pre-processing: identify high- and low-density values (upper left)
- Threshold: ≥ 50% *decrease* from background density
- Scoring: Assign scores based on amount of decrease. Values with score above 1 are kept. Low electron density indicates drop compared to background (upper right / lower left)
- Mask: Regions outside auroral oval of proper geometry are kept
- Result: Dark, semi-circle regions which represent the MIT (lower right)

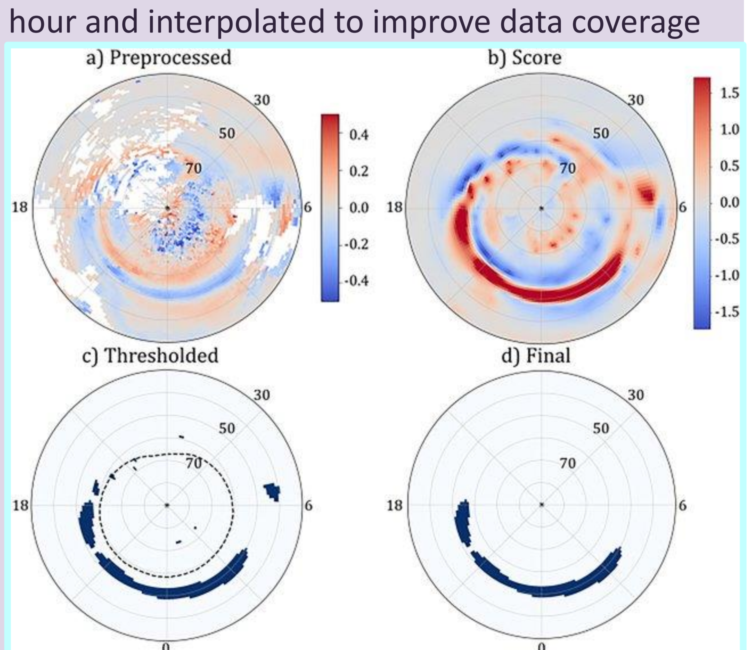

Figure 1. This figure is Figure 2 from [3]. Represents an overview of basic steps for the algorithm. All plots are in MLT coordinates, with noon on top and midnight on bottom

Mid-latitude Ionospheric Trough (MIT):

- Described by [4] as a region of depleted electron density, occurring in the nighttime F-region ionosphere (~150 – 400 km) at sub-auroral latitudes
- Can be thought of as ionospheric "footprint" of activity in the magnetosphere due to location and affects magnetospheric processes exert on the trough
- NH trough spans dusk to dawn, SH trough shorter in span and wanders with MLT
- Hemispherical trough symmetry near equinoxes, asymmetry near solstices

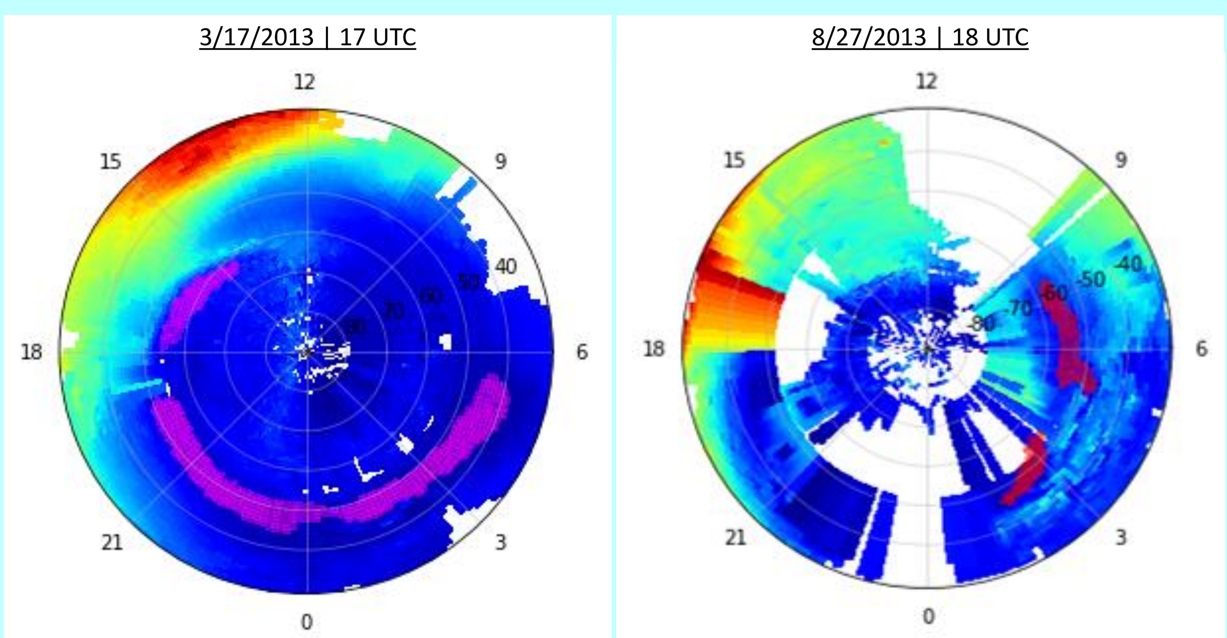

Figure 2. Shown above are plots of ionospheric TEC in MLT coordinates for the Northern (shown left) and Southern hemisphere (shown right). Calculations of the MIT are overlaid as a mask in pink for the Northern hemisphere and red for the Southern hemisphere.

Background and Data Visualization

Sub-Auroral Polarization Streams

- Sub-Auroral Polarization Streams (SAPS) are a meso-scale (100 - 500 km) plasma flow channel typically observed in the sub-auroral, dusk-side ionosphere

Process of SAPS:

- Magnetosphere compresses due to solar wind effects on the Interplanetary Magnetic Field
- Plasma flows along anti-parallel field lines, form thin current sheets until field lines reconnect
- Charged particles accelerated towards Earth due to magnetic tension force
- Particles caught in convection and co-rotating electric fields; charge separation initiated
- Electron and ion plasma sheet boundaries along R1 and R2 region field-aligned currents (FACs) [5]
- Current closes in ionosphere, poleward electric field forms between FACs
- Enhanced E-field creates *strong* particle flow known as SAPS

Poynting Flux, Electric Field, and Ion Drift Velocity

Data:

- DMSP satellites in Low-Earth Orbit (LEO) (~850 km) with orbital period of 110 minutes
- Satellites measure properties of electric (E) and magnetic (B) fields, variations (dE and dB, respectively), and ion drift velocity (VF)
- These measurements are used to calculate Poynting flux (PF)

Calculation:

- PF is a Poynting vector associated with electromagnetic energy transfer in the magnetosphere, consistent with energy dissipation in the ionosphere below the satellite as described in [7]
- Calculation begins with magnetic perturbation, as given by: $\vec{S} = -\frac{1}{\mu_0}\vec{E} \times \vec{\delta B}$
- According to [8], PF defined as Poynting vector component parallel to the geomagnetic main field (radial direction): $\vec{S_z} = \vec{S} \cdot \hat{z}$

Analysis:

- Code for plotting DMSP data values was provided by Adam Gourmos
- Since PF is a measurement derived from magnetic field perturbation, electric field, and ion drift observations, strong flows are a good indication of SAPS

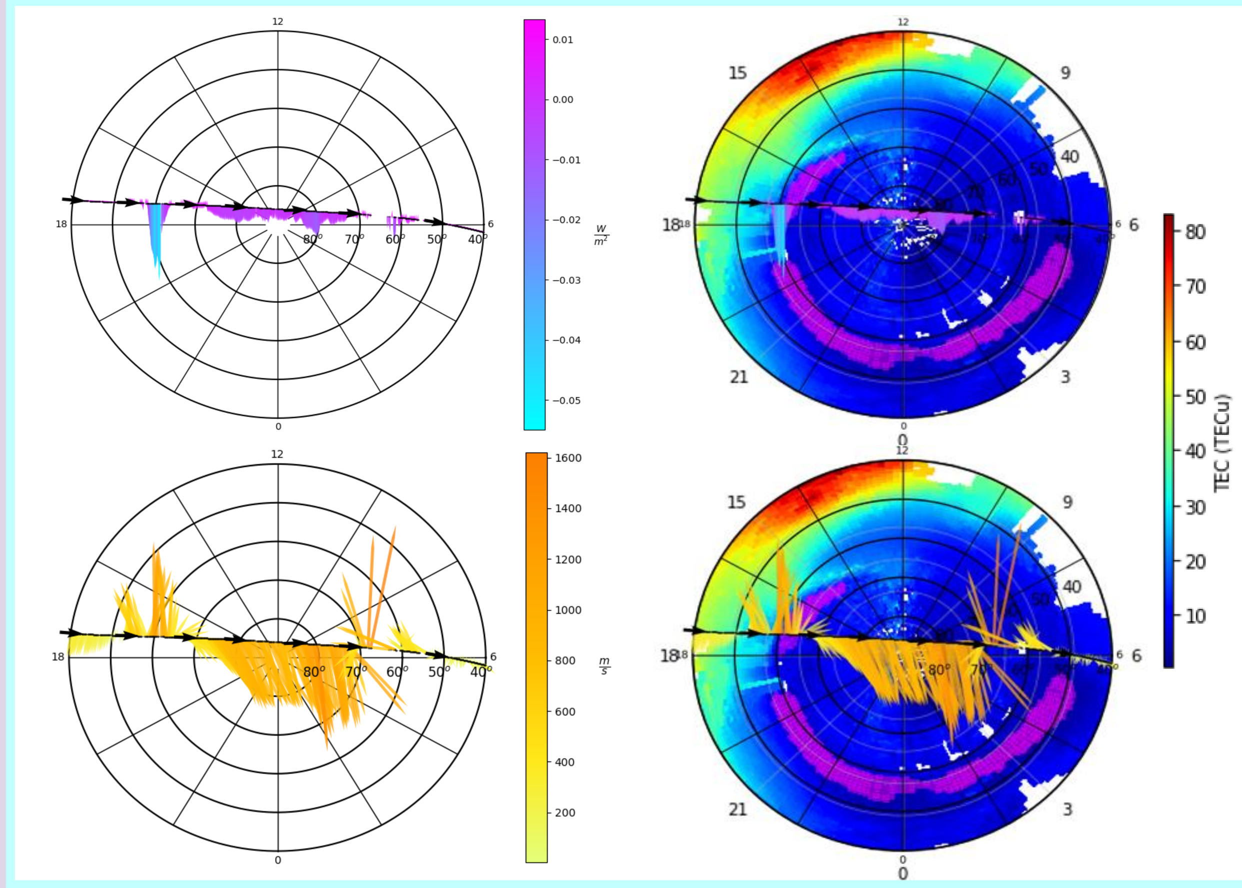

Figure 4. From top to bottom: PF and VF are shown in MLT coordinates for 17 March 2013 around 20 UTC from DMSP spacecraft F16. Left plots are DMSP data, right plots are the DMSP data overlaid on the MIT. Note that PF is shown antisunward for visualization, but PF actually points directly downward

Observations and Analysis

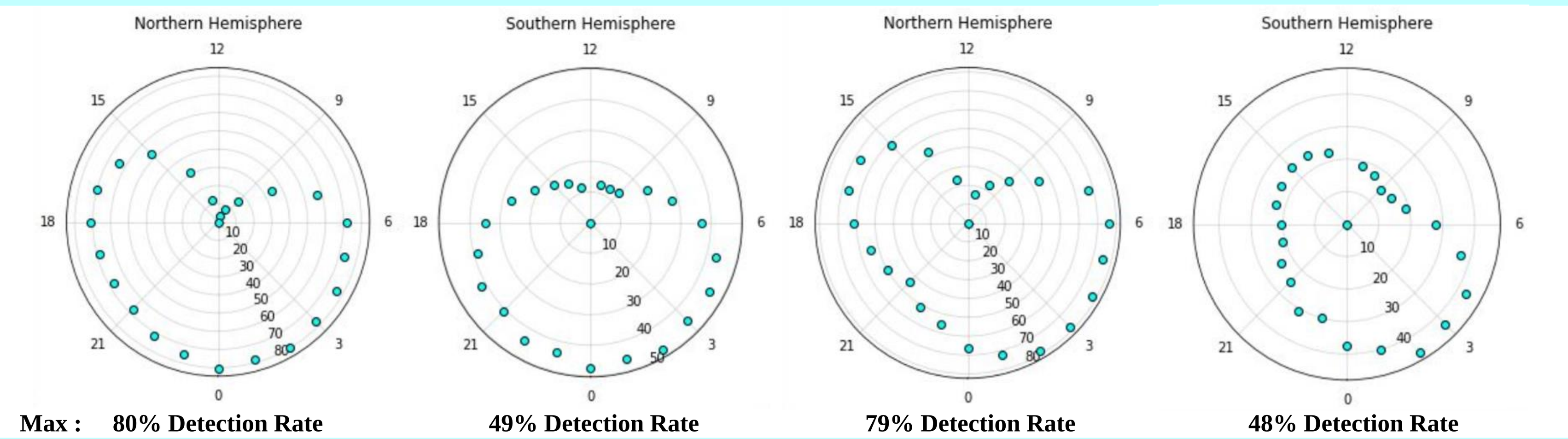

Figure 6. Detection rate (%) of the MIT per each MLT hour based on data from 2012-2022.
From left to right: Geomagnetically active NH, active SH, quiet NH, quiet SH. Each sector is searched per every UTC hour of every date investigated, resulting in 675 searches per MLT hour. Please note plots are not scaled the same and detection rates differ with each, thus underneath each figure is the maximum detection percentage of the MIT for the dates searched
Main takeaways are the difference in detection rate between the Northern and Southern hemisphere (which may be due to data coverage), and the change in duskside detection during geomagnetically quiet dates. The number of dayside detections also seems to increase with less geomagnetic activity.

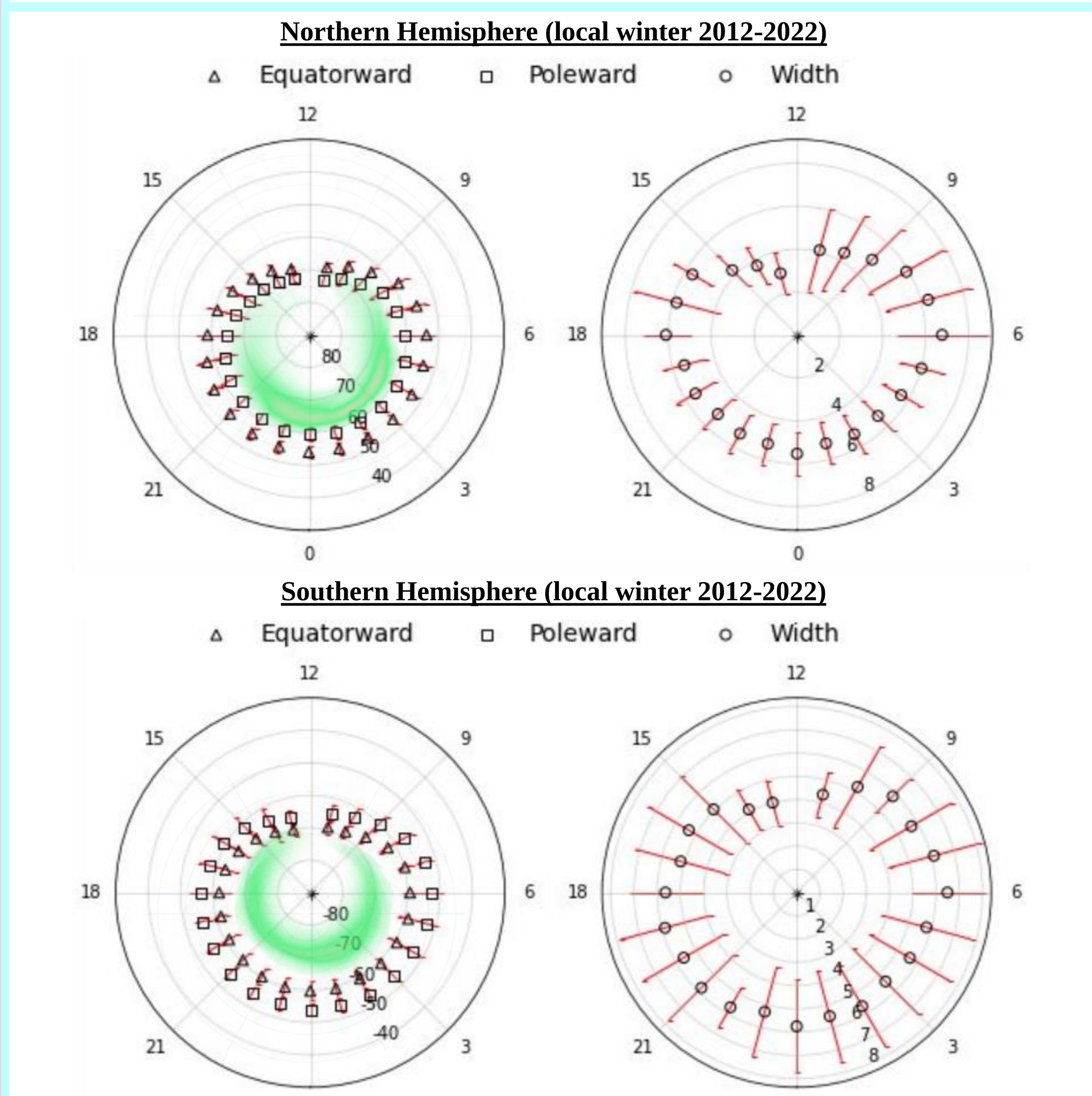

Figure 7. Top plots show geomagnetically active dates in the Northern hemisphere, while bottom plots show the Southern hemisphere. Plots on the left show MLT-averaged latitudes of the equatorward (triangles) and poleward (squares) walls of the MIT. Plots on the right show the MLT-averaged width (in degrees) of the MIT. The auroral oval is overlaid in green using data and code provided by NOAA [9].

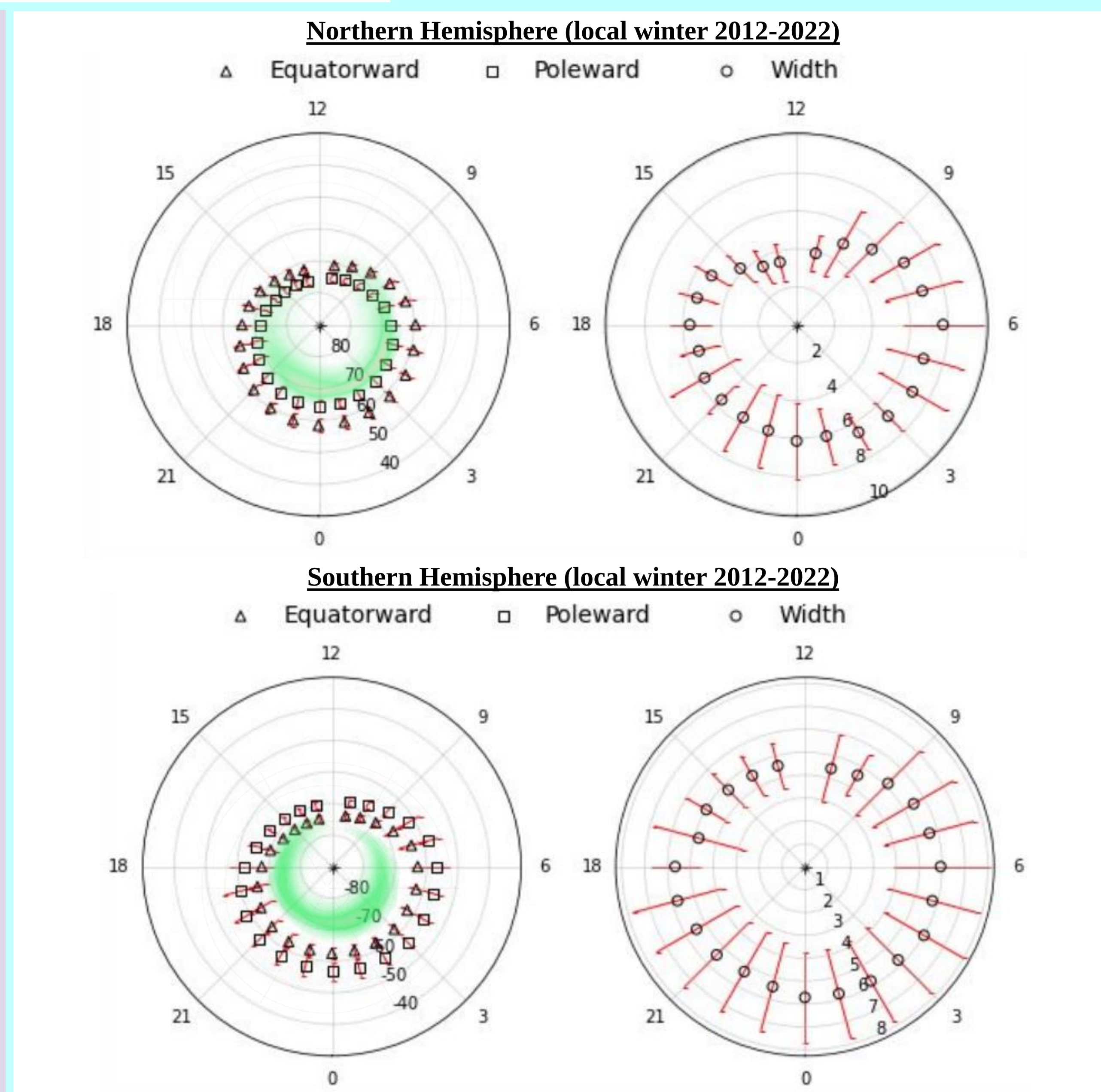

Figure 8. Same as Figure 7, but for geomagnetically quiet dates. We compare average evolution of the MIT with latitude and how it relates to the auroral oval and polar convection patterns. Note that data from ~8 – 13 MLT is very sparse, so values are more scattered with higher errors. We mainly observe trends between dusk and dawn. The MIT tends to move poleward with the auroral oval with lower geomagnetic activity.

Conclusions

Trough Behavior

- Trough latitude in both hemispheres is generally poleward on the dayside of the earth, moving equatorward at night. Appears most equatorward during dawn (seen in Figure 2, consistent with [4])
- Trough is widest during dusk but tends to narrow or fade around ~18 MLT
- Trough moves poleward with decreased geomagnetic activity, especially during local winter when it is most prominent
- Trough is wider and wanders more with latitude in the SH (though there are less detections here) and during quiet activity
- Trough is more likely to be detected in the NH, with more dawnside and dayside detections during quiet geomagnetic activity

Detection of PF and Gaps in the MIT

- PF tends to occur 5° - 10° higher in latitude than the trough itself, but note that PF measurements are made at ~850km while TEC is measured around ~350km
- Dawnside trough gap occurrences tends to happen at lower latitudes (equatorward) than duskside occurrences (consistent with trough behavior described above)
- PF observed on the dawnside varies between 55° - 70° latitude
- Local time of PF measurements tend to be 1-2 hours behind occurrences of the trough gap, but we suspect these energy flows need time to travel to the ionosphere
- PF and the MIT gaps tend to align best in Spring and Summer

Sub- and Dawnside-Auroral Polarization Streams

- Does DMSP-derived Poynting flux overlay the Main Ionospheric Trough (MIT) and SAPS on the Duskside?
  - Yes, we generally see agreement on the dusk side mostly in the NH. Gaps in the MIT align with strong poleward E and sunward plasma flows. The E and δB contribute to significant Poynting flux in the gaps and SAPS region
- Does DMSP-derived Poynting flux overlay the MIT and Dawn Polarization Stream (DAPS) on the Dawnside?
  - Yes, typically seen in SH dawnside Poynting flux plotted onto the SH MIT. Dawnside alignments in the SH occur mostly in the Fall and Summer. The PF is at higher latitudes than the MIT. Consistent with the ideas of the DAPS flow being in the auroral zone (Liu et al. 2020) the Poynting flux is poleward of the dawnside MIT
  - There are no occurrences of dawnside alignment in the NH, only one observation of duskside alignment in the SH

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Acknowledgements

This project is sponsored by the National Center for Atmospheric Research (NCAR). NASA HIWIND 80NAAC21K0014 P00001. Program was developed by Greg Starr and was based on work by Ercha Aa et al. which also inspired this project. Poynting Flux data processing based on programs by Liam Kilcommons and Adam Gourmos. GNSS Total Electron Content and DMSP data comes from the CEDAR Madrigal Database