Characterizing High-Resolution Temporal and Spatial Changes of the EIA and ETA

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Motivation

- Two prominent features in the Ionosphere-Thermosphere (I-T) region are called the Equatorial Ionization Anomaly (EIA) and Equatorial Thermospheric Anomaly (ETA)
- The mechanisms behind the formation of the ETA are not well understood due to the lack of satellite observations with suborbital temporal and small-scale spatial resolutions
- This poster utilizes NCAR's high-resolution TIEGCM to simulate the I-T region while modeling a constellation to simulate instrument sampling
  - The constellation is based off the SWARM-EX mission, which consists of 3 identical spacecraft that will take in-situ measurements of the I-T region
- This poster will also explore how ETA formation theories, particularly a theory dealing with the field-aligned ion drag term, can be supported or rejected using the higher temporal and spatial resolutions of a constellation

Science Background

The EIA is a dayside, equatorial feature with crests at ±15° in magnetic latitude and a trough at the magnetic equator as shown in Fig. 1

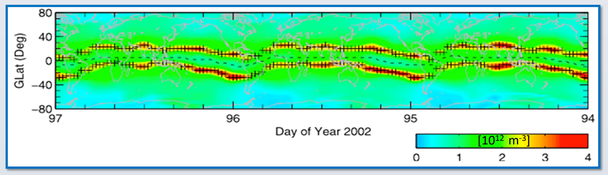

Figure 1: Electron Density at 400 km from the CHAMP mission [1]

The ETA is also a dayside, equatorial feature but has two crests at ±20-30° in magnetic latitude and a trough near the magnetic equator as shown in Fig. 2. Although the ETA is a neutral feature, it is magnetically aligned, showing strong ion-neutral coupling between the EIA and ETA.

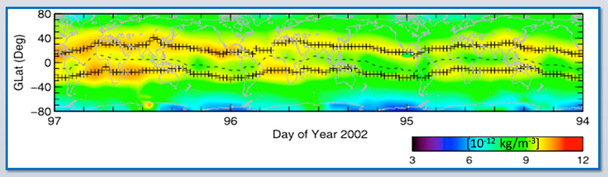

Figure 2: Neutral Density at 400 km from the CHAMP mission [1]

ETA Formation Theory: Field-Aligned Ion Drag [2]

One of the latest theories dealing with the formation of the ETA is a paper by Hsu et al (2014). This theory states that the field-aligned ion drag force, $F_{ni,||}$, is a non-negligible term that creates a trough in the thermosphere, forming the ETA. This theory is broken down into a 4-step process:

1. Field-Aligned Ion Drag Force
2. Divergence of meridional winds
3. Change in vertical winds, adiabatic heating/cooling, and neutral temperature
4. Reactive Pressure Gradient to rebalance forces

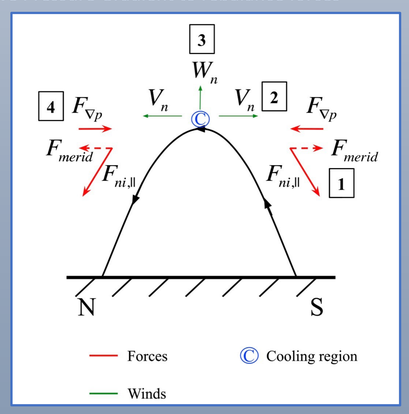

Figure 3: Four Step ETA Formation Diagram

Model Approach & Constellation Design

Model Approach

- NCAR's High-Resolution Thermosphere-Ionosphere-Electrodynamic General Circulation Model (HR-TIEGCM) is utilized [3]
- HR-TIEGCM can numerically solve for the coupled I-T system and accommodate the different timescales for plasmas and neutrals
- HR-TIEGCM has a grid resolution of 0.625°x0.625° with a 1-minute sampling timestep
- Two simulations are run in a quiet environment (Kp = 2, F10.7=120) during solar max at vernal equinox with run 1 having $F_{ni,||}$ ***turned on*** and run 2 having $F_{ni,||}$ ***turned off***

Constellation Design

- A satellite fly-through scheme is implemented to simulate instrument sampling
- Constellation parameters are based off SWARM-EX's mission design with a nominal altitude of 400km, an inclination of 60°, and 5 minute separation between each of the 3 satellites
  - This design allows the I-T region to be observed on suborbital timescales and spatial scales not previously observed
- Figure 4 shows the ground track for the SWARM-EX constellation and Fig. 5 shows a visual of the spatial and temporal resolutions

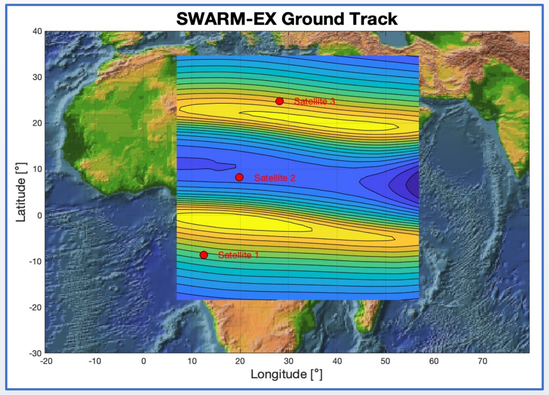

Figure 4: SWARM-EX Ground Track Visual

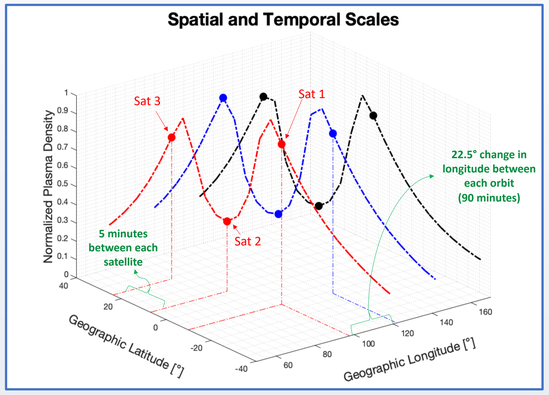

Figure 5: SWARM-EX Spatial and Temporal Scales

Results

Constellation Observations

- Figure 6 shows the simulation output from the HR-TIEGCM
  - The magnetic dip in the North American (NA) sector shown in Fig. 7 is an example where significant spatial changes in magnetic topology can be mistaken for temporal changes in plasma and neutrals if not sampled adequately
- To differentiate between spatial and temporal change, the EIA and ETA must meet the persistence criteria
  - Persistence can be defined as a feature that is spatially coherent with little change in phase and whose uncorrelated geophysical noise is below some percent change
  - Table 1 shows the persistence criteria for the EIA and ETA inside and outside the NA sector based on the 3-satellite constellation

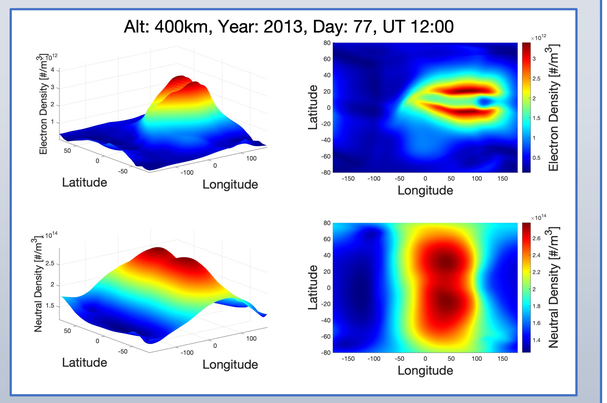

Figure 6: Global Representation of the I-T Region

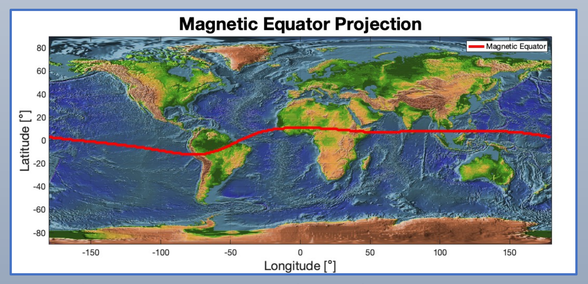

Figure 7: Magnetic Dip in the North American Sector

Table 1: Persistence Criteria

Feature	Value
ETA	<±0.5% change over 5 min inside the NA sector <±0.2% change over 5 min outside the NA sector
EIA	<±6.0% change over 5 min inside the NA sector <±2.0% change over 5 min outside the NA sector

Theory Observations

- Figure 8 observes key parameters mentioned in the field-aligned ion drag ETA theory between runs 1 and 2 for one satellite
  - The theory indicates a decrease in neutral temperature and neutral density at the magnetic equator, which is evident in Fig. 8
- Figure 9 shows how a satellite constellation can isolate persistent features to avoid disturbances unrelated to the ETA formation using the persistence criteria from Table 1

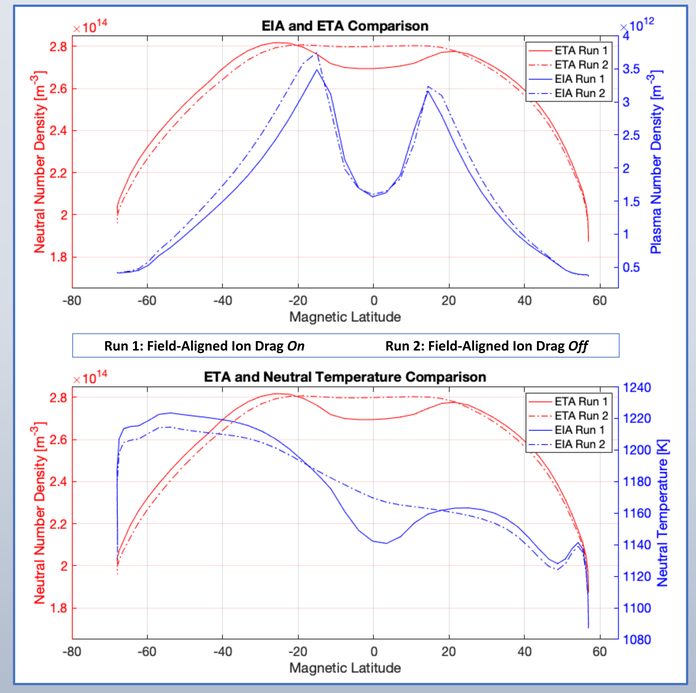

Figure 8: Comparison of Various Parameters Between Runs 1 and 2

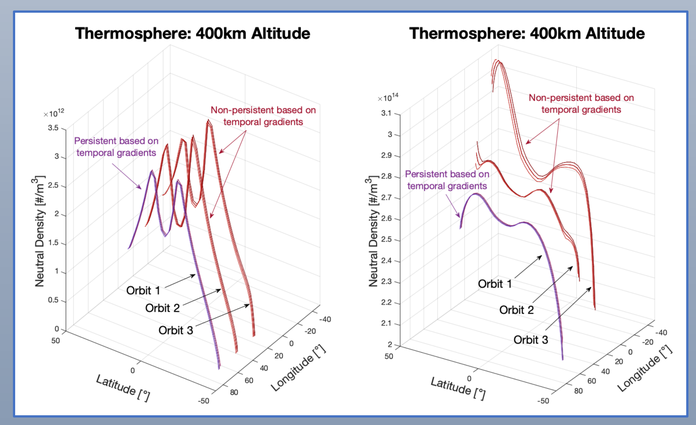

Figure 9: Representation of Persistence During a Geomagnetic Storm

Discussion

- HR-TIEGCM simulates the ETA comparable to orbital data and with the HR-TIEGCM being capable of resolving mesoscale changes in the I-T region, orbital data from a satellite constellations can be directly compared to explore ETA formation theories
- Instrument sampling of the ETA using HR-TIEGCM showed the ETA density and temperature changes aligned with the field-aligned ion drag theory proposed
- Using a quantitative definition for persistence, a multi-satellite constellation can capture small scale changes to determine whether the satellites are observing ETA formation processes or transients
  - In the case where the magnetic kink is present, the persistence definition can establish that the EIA/ETA features are persistent and spatially coherent
- To capture all aspects of the ion-neutral coupling in the I-T region, a larger constellation is required to optimize the different timescales of plasmas and neutrals (NASA GDC multi-satellite mission will enable such investigations)

Future Work

- Explore methods of extracting spatial and temporal gradients from a satellite constellation to determine limiting resolution factors
- Explore constellation designs that can utilize the least number of spacecraft to capture I-T processes
- Continue characterizing correlations between the EIA and ETA trough locations as well as their associated densities
- Explore other parameters that can be observed in a constellation to validate/reject ETA formation theories
- Follow up on the SWARM-EX mission to compare orbital data to HR-TIEGCM simulations

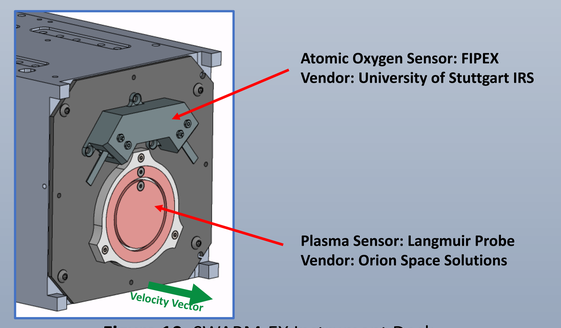

Figure 10: SWARM-EX Instrument Deck

References

1. Lei, J., Thayer, J. P., & Forbes, J. M. (2010). Longitudinal and geomagnetic activity modulation of the equatorial thermosphere anomaly. *Journal of Geophysical Research: Space Physics*, *115*(8), 1–13. https://doi.org/10.1029/2009JA015177
2. Hsu, V. W., Thayer, J. P., Lei, J., & Wang, W. (2014). *Journal of Geophysical Research : Space Physics Formation of the equatorial thermosphere anomaly trough : Local time and solar cycle variations*. 1–18. https://doi.org/10.1002/2014JA020416.
3. Dang, T., Zhang, B., Lei, J., Wang, W., Burns, A., & Liu, H. (2020). *Development of high-resolution Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM) using Ring Average technique*. *September*.