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Characterization of the Ionospheric Perturbation Degree at Mid-Scales with Swarm's NeGIX and TEGIX

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Since its launch in November 2013, ESA's Swarm mission has provided unprecedented data products and services, greatly enhancing our understanding of solar, magnetospheric, thermospheric, ionospheric, and atmospheric processes, as well as their coupling and impact on human-made technological systems. Currently, the Swarm Product Data Handbook includes over 70 Level 1 and Level 2 data products derived from Swarm measurements, along with more than 20 additional products from other spacecraft. All of these activities are curated by the Swarm Data, Innovation, and Science Cluster (DISC).

We have introduced two novel data products to the Swarm data family, now available to the community via the Swarm Data Access: **the electron density gradient ionospheric index (NeGIX) and the total electron content gradient ionospheric index (TEGIX).**

These products combine **measurements from Swarm A and C**, obtained along their near-polar, parallel orbits, to estimate ionospheric gradients.

NeGIX and TEGIX enable the investigation of ionospheric plasma irregularities and perturbations at mid-scales (on the order of 100 km). They provide information not only along the meridional transit direction of the Swarm satellites but also along the longitudinal (zonal) direction. Consequently, Swarm's space-based observations, combined with the methodologies of NeGIX and TEGIX, offer new insights into several critical areas of space weather research, risk mitigation, and applications. Initial studies using these products have already demonstrated their effectiveness in applications such as scintillation modeling, characterization of ionospheric plasma bubbles, and monitoring of ionospheric indices in conjunction with GNSS ground-based observations.

In this work, we provide an assessment of the capabilities of NeGIX and TEGIX to characterize the ionospheric state under both quiet and stormy geomagnetic conditions. We examine some of the most intense geomagnetic events from solar cycles 24 and 25. Furthermore, with over ten years of Swarm data available, a climatological analysis of the ionosphere has been conducted using these newly-developed indices.

This analysis provides a basis for future modeling and combined studies, while also supporting the development of enhanced proxies for characterizing ionospheric behavior. It enables their practical application in navigation, communication, and remote sensing systems.

Product Definition

Both data products leverage the near-polar, parallel orbits of Swarm A and C to combine data with a resolution of 0.5° in latitude along the satellite tracks.

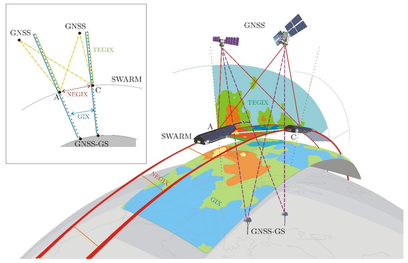

Figure 1. Scheme of the spatial configuration and definition of NeGIX and TEGIX with respect to the Swarm and GNSS satellites.

The NeGIX (Electron Density Gradient Ionospheric Index):

- Is defined at an altitude of approximately 470 km, corresponding to the orbit of the Swarm satellites.
- Utilizes in-situ Langmuir Probe data from Swarm A and C, combining measurements to estimate electron density gradients within a range of 30 to 200 km.
- Provides information on both zonal (West-East) and meridional (South-North) gradient components.
- Daily data with approximately 8-second resolution is made available as CDF files, with a latency of 4 days, through the Swarm Data Portal.

The TEGIX (Total Electron Content (TEC) Gradient Index):

- Is defined at an altitude of 200 km above the Swarm satellites, based on ionospheric pierce points (IPPs) and calibrated vertical TEC measurements.
- Uses GNSS precise orbit determination (POD) data acquired separately by Swarm A and C, combining TEC measurements to estimate gradients within a range of 30 to 200 km.
- Provides information on both zonal (West-East) and meridional (South-North) TEC gradient components.
- Daily data with an 8-second resolution is made available as CDF files, with a latency of 5 days, through the Swarm Data Portal.

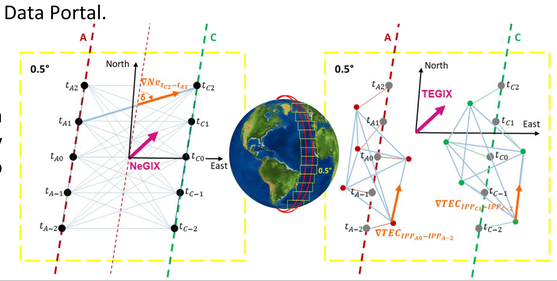

Figure 2. Scheme of data combination used by NeGIX and TEGIX to estimate gradients.

Product Validation

NeGIX and TEGIX have demonstrated strong correlation with existing ionospheric indices that characterize and monitor the ionosphere at similar spatial scales. Specifically:

- **The ground-based Gradient Ionosphere Index (GIX)**, which serves as the foundation for defining the new proxies, shows significant agreement with NeGIX and TEGIX. Combined studies of NeGIX, TEGIX, and GIX will provide valuable insights into altitude-related dependencies in gradient structures and enhance observations over oceans.
- **The Swarm IPIR gradients**, derived from Langmuir Probe data along the satellite paths, also show strong agreement with NeGIX and TEGIX. The meridional components of IPIR were used to validate our computations. NeGIX is expected to be more statistically robust, providing exclusively zonal (West-East) gradient data.

The validation was carried out for both quiet and perturbed geomagnetic conditions, including individual case studies and large datasets.

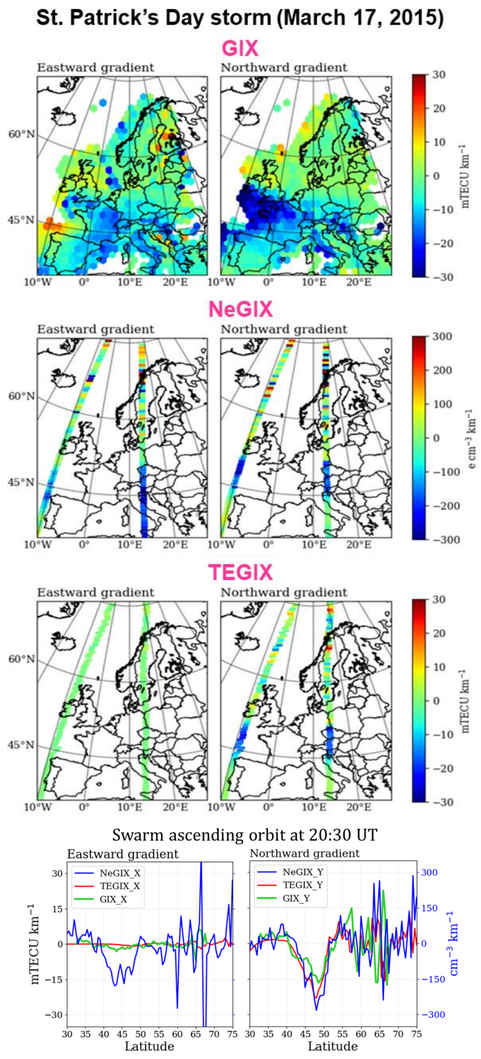

Figure 3. Comparison of the performance of NeGIX, TEGIX, and GIX, during the severe St. Patrick's Day storm on March 17, 2015, over Europe.

Product Applicability

NeGIX and TEGIX have significant potential to support ionospheric research, practical applications, and low-latency monitoring services, particularly during periods of perturbed geomagnetic activity. Their applicability spans several areas, including:

- **Impact of space weather on precision, Safety-of-Life applications, and augmentation systems (e.g., EGNOS):** Trans-ionospheric signals are vulnerable to severe spatial gradients and rapid fluctuations in TEC, necessitating effective ionospheric monitoring tools.
- **Dynamical evolution and forecasting of geomagnetic storms:** By providing gradient information in both zonal and meridional directions, NeGIX and TEGIX can be used to track the dynamic evolution of ionospheric fronts and traveling ionospheric disturbances during storm events.
- **Impact of the solar terminator:** The ability to distinguish between zonal and meridional gradients also aids in the analysis of ionospheric variability and the propagation/deflection of radio waves during twilight conditions.
- **Investigation of scintillation occurrence and the morphology of plasma bubbles:** The horizontal gradients captured by NeGIX and TEGIX, along with their decomposition into components, can be employed to study ionization patch borders linked to scintillation events and sharp gradients associated with plasma bubbles.
- **Empirical and numerical modeling of ionospheric processes:** Leveraging the extensive Swarm dataset, which has been collected over more than 11 years, these indices contribute to improving ionospheric models. Additionally, the enhanced data dissemination capabilities of the Fast Track (FAST) database, offering near-real-time latency of just a few hours, will significantly enhance the scientific and practical applications of these products.

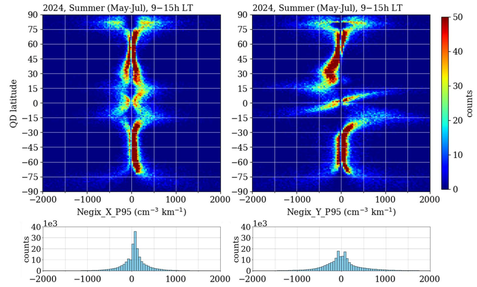

Figure 4. NeGIX zonal and meridional components shown for a large dataset covering the diurnal hours of the Northern summer months in 2024.

Got curious?

Scan me to access references, data, and more from the study!