COSPAR 2024 – PSW.3

CHARACTERIZATION OF THE TOPSIDE IONOSPHERE USING SWARM DATA: THE TEGIX AND NEGIX INDICES

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Main points of the presentation

1. Report on the Swarm DISC Project MIGRAS
2. Introduction of the ionospheric gradient indices for the topside ionosphere using Swarm data – NeGIX and TEGIX
3. NeGIX and TEGIX: from definition to validation
4. NeGIX and TEGIX: operational Swarm product
5. Conclusions

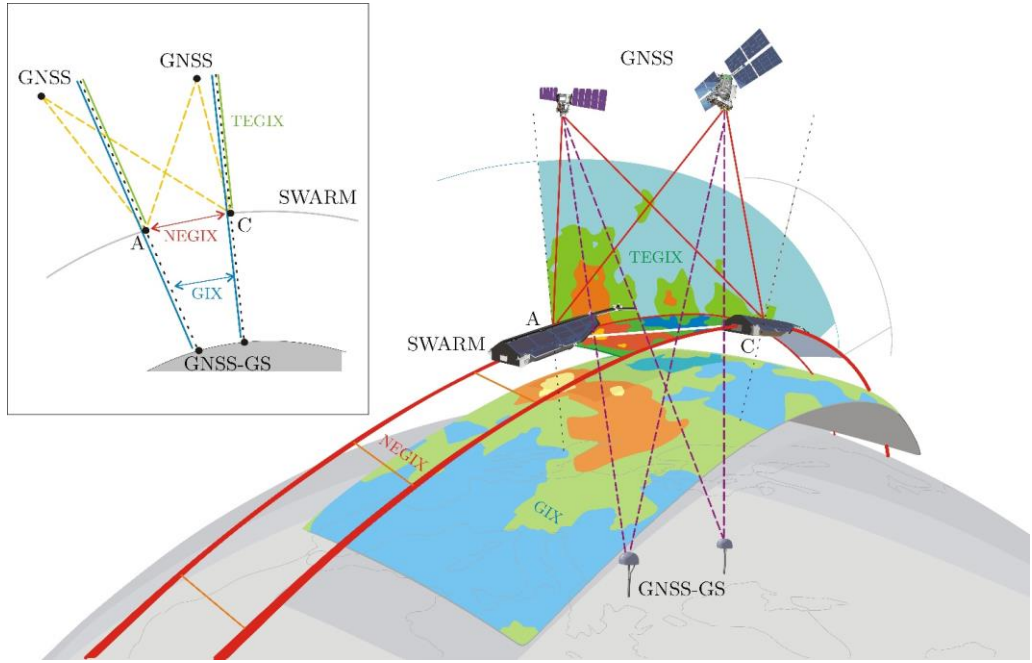
Monitoring Ionospheric GRAdients using Swarm – MIGRAS (Swarm DISC Subcontract SW-CO-DTU-GS-133)

DLR has developed a cluster of ionospheric indices and products for the characterization of the ionospheric perturbation degree. They are based on ground-based GNSS measurements:

- Disturbance Ionosphere IndeX Spatial Gradient – DIXSG (review by Jens Berdermann)
- Gradient Ionospheric indeX – GIX (review by Norbert Jakowski)
- Sudden Ionospheric Disturbance indeX – SIDX

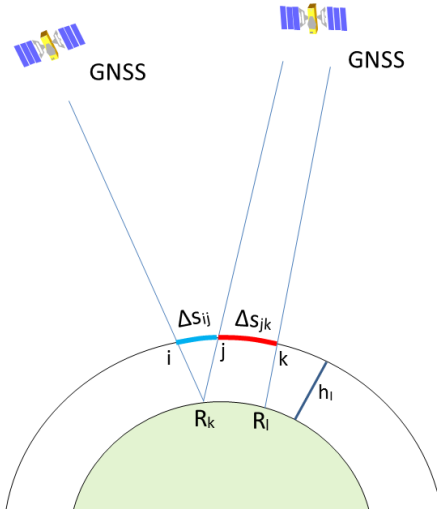
Space-based observations with Swarm offer a broad spectrum of data for space weather monitoring and research. The MIGRAS project has aimed at:

- broadening the Swarm data products, tools and services for monitoring small- to mid-scale irregularities – in the order of about 100 km
- **developing two new data products using Swarm satellites A and C – NeGIX and TEGIX**

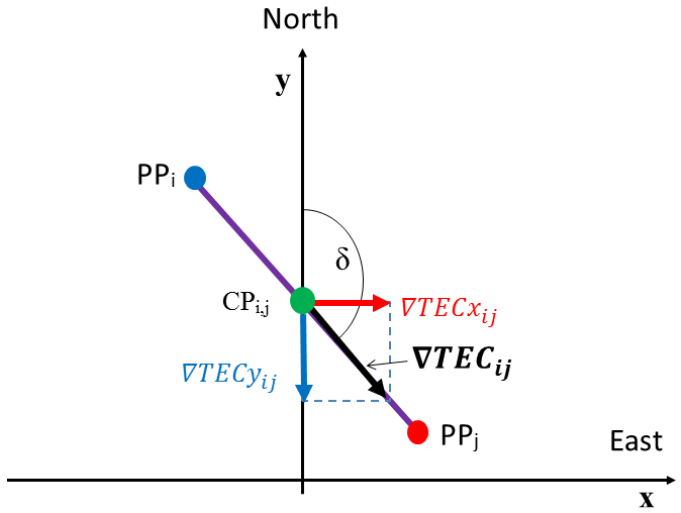


GIX – the base for the definition of NeGIX and TEGIX

NeGIX and TEGIX are developed following the approach of the ground-based Gradient Ionospheric indeX (GIX)*



$$\nabla TEC_{ij} = (VTEC_i - VTEC_j) \cdot \frac{1}{\Delta s_{ij}}$$



$$\nabla TEC_{Xij} = \nabla TEC_{ij} \cdot \sin\delta \quad \text{(zonal)}$$

$$\nabla TEC_{Yij} = \nabla TEC_{ij} \cdot \cos\delta \quad \text{(meridional)}$$

GIX is a spatial TEC gradient for the regional characterization of ionospheric perturbations from medium to large scales (about 30-300 km)

$$\langle \nabla TECx \rangle = \frac{1}{N_C} \sum_{i=1}^{N_C} \nabla TECx_{ij}$$

$$\langle \nabla TECy \rangle = \frac{1}{N_C} \sum_{i=1}^{N_C} \nabla TECy_{ij}$$

$$GIX = \langle \nabla TEC \rangle = \sqrt[2]{\langle \nabla TECx \rangle^2 + \langle \nabla TECy \rangle^2}$$

$$GIXS \equiv \sigma(\nabla TEC) = \sqrt[2]{(\langle \nabla TEC^2 \rangle - \langle \nabla TEC \rangle^2)}$$

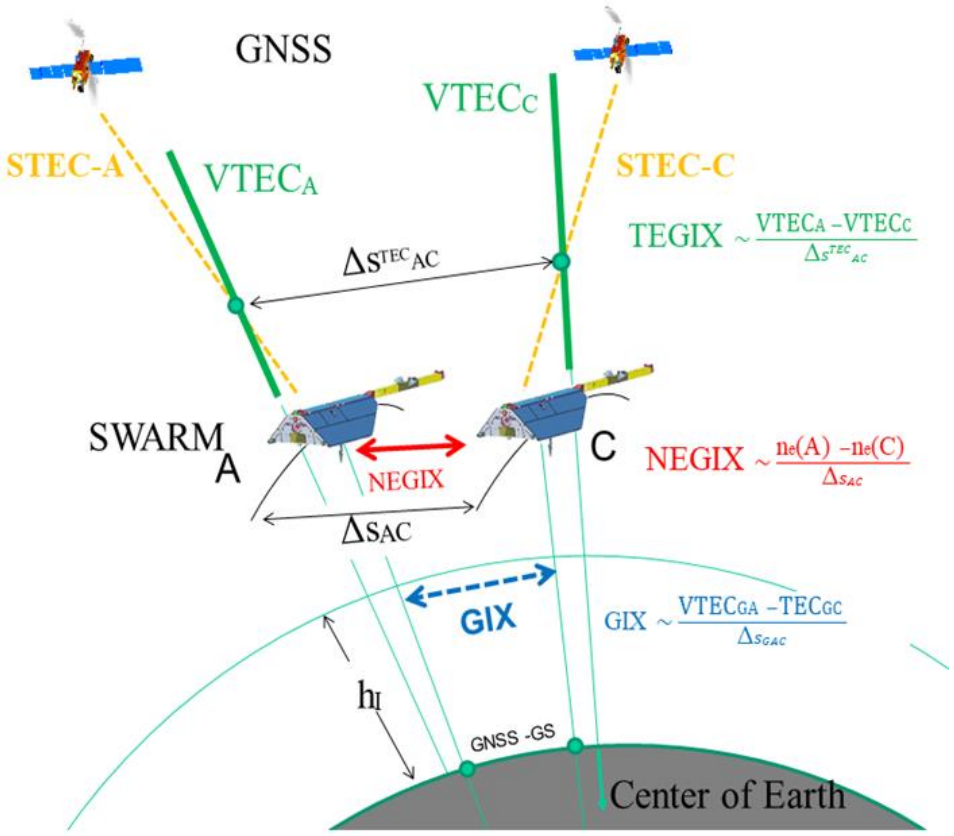
*Jakowski, N. and M. M. Hoque (2019), Space Weather, doi: 10.1029/2018SW002119

NeGIX and TEGIX: MIGRAS products for the characterization of the topside ionosphere using Swarm A and C

TEGIX

spatial TEC-gradient index product based on Swarm GNSS Precise Orbit Determination observations

- It is the statistical measurement (mean, standard deviation, 95-percentile) of gradient vectors that characterize the topside TEC-structure of the ionosphere over a selected area along the Swarm orbit
- It is defined at an altitude of ca. 660 km
- It uses absolute/calibrated Vertical Total Electron Content (VTEC) obtained from POD data of Swarm-A and Swarm-C satellites (Level-2 data TECATMS_2F with 1 second resolution)
- To avoid Differential Code Biases (DCB) from Swarms A and C, it combines only ionospheric pierce points (IPPs) from the same Swarm satellite
- It has a resolution of 0.5 degrees along the satellites track (latitudinally), or 8 seconds



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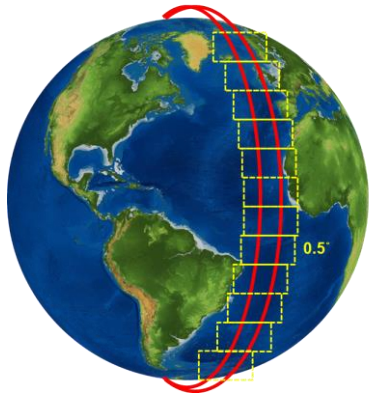
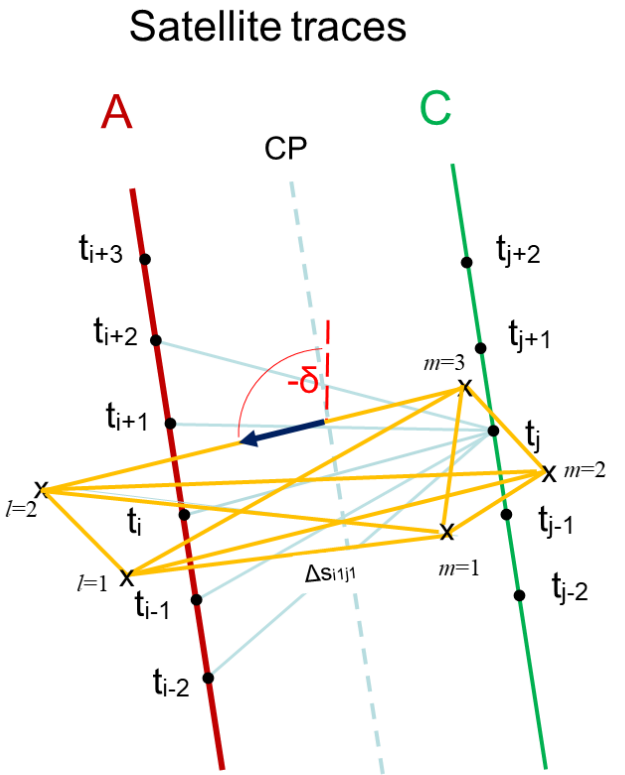




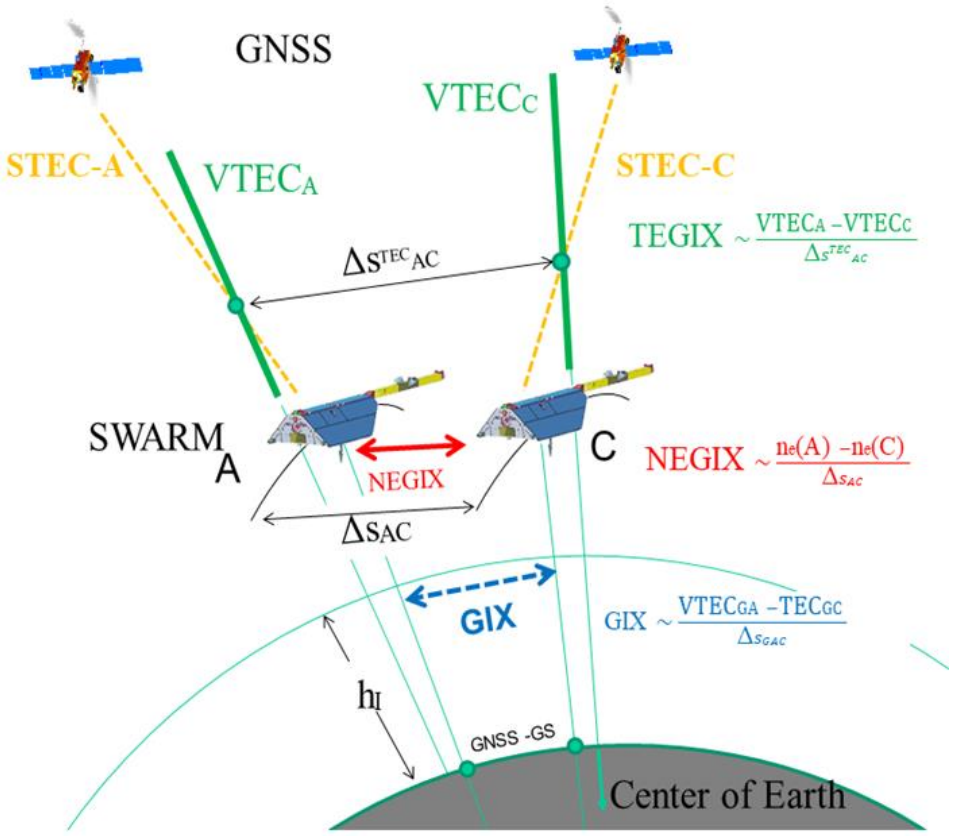
Combination of VTEC measurements onboard Swarm satellites A and C

NeGIX and TEGIX: MIGRAS products for the characterization of the topside ionosphere using Swarm A and C

NeGIX

spatial Ne-gradient index product based on Langmuir probe observations

- It is the statistical measurement (mean, standard deviation, 95-percentile) of gradient vectors that characterize the electron density structure of the ionosphere over a selected area along the Swarm orbit
- It is defined at an altitude of ca. 460 km (Swarm positions)
- It uses in-situ electron density data from Langmuir probes onboard Swarm A and Swarm C satellites (Level-1 data EFIA_LP_1B with 0.5 second resolution)
- It combines Ne-measurements between same satellite and also in the longitudinal (zonal) direction between different satellites
- It has a resolution of 0.5 degrees along the satellites track (latitudinally), or 8 seconds



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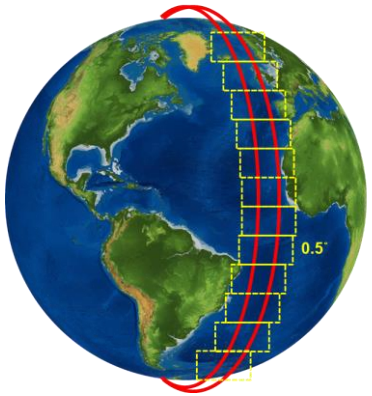
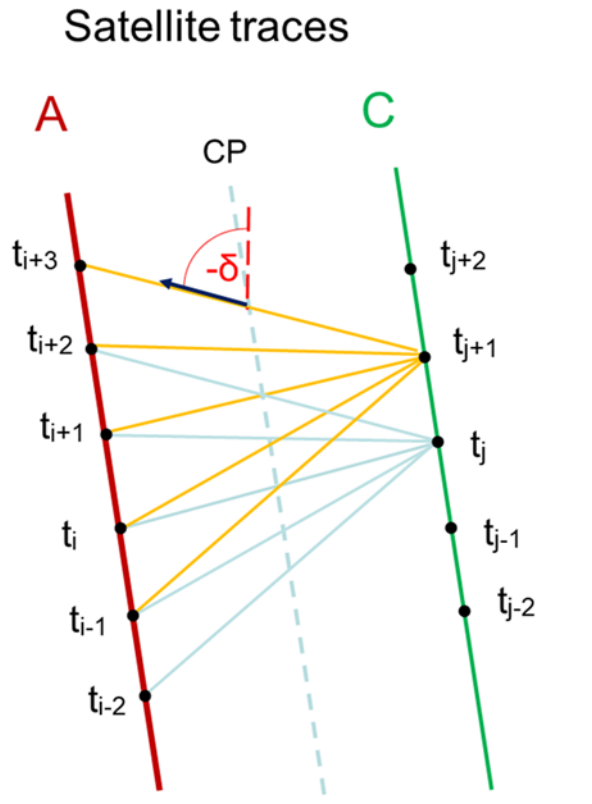
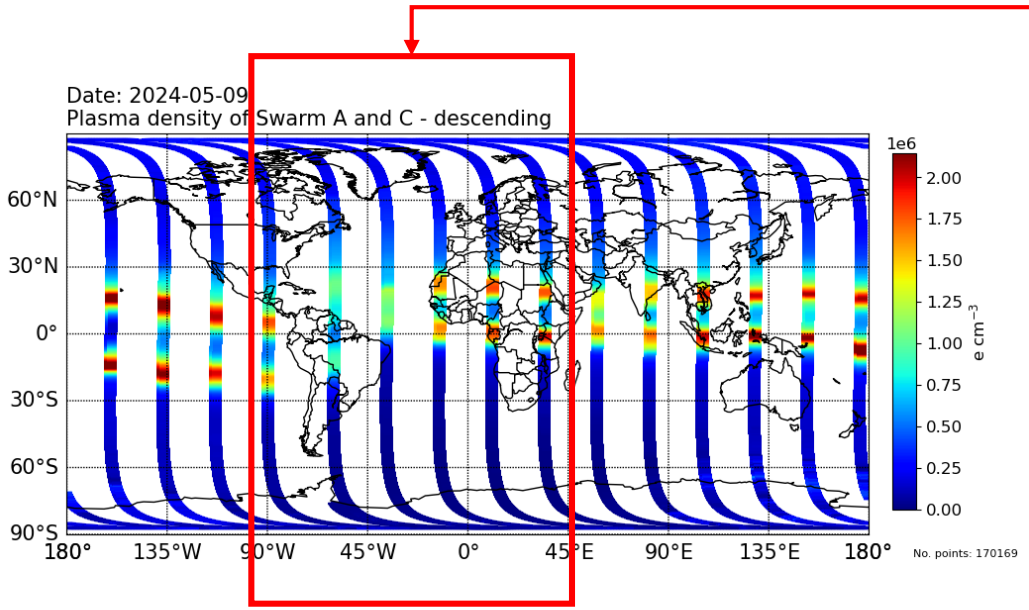
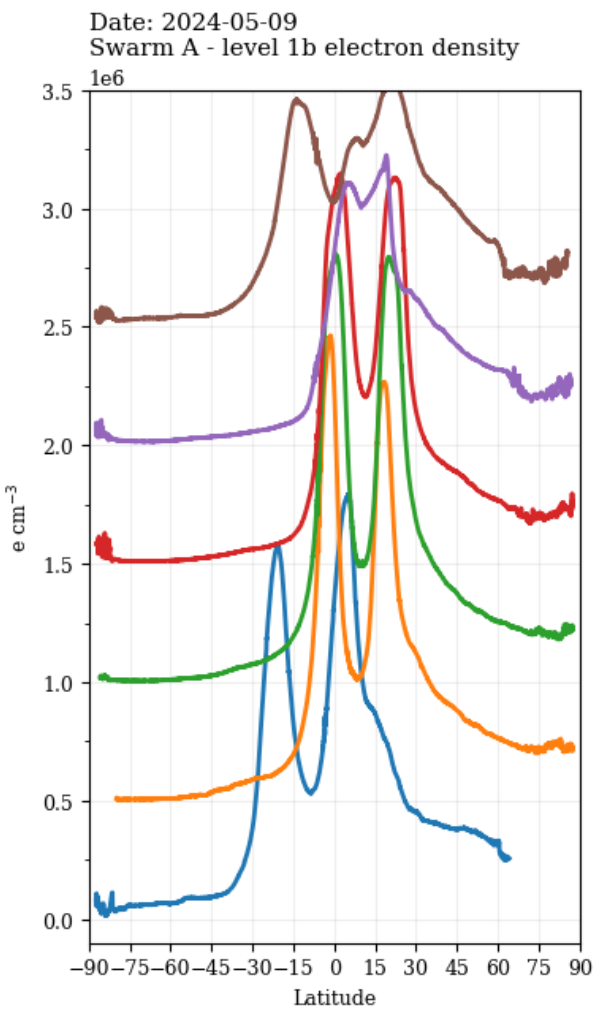


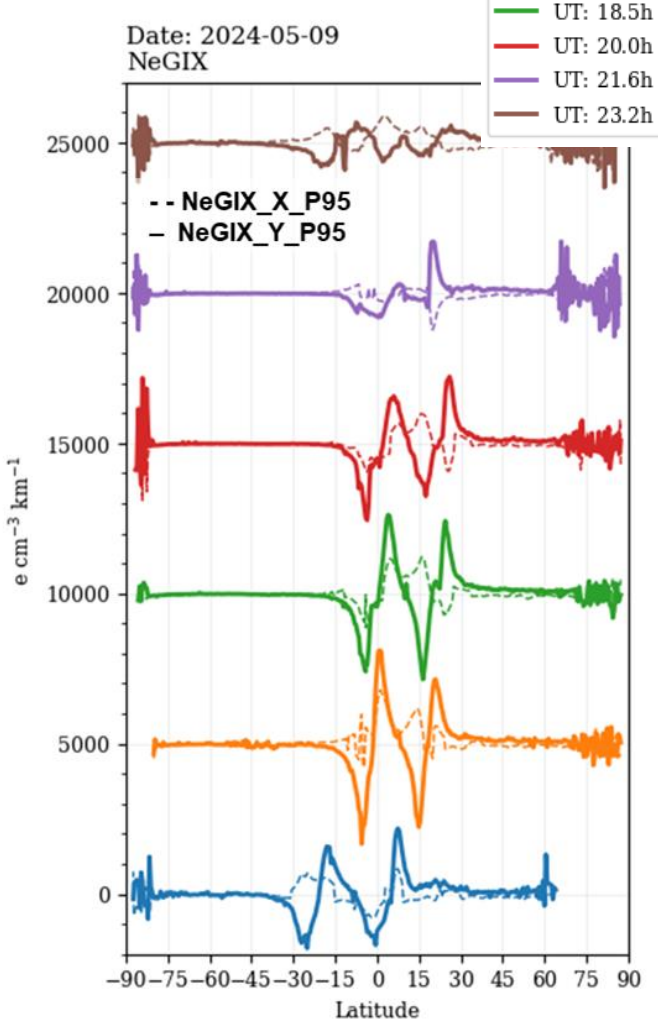


Combination of Ne measurements onboard satellites A and C at different epochs

Validation of products – capacity of NeGIX to characterize ionospheric features during quiet geomagnetic conditions

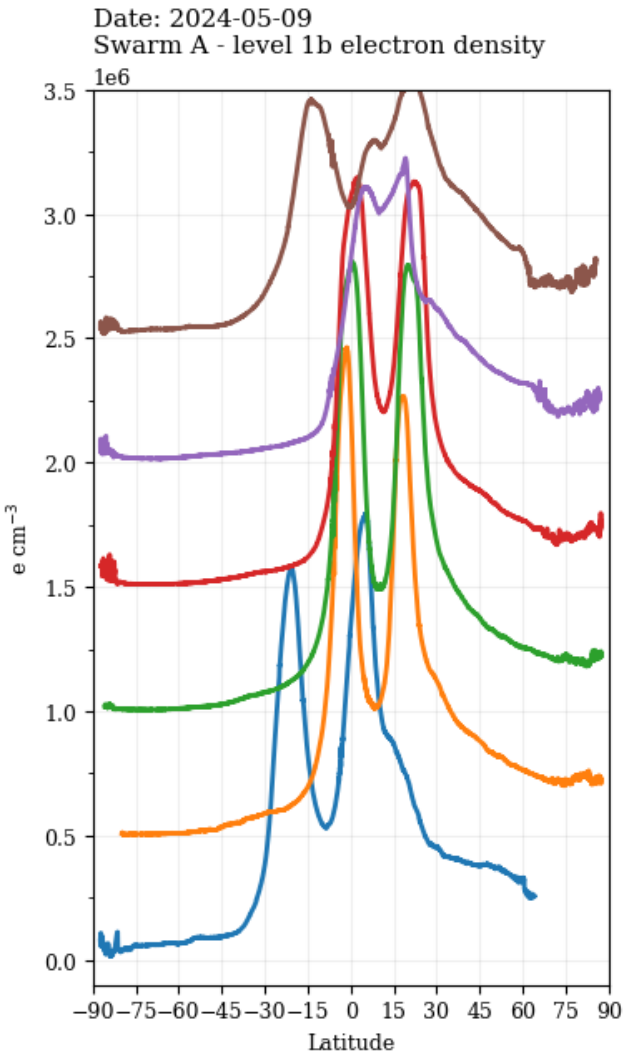


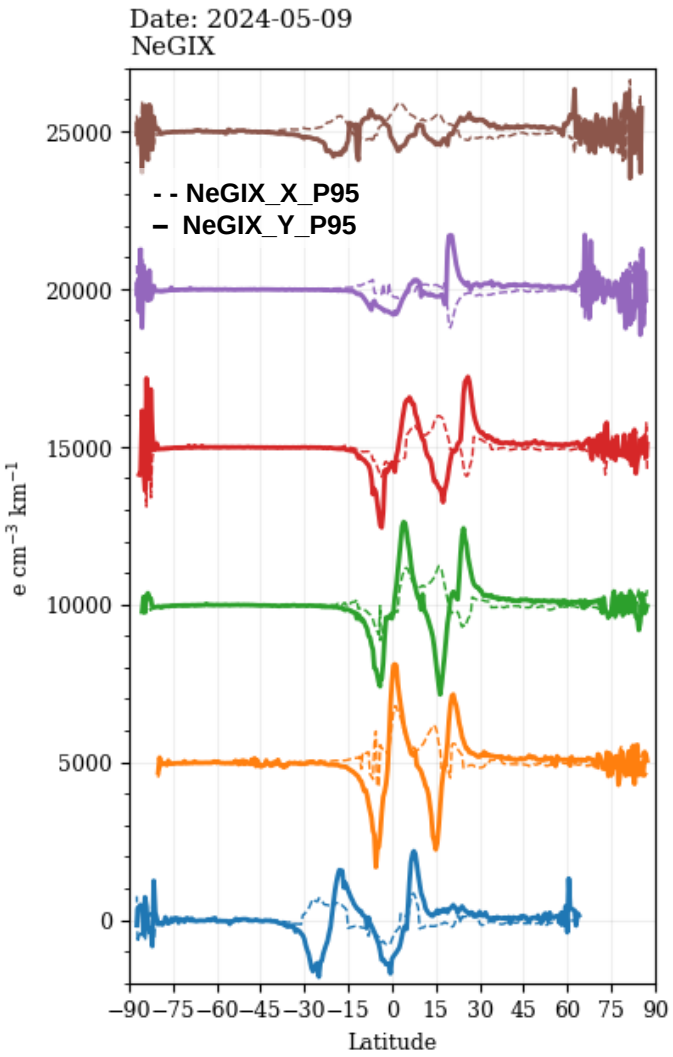


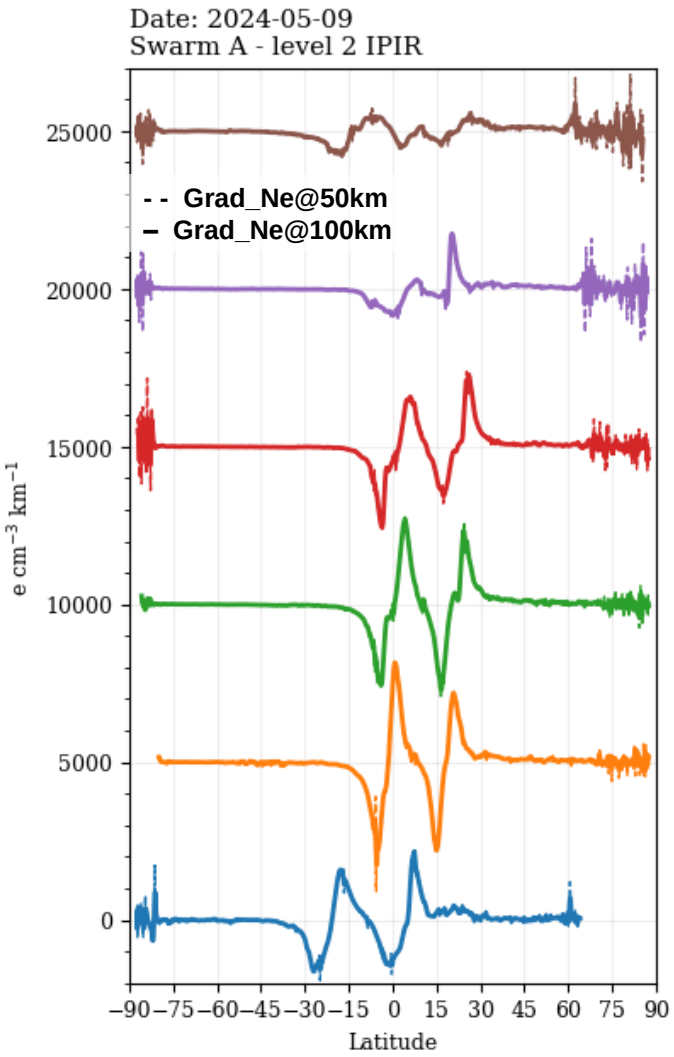


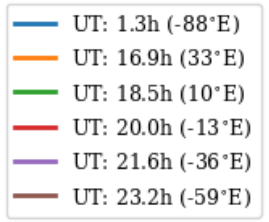
- For the quiet day of May 9th, 2024 (eq. pass at 19.3h LT), NeGIX clearly characterizes the double equatorial crests observed with the Langmuir probe in-situ data as a double positive-negative spikes (NeGIX Y P95)
- In addition to the meridional structures, also the zonal gradient (NeGIX X P95) presents variability due to ionospheric perturbations in a range of about 170 km (separation between Swarm A and C for this date)
- Signatures of the mid-latitude trough are also identified by NeGIX at sub-auroral latitude

Validation of products – comparison of NeGIX to other Swarm products based on Langmuir probe data for quiet conditions



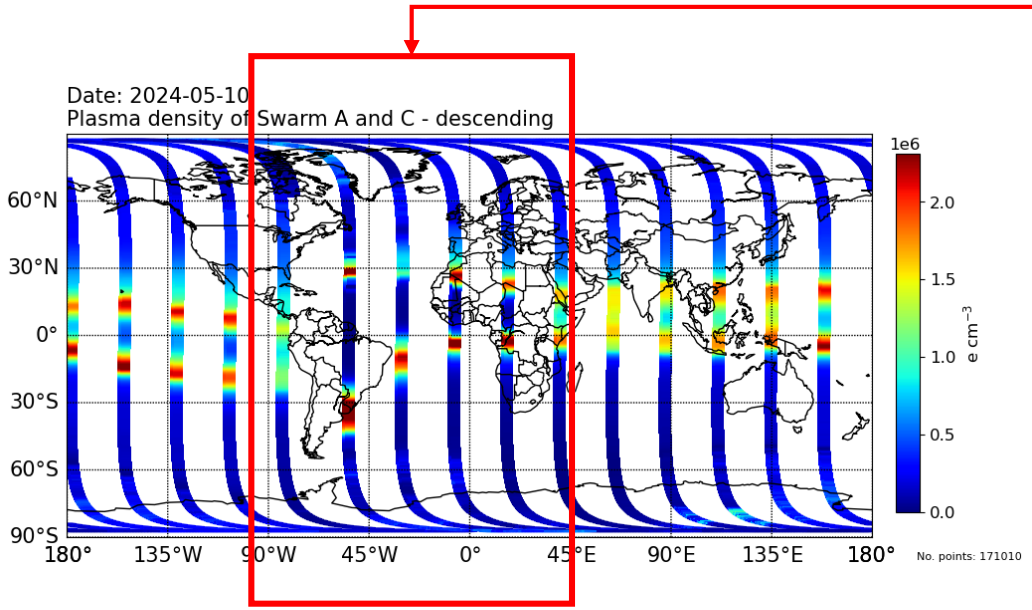


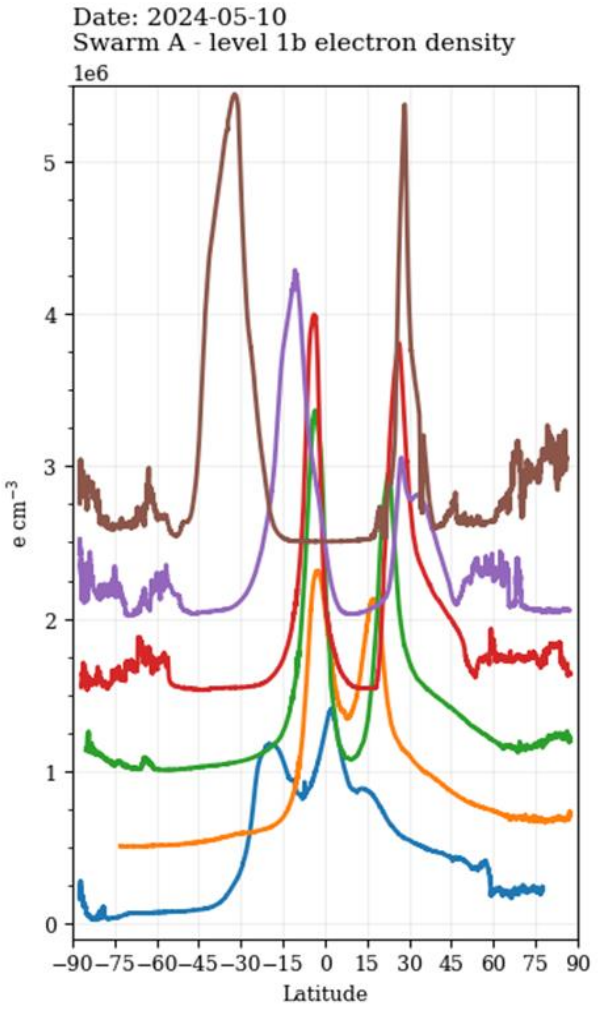


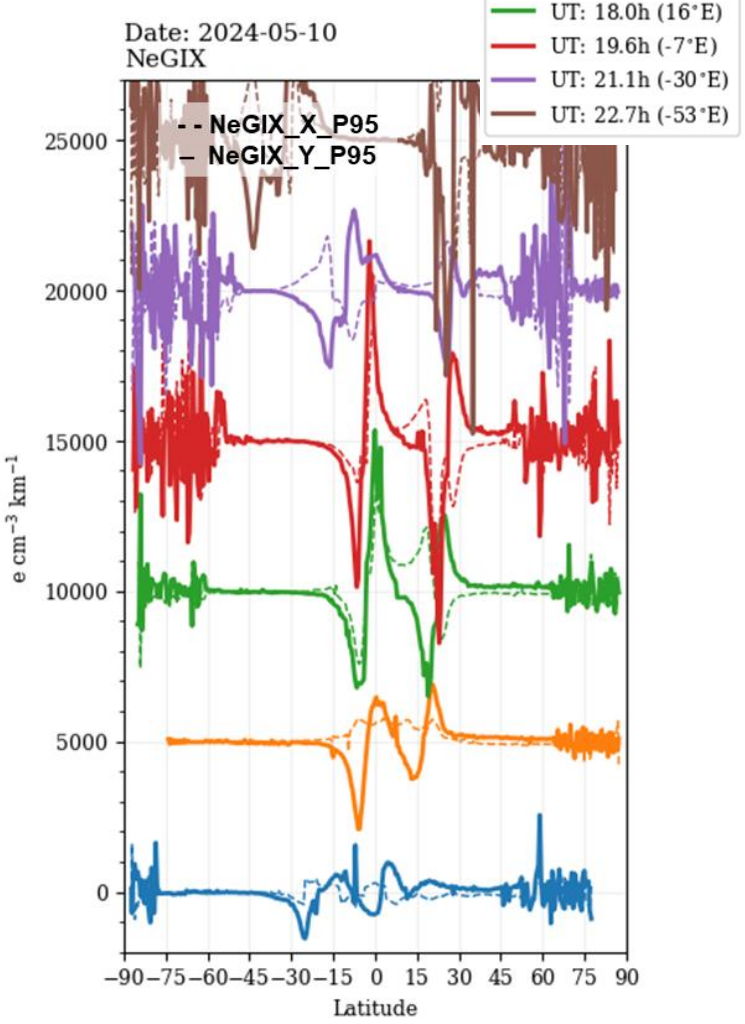


- NeGIX_Y_P95 shows identical structure as the gradients of the plasma density fluctuations product IPIR – the 95% value avoids averaging due to the geometry of combination of data points
- NeGIX_X_P95 provides additional information in the longitudinal direction for the characterization of structures from small to mid-scales

Validation of products – capacity of NeGIX to characterize ionospheric features during perturbed geomagnetic conditions

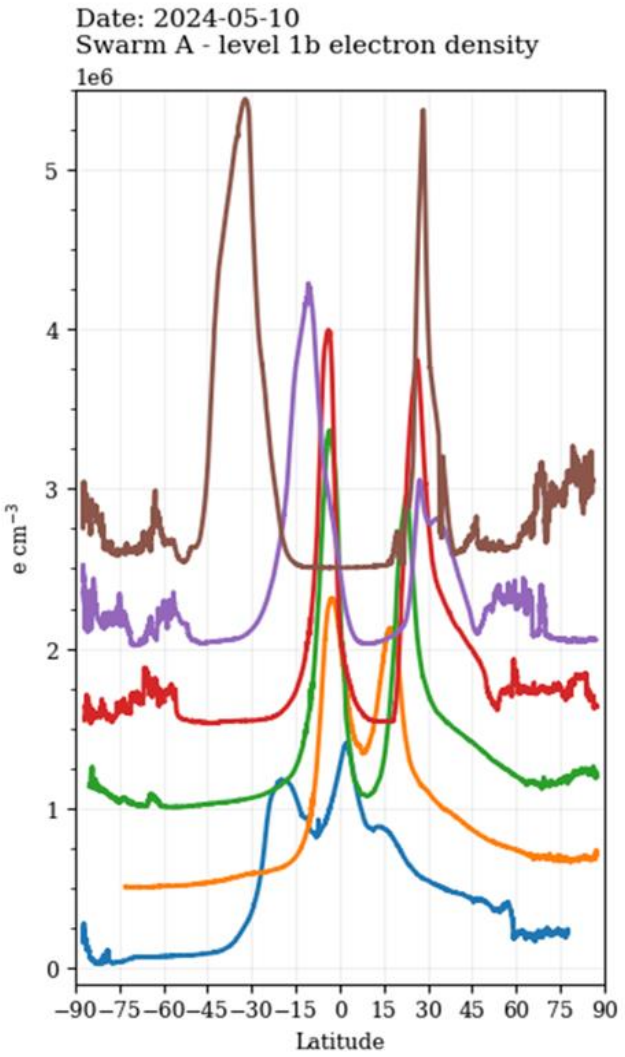


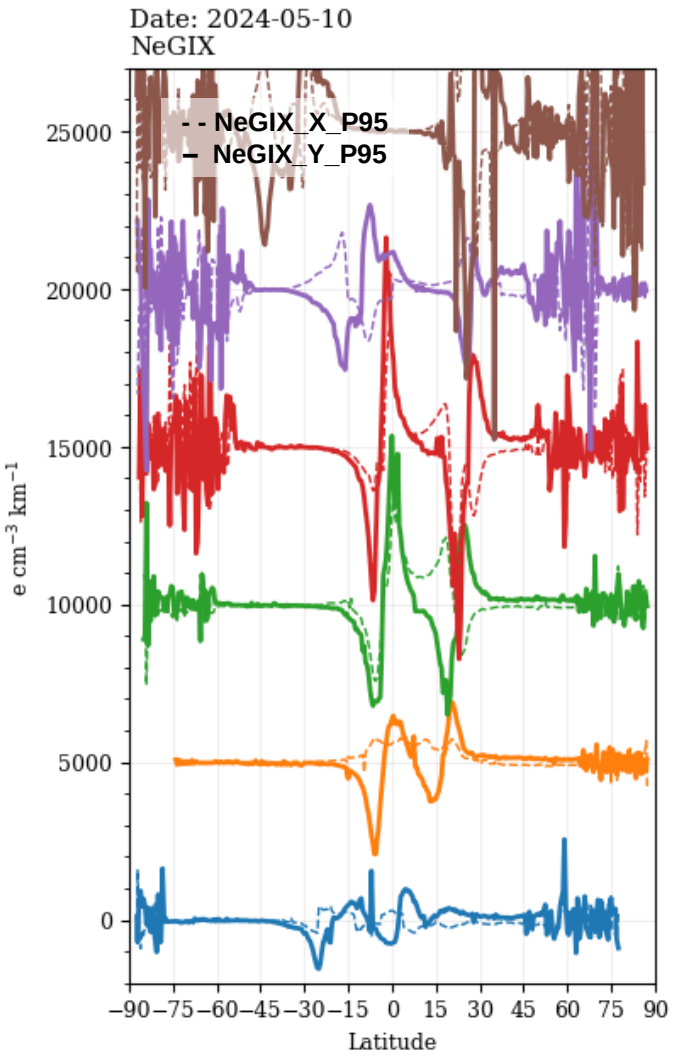


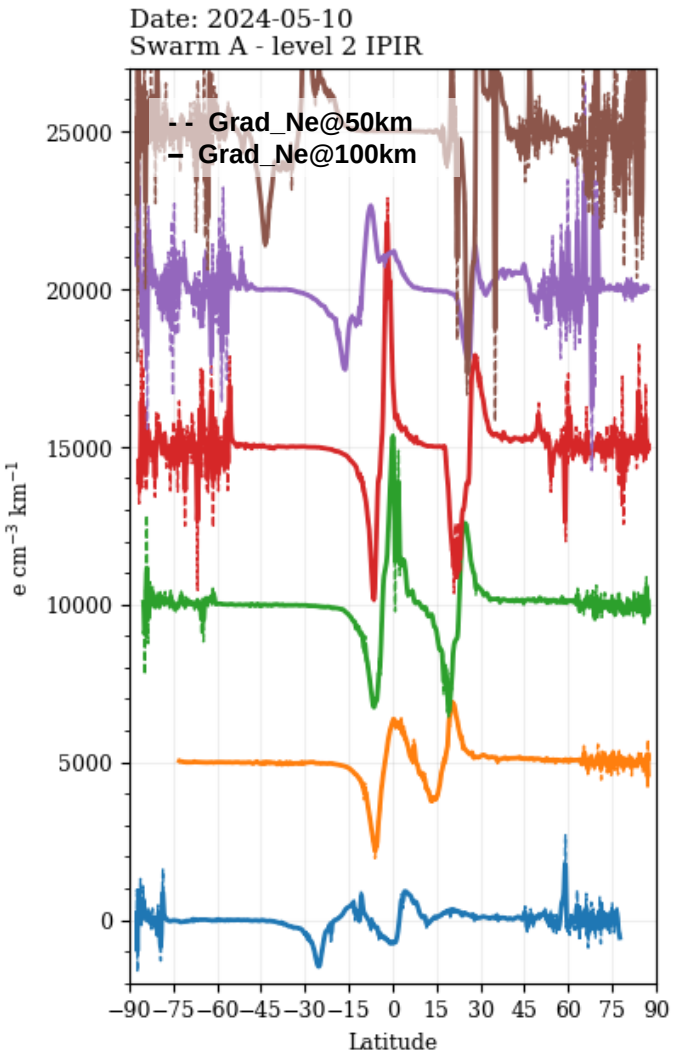


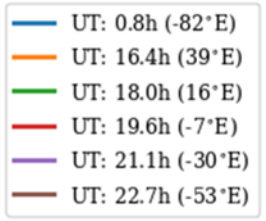
- For the perturbed day of May 10th, 2024 (eq. pass at 19.2h LT), NeGIX characterizes the double equatorial structure observed with the Langmuir probe in-situ data as a double positive-negative feature
- In addition to the meridional features, also strong peaks in the zonal component (NeGIX X) are seen. Separation at the equator between Swarm A and C for this date is ca. 170 km.
- Strong variability that reaches mid-latitudes is observed in the Northern and Southern hemispheres
- Strong assimetry of the equatorial crests is observed for the orbit at 22.7h UT

Validation of products – comparison of NeGIX to other Swarm products based on Langmuir probe data for perturbed conditions









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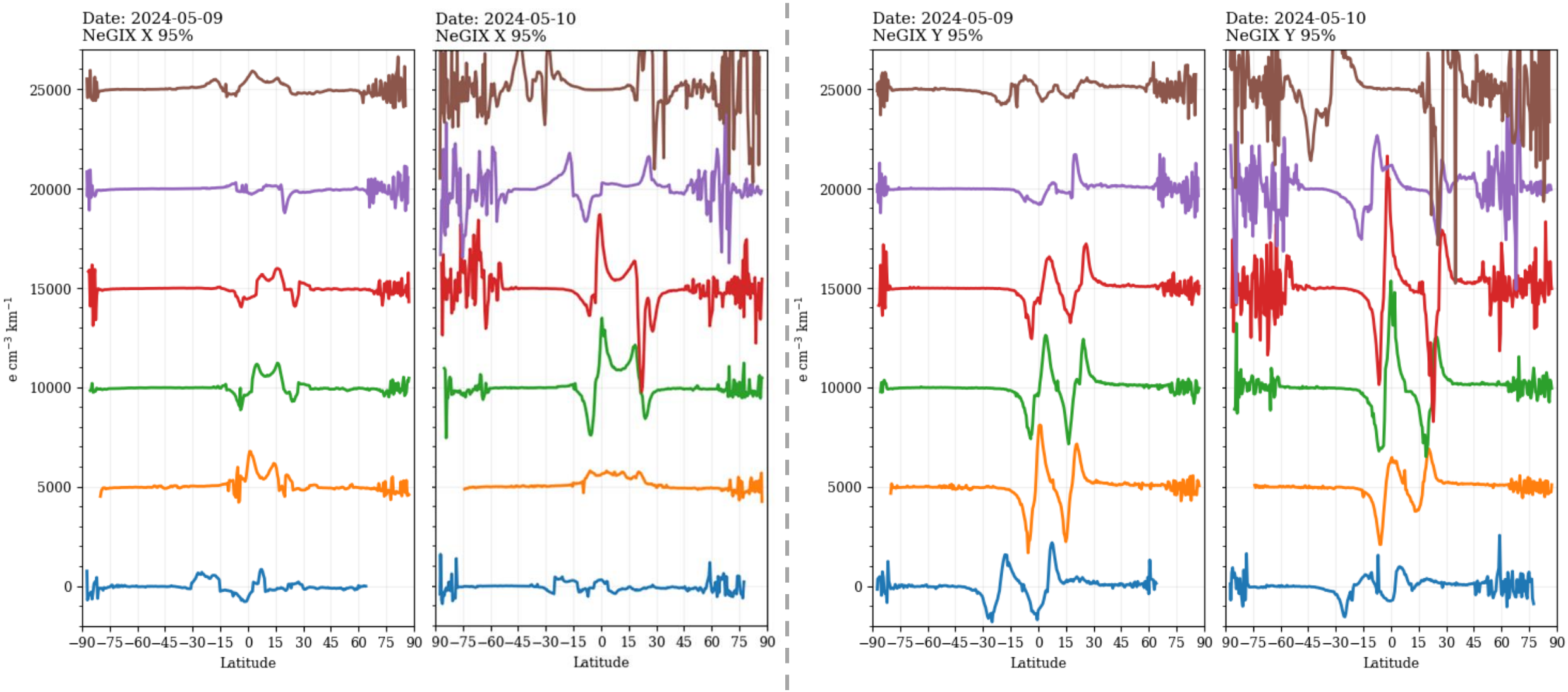
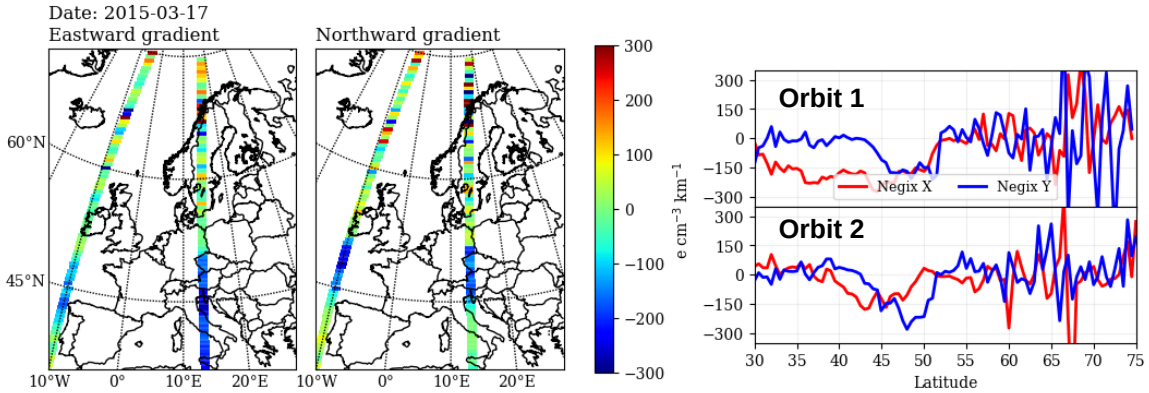
Validation of products – NeGIX difference between quiet and perturbed conditions for zonal and meridional components



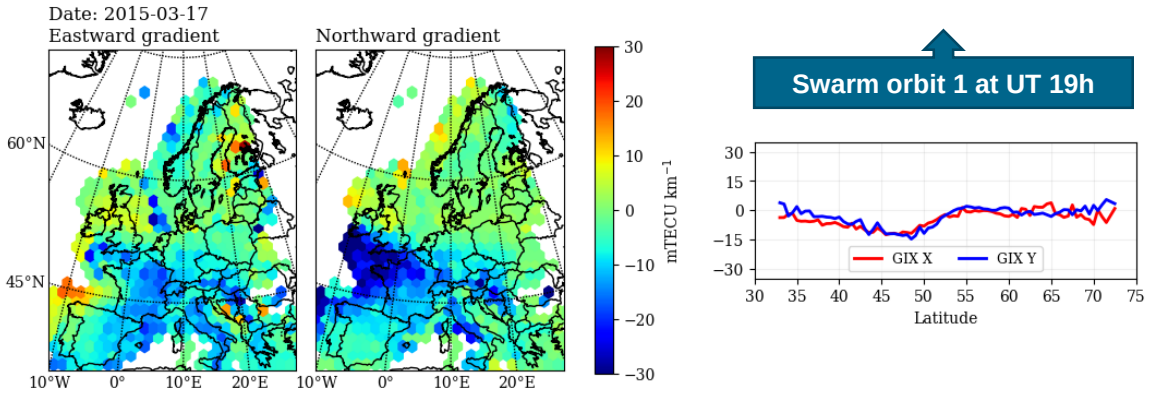
Validation of products – comparison of NeGIX and TEGIX to the ground-based index GIX over Europe

St. Patrick's Day storm on March 17th, 2015 (Dst down to -230 nT, Swarm eq. pass at 19.8h LT)

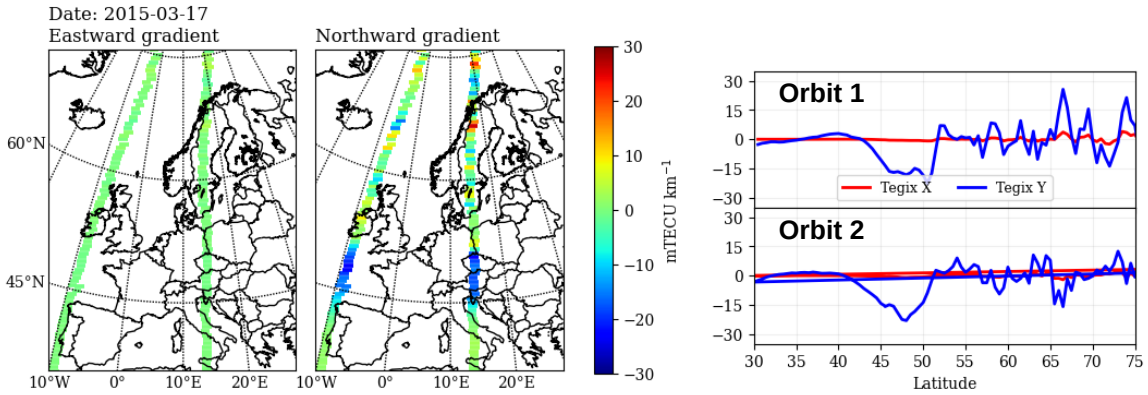
NeGIX



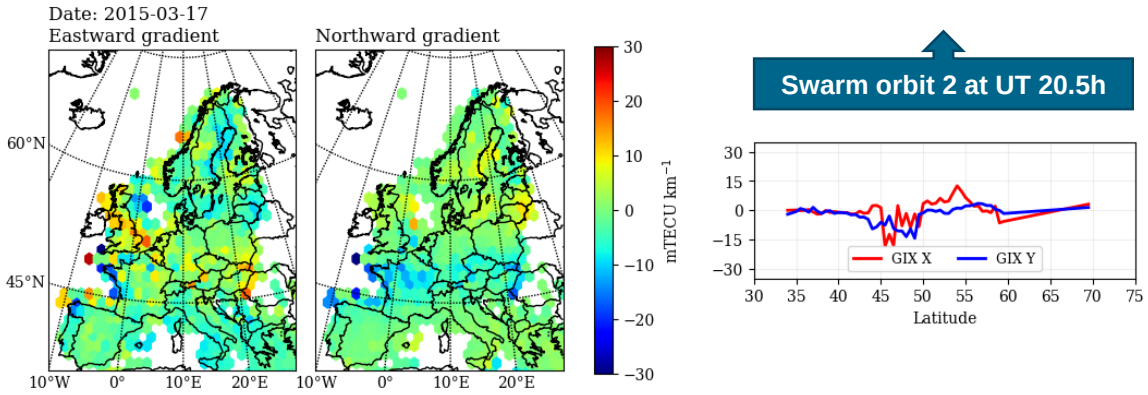
GIX



TEGIX



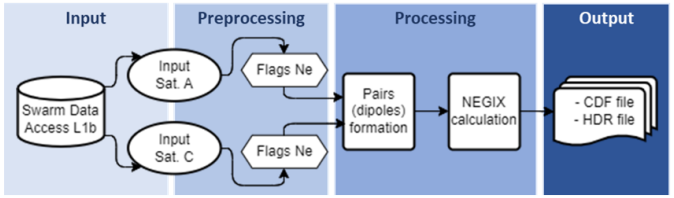
GIX



Operational services and availability of NeGIX and TEGIX

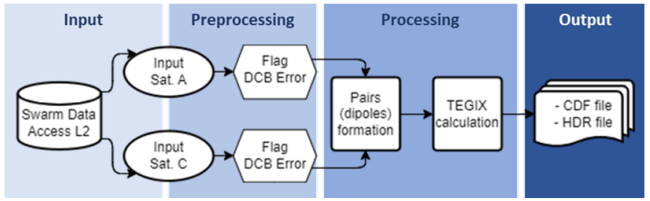
NEGIX

Inputs	Definition	Outputs
Swarm Level 1b plasma density data – Langmuir Probe measurements with 2 Hz resolution	- 0.5˚ in latitude - 32 measurements (8 sec.) - Pair combination between same and different Swarm satellites	Swarm Level 2 product with around 10,800 dataset records (daily file)

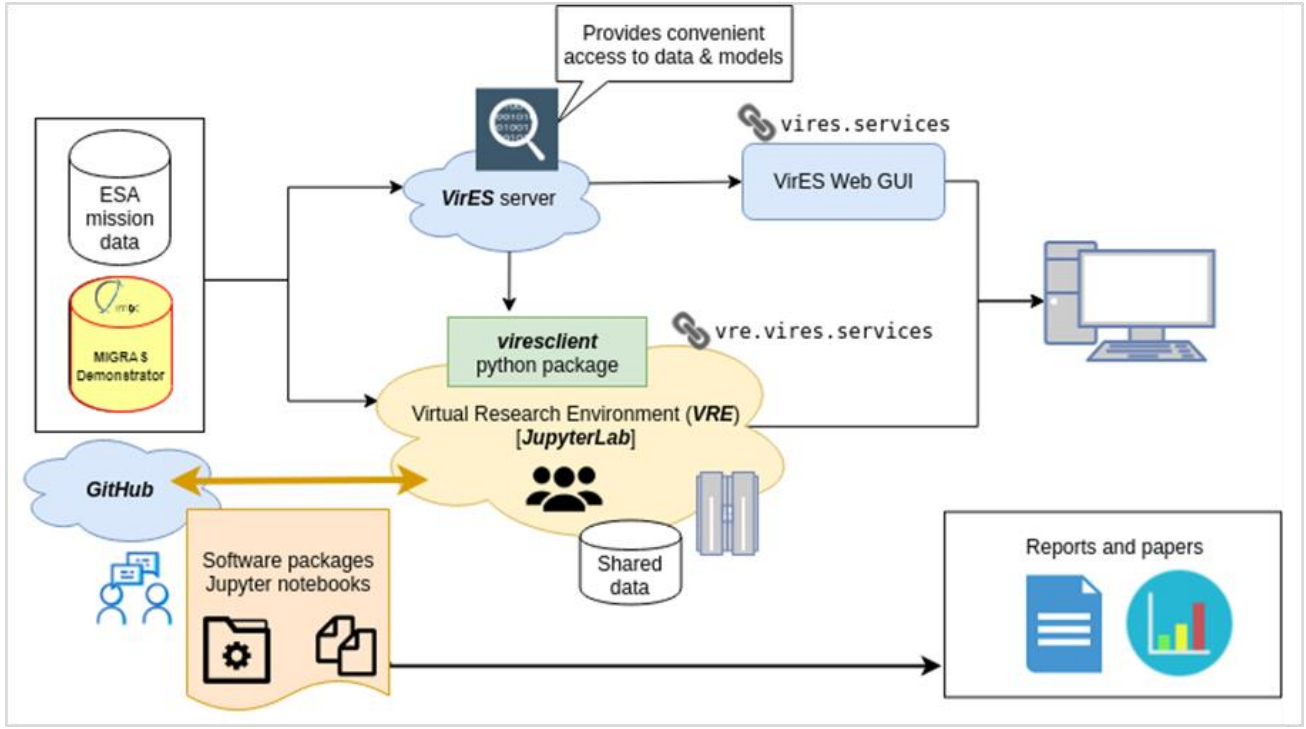


TEGIX

Inputs	Definition	Outputs
Swarm Level 2 TEC data – measure-ments with 1 Hz resolution	- 0.5˚ in latitude - measurements (8 sec.) - Pair combination only between same Swarm satellites	Swarm Level 2 product with around 10,800 dataset records (daily file)



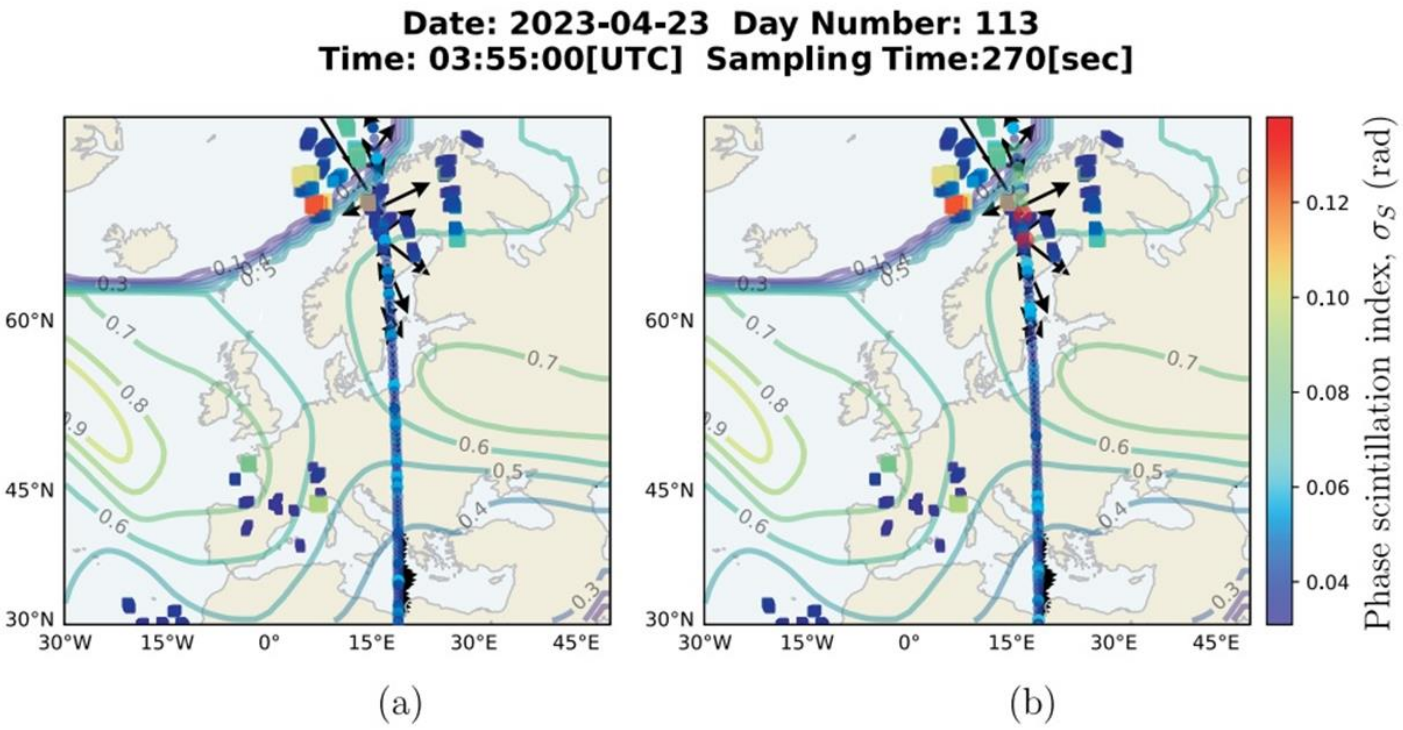
- The MIGRAS products have been developed in compatibility with the Swarm-DTU requirements and ViRES ecosystem (as an external data source), thus leveraging data exploration tools that are already available and accepted by a wide user community.
- Implementation of HAPI interface, basic interface/routes implemented, adaption of TEGIX/NEGIX modules



Applications of MIGRAS data products

NEGIX applied for “Scintillation modelling with random phase gradient screens”

(Vasylyev, Cahuasquí, Hoque, Jakowski et al. 2024 – last stages of reviewing)



Comparison of simulated phase scintillation indices (colored circles along the orbit of the Swarm satellite) with the reference values (colored squares) for L1 radio signals. Simulations are performed using the conventional random phase screen technique (a), and by using the phase gradient screens (b).

The reference values are obtained from several GNSS receivers located in Europe and their geographical locations are given by the position of their ionospheric piercing points. The black arrows correspond to the NEGIX vectors (arbitrary scale). For reference, the contours for the magnitude of the vertical TEC gradient (in units of mm/km on GPS L1) are also shown.

Conclusions

- Two new products, namely, TEGIX (Spatial TEC gradients Product) and NEGIX (Spatial Ne gradients Product) have joined the family of ionospheric indices developed at DLR.
- We have exploited the broad capacity and coverage of Swarm satellites A and C, and used Swarm GPS and Langmuir probe observations, respectively, for the definition of the new products.
- Validation analysis and comparison with existing ground-based (e.g. GIX) and Swarm products (e.g. IPIR) show that TEGIX and NEGIX correlate very well, and are capable of characterizing the state of the ionosphere during quiet and perturbed geomagnetic conditions.
- Scientific applications of the MIGRAS products have started (e.g. NEGIX for scintillation modelling shows promising results utilizing the phase gradient screen approach) and collaboration is very encouraged.
- Availability of MIGRAS products will be possible via DLR-IMPC at impc.dlr.de and Swarm data interfaces.

Thanks to SWARM DISC DTU

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