Monitoring Ionospheric Gradients using Swarm onboard GPS and Langmuir-probe data

J Andrés Cahuasquí, *M Hoque, N Jakowski, S Buchert, M Kriegel, P David, D Vasylyev, Y Tagargouste, J Berdermann, K Nielsen*

German Aerospace Center (DLR), Swedish Institute of Space Physics (IRF), Technical University of Denmark (DTU)

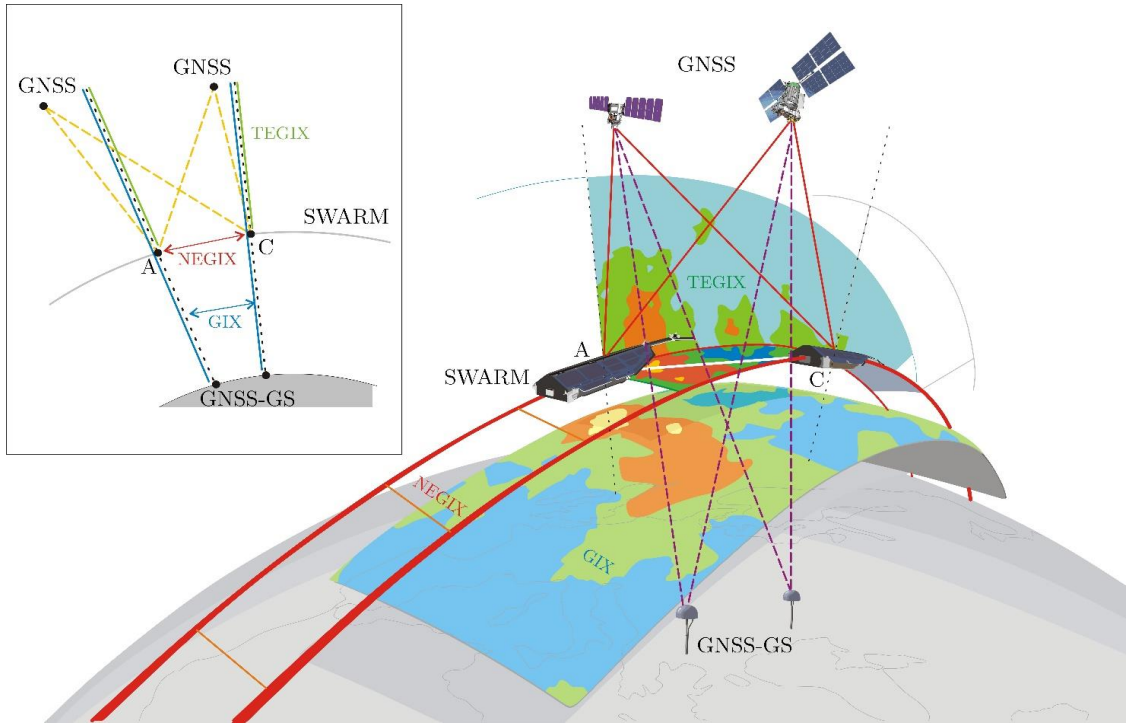
Swarm 10 Year Anniversary & Science Conference 2024

Monitoring Ionospheric GRAdients using Swarm
MIGRAS

(Swarm DISC Subcontract SW-CO-DTU-GS-133)

Motivation:

- Ionospheric irregularities and TEC perturbations may cause scintillation of radio signals and degrade the quality and availability of GNSS-based applications for navigation and communication



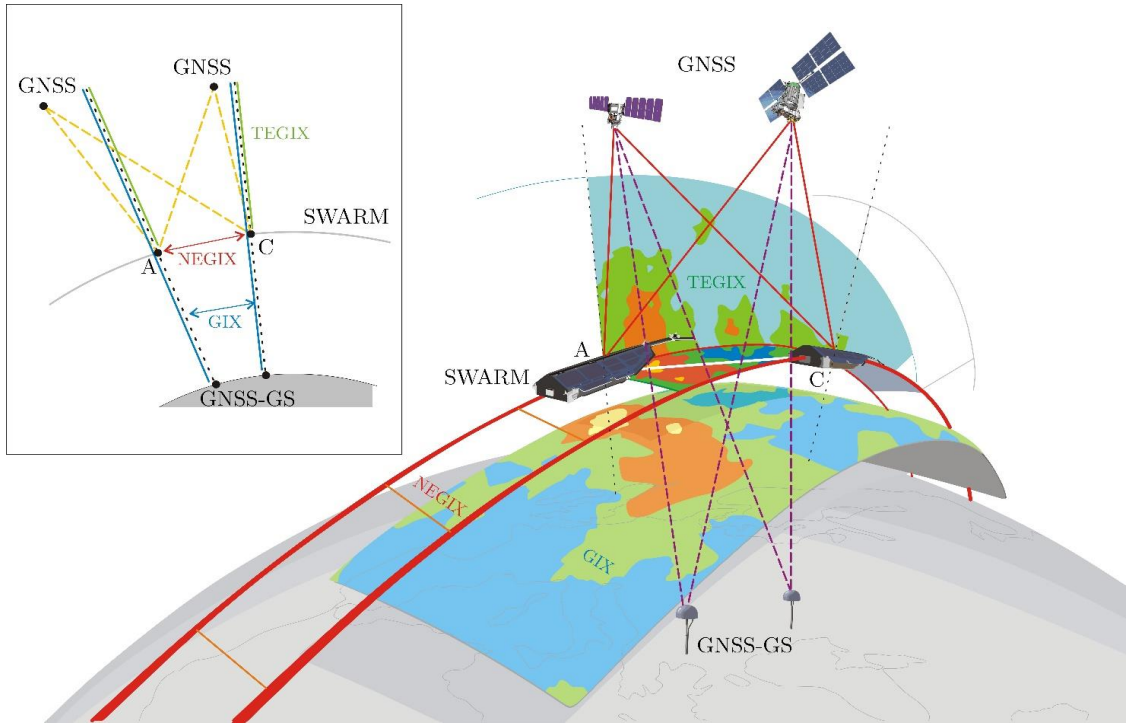
Monitoring Ionospheric GRAdients using Swarm
MIGRAS

(Swarm DISC Subcontract SW-CO-DTU-GS-133)

Swarm offers a unique and broad spectrum of data for space weather monitoring and research

MIGRAS primary tasks:

- Putting Swarm into a space weather context
- Defining Swarm products, tools and services for monitoring small- to mid-scale irregularities – in the order of about 100 km
- Automatization and demonstration
- Product validation and quality assurance



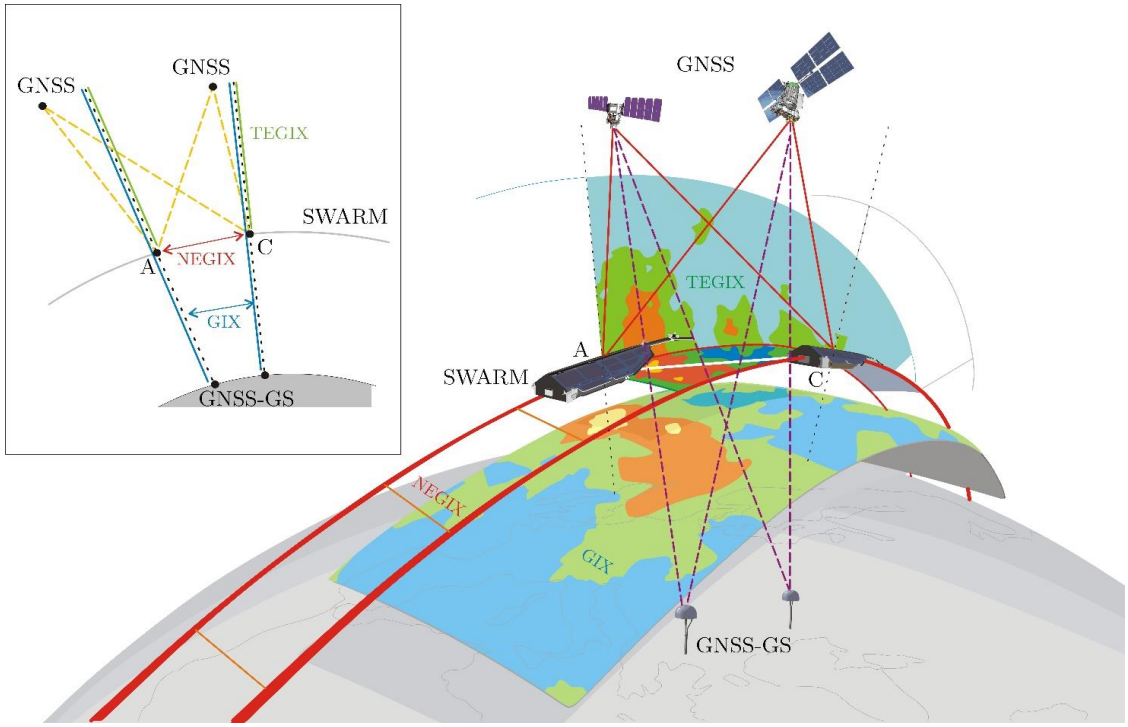
Monitoring Ionospheric GRAdients using Swarm
MIGRAS

(Swarm DISC Subcontract SW-CO-DTU-GS-133)

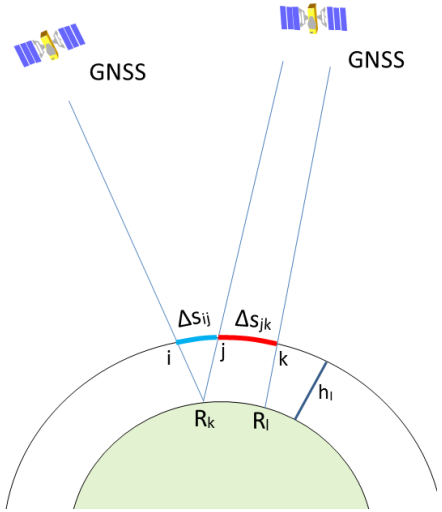
MIGRAS products:

1. **TEGIX** – spatial TEC-gradients product based on GNSS Precise Orbit Determination observations
2. **NEGIX** – spatial Ne-gradients product based on Langmuir probe observations

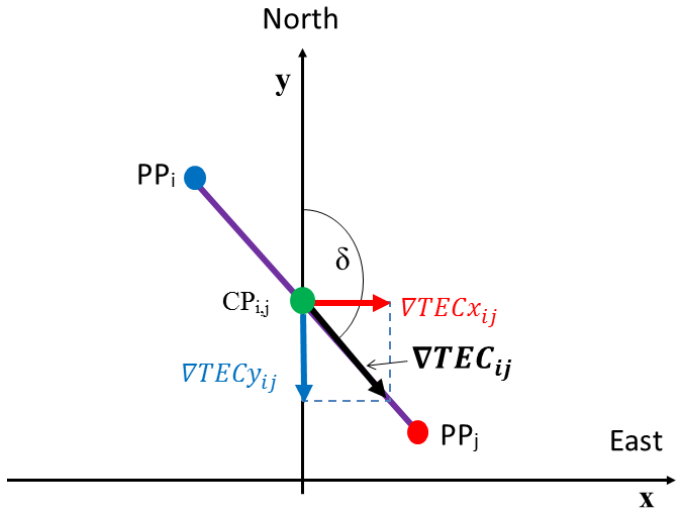
The product development comprehends all technical requirements and resources needed for their computation (type, latency, storage, HAPI compliance etc.)



TEGIX and NEGIX 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)

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

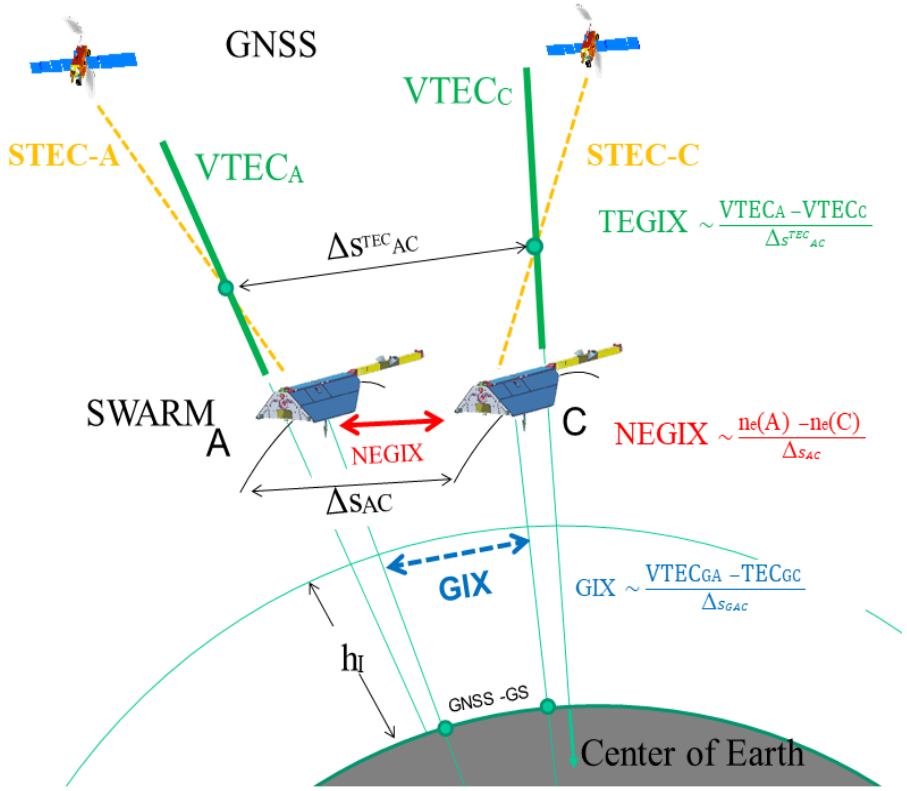
$$\langle \nabla TECy \rangle = \frac{1}{N_C} \sum_{i=1}^{N_C} \nabla TECy_{ij}$$

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

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

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

TEGIX – the Total Electron content Gradient IndeX



Definition:

- TEGIX 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

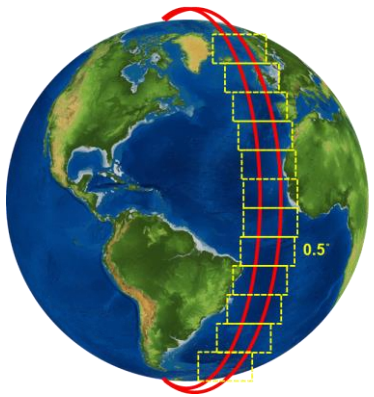
Input data:

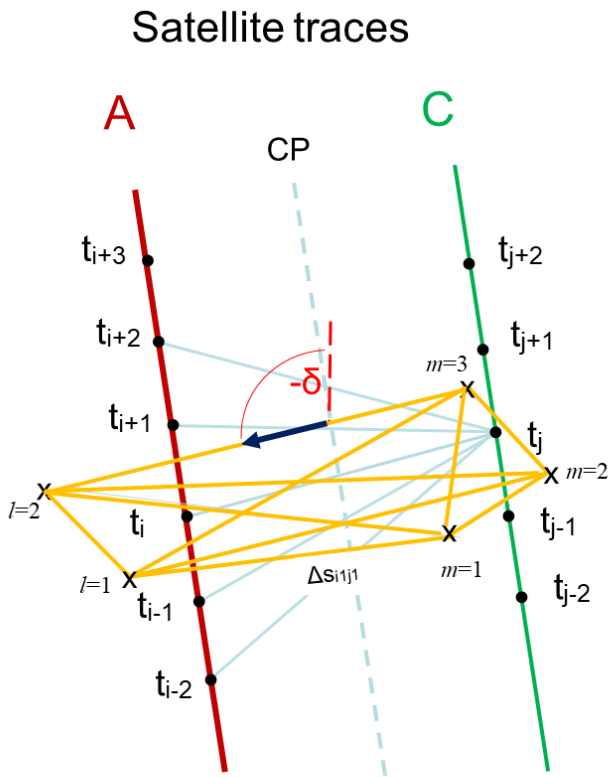
- Absolute/calibrated Vertical Total Electron Content (VTEC) obtained from POD data of Swarm-A and Swarm-C satellites (Level-2 data TECATMS_2F with 1 second resolution)

Output:

- TEGIX product – Level-2 data with resolution of 0.5° in latitude

TEGIX – the Total Electron content Gradient IndeX





Combination of VTEC measurements onboard Swarm satellites A and C

Definition:

- TEGIX 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

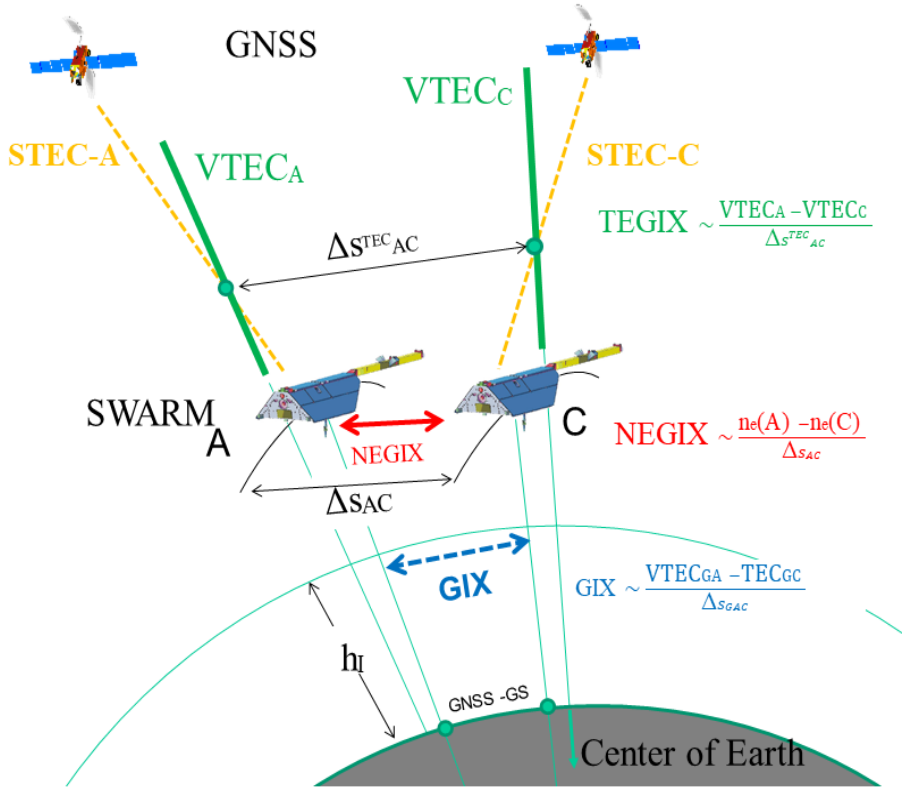
Input data:

- 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)

Output:

- TEGIX product – Level-2 data with resolution of 0.5° in latitude

NEGIX – the electron density (Ne) Gradient IndeX



Definition:

- NEGIX 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

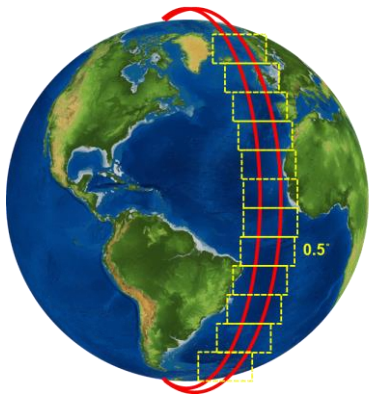
Input data:

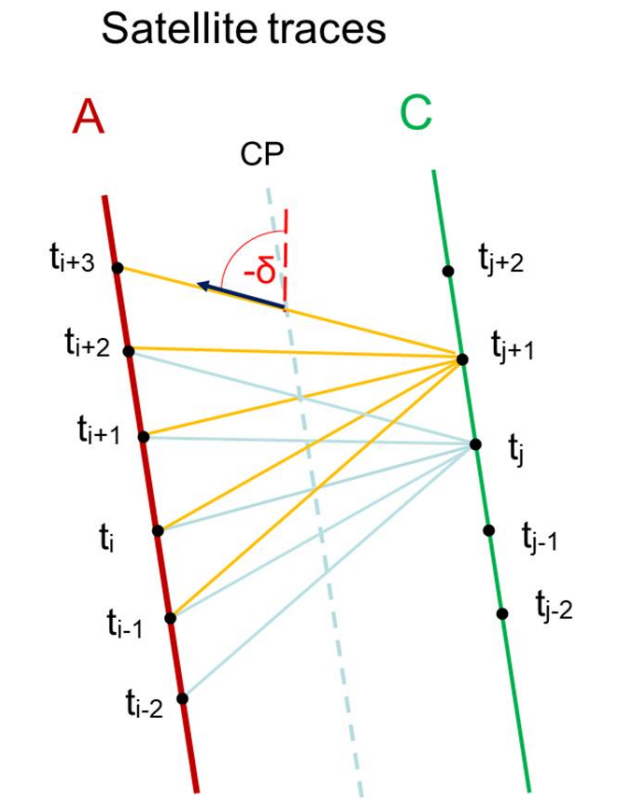
- In-situ electron density data from Langmuir probes onboard Swarm-A and Swarm-C satellites (Level-1 data EFIA_LP_1B with 0.5 second resolution)

Output:

- NEGIX product – Level-2 data with resolution of 0.5° in latitude

NEGIX – the electron density (Ne) Gradient IndeX





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

Definition:

- NEGIX 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

Input data:

- 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)

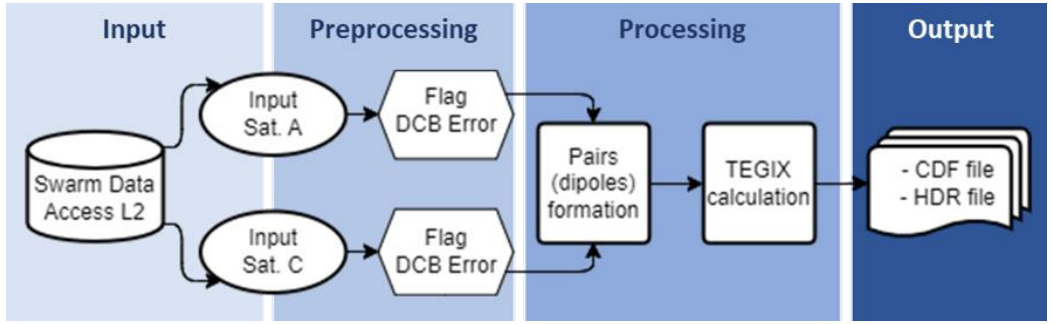
Output:

- NEGIX product – Level-2 data with resolution of 0.5° in latitude

TEGIX and NEGIX - product definition and processing

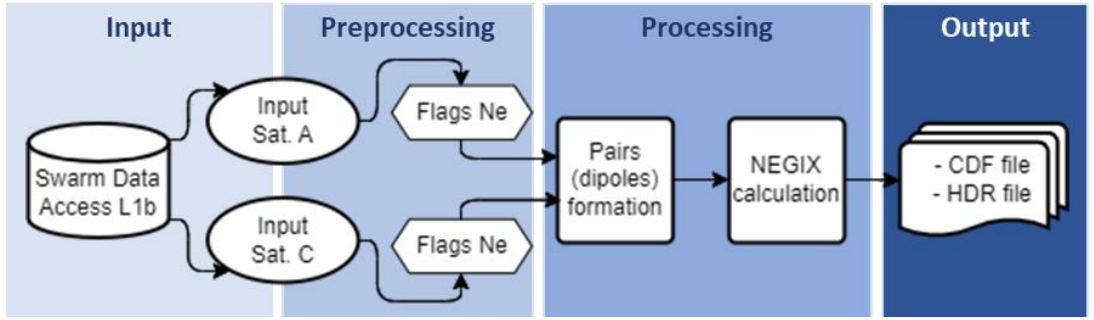
TEGIX

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)



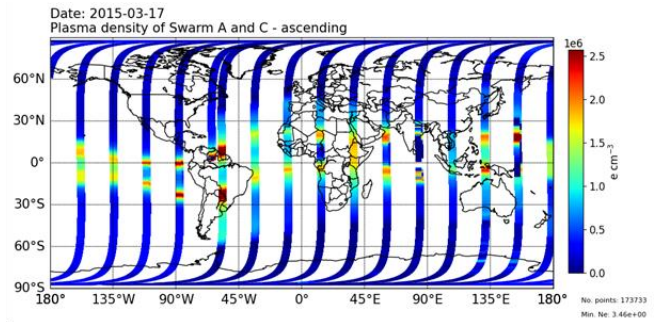
NEGIX

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)

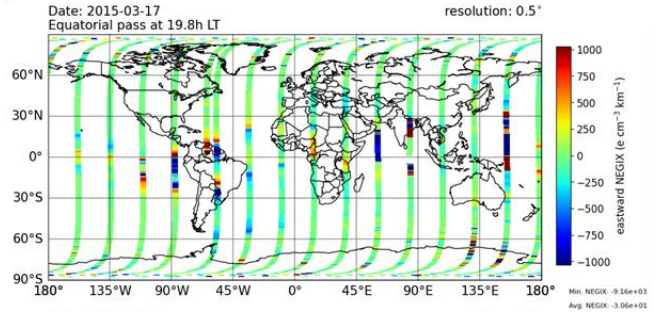


NEGIX and TEGIX – data products sample (St. Patrick's Day storm, 17.03.2015)

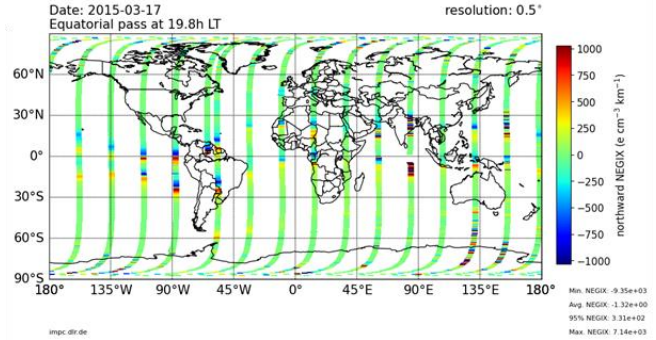
NEGIX



Plasma density

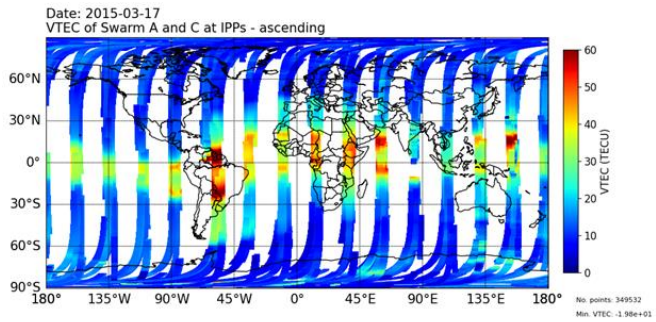


West-East component

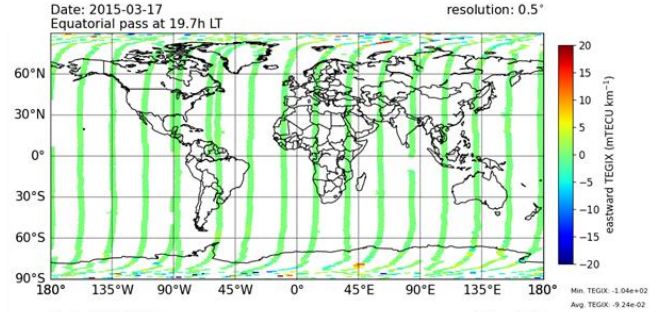


South-North component

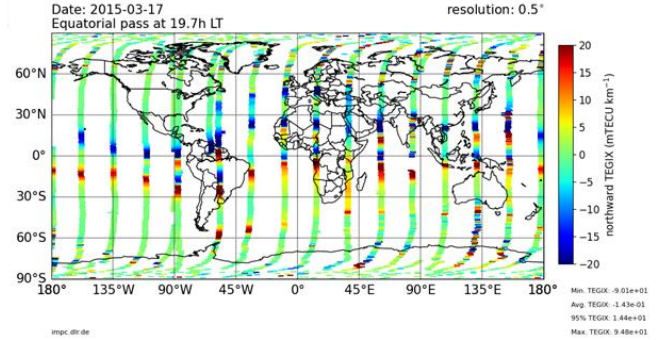
TEGIX



Vertical TEC



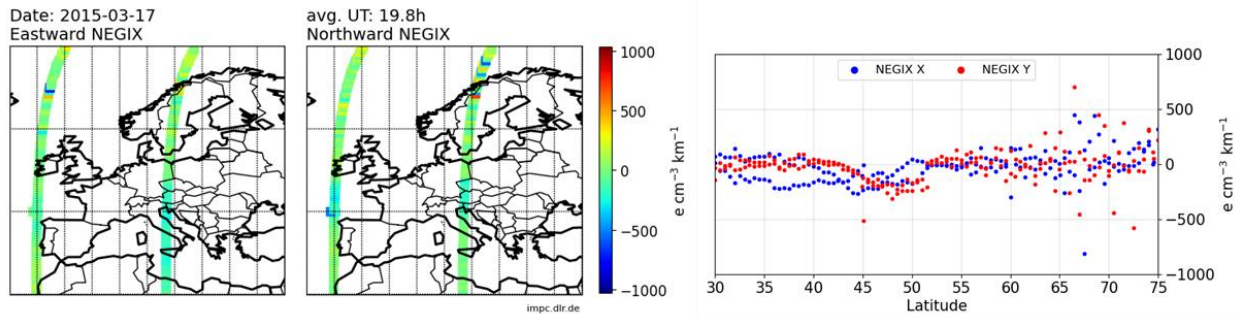
West-East component



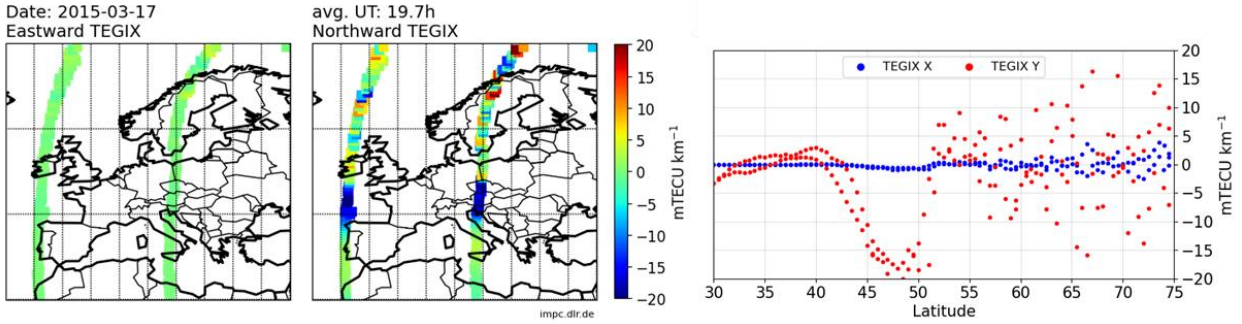
South-North component

NEGIX and TEGIX – product validation (St. Patrick's Day storm, 17.03.2015)

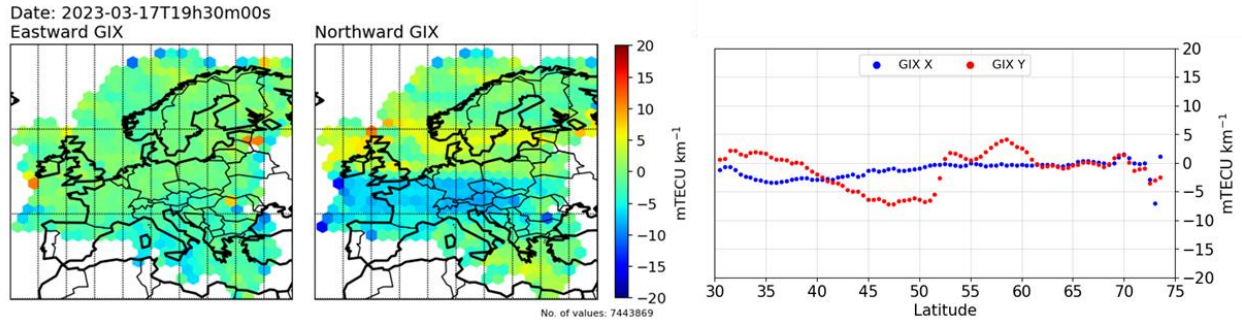
Swarm NEGIX



Swarm TEGIX

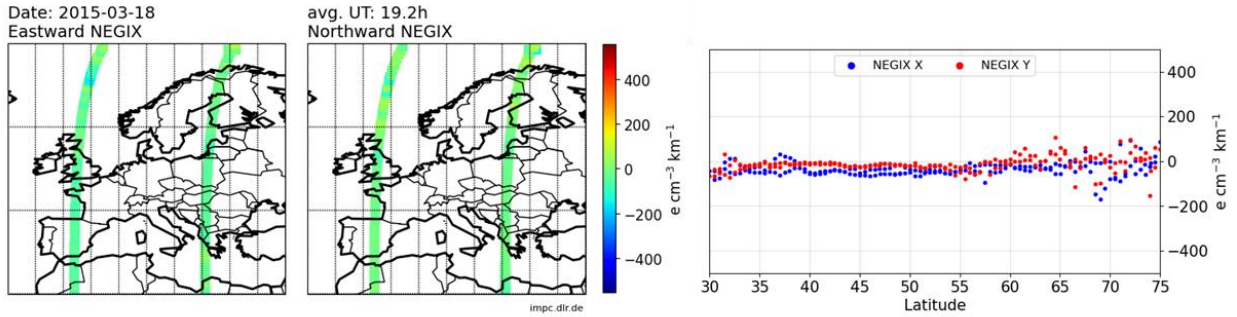


Ground-based GIX

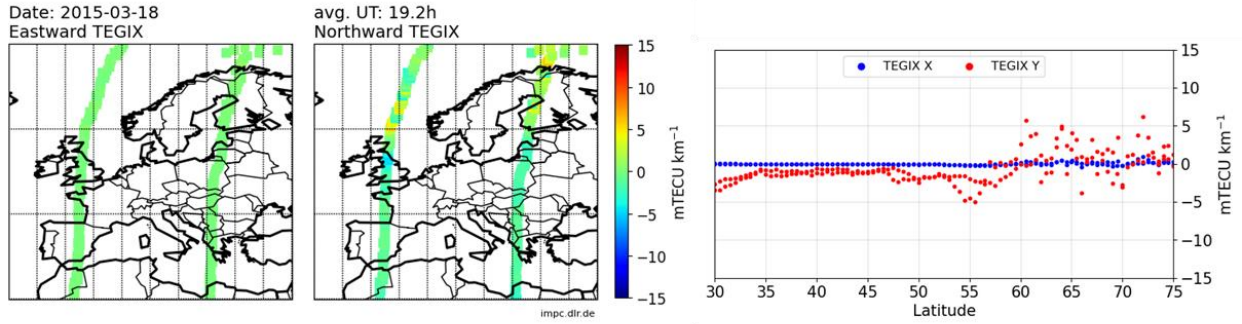


NEGIX and TEGIX – product validation (St. Patrick's Day storm, 18.03.2015)

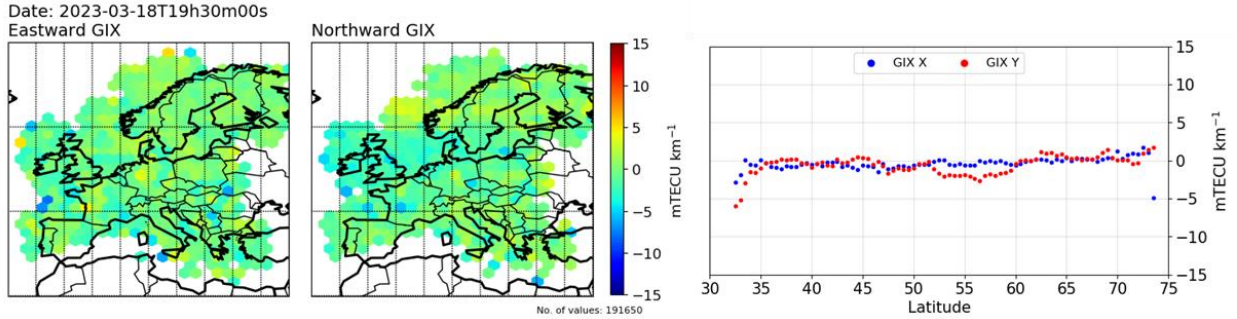
Swarm NEGIX



Swarm TEGIX



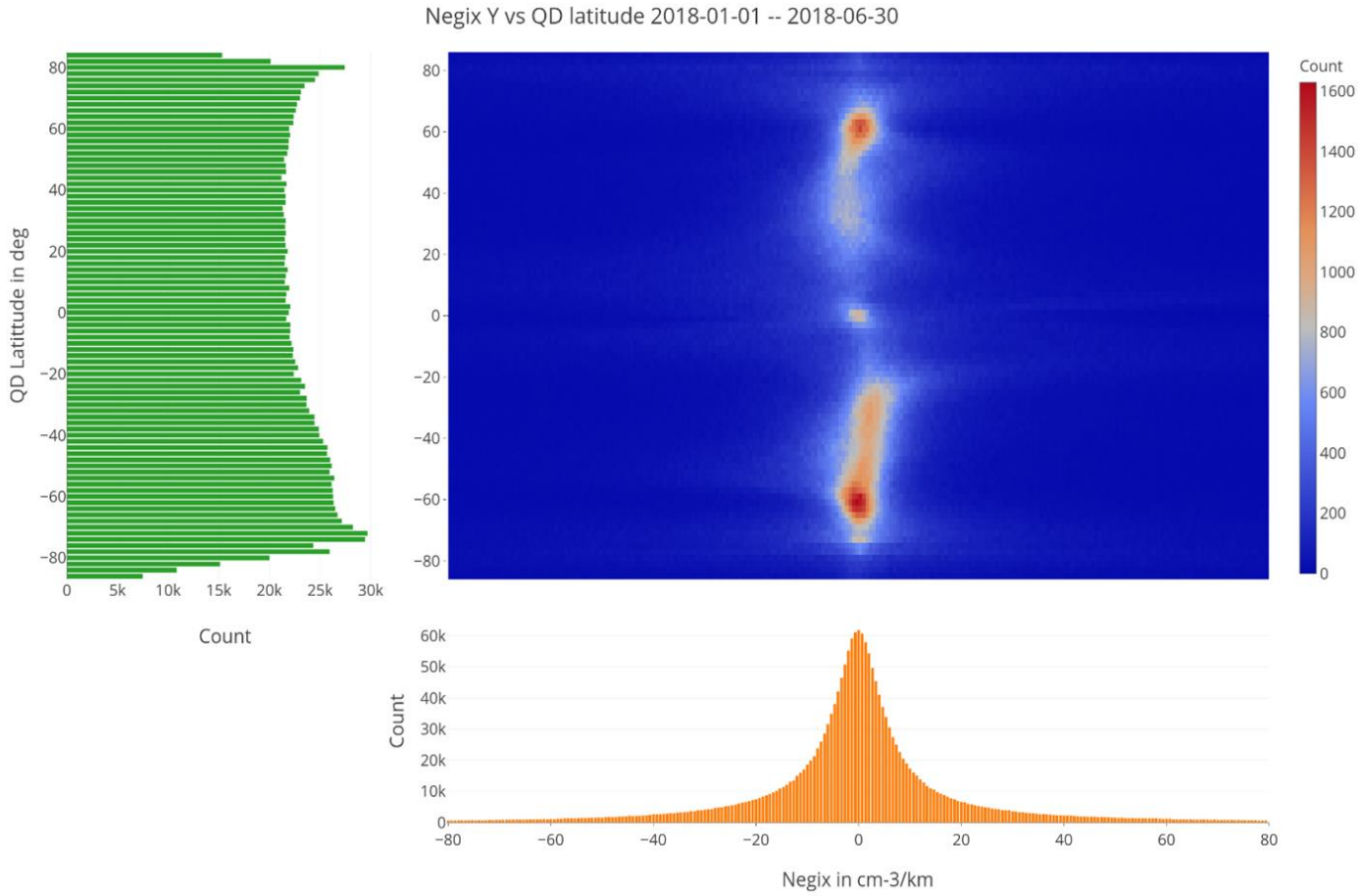
Ground-based GIX



NEGIX and TEGIX – product validation

Validation of NEGIX over six months (January – June 2018) shows expected effects:

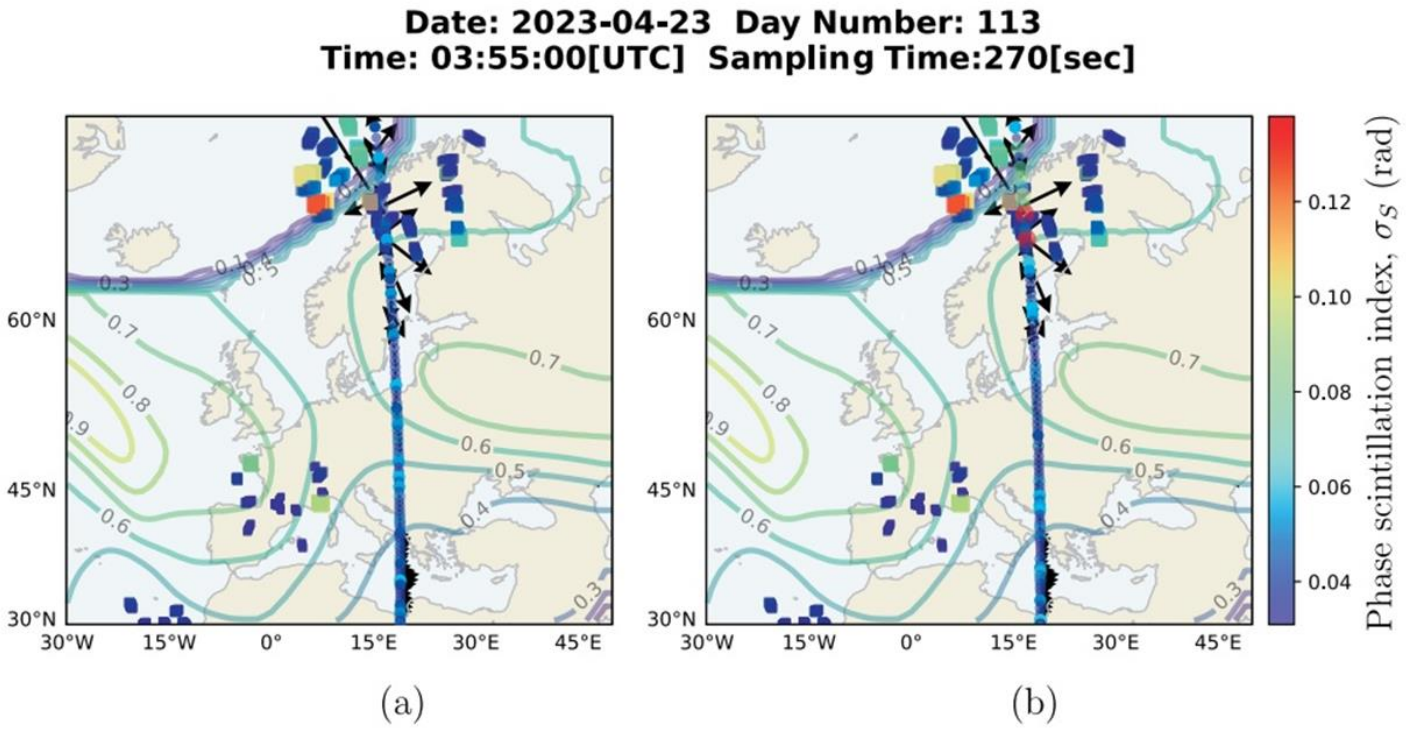
- The strongest gradients are seen around latitudes about +60 and -60 degrees. This is roughly the location of the ionospheric mid-latitude trough
- The south-north NEGIX component has as expected features depending on the magnetic (quasi-dipolar) latitude



NEGIX application – Scintillation modelling with random phase gradient screens (Vasylyev et al. 2024 – submitted)

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.



Automatization and Demonstration

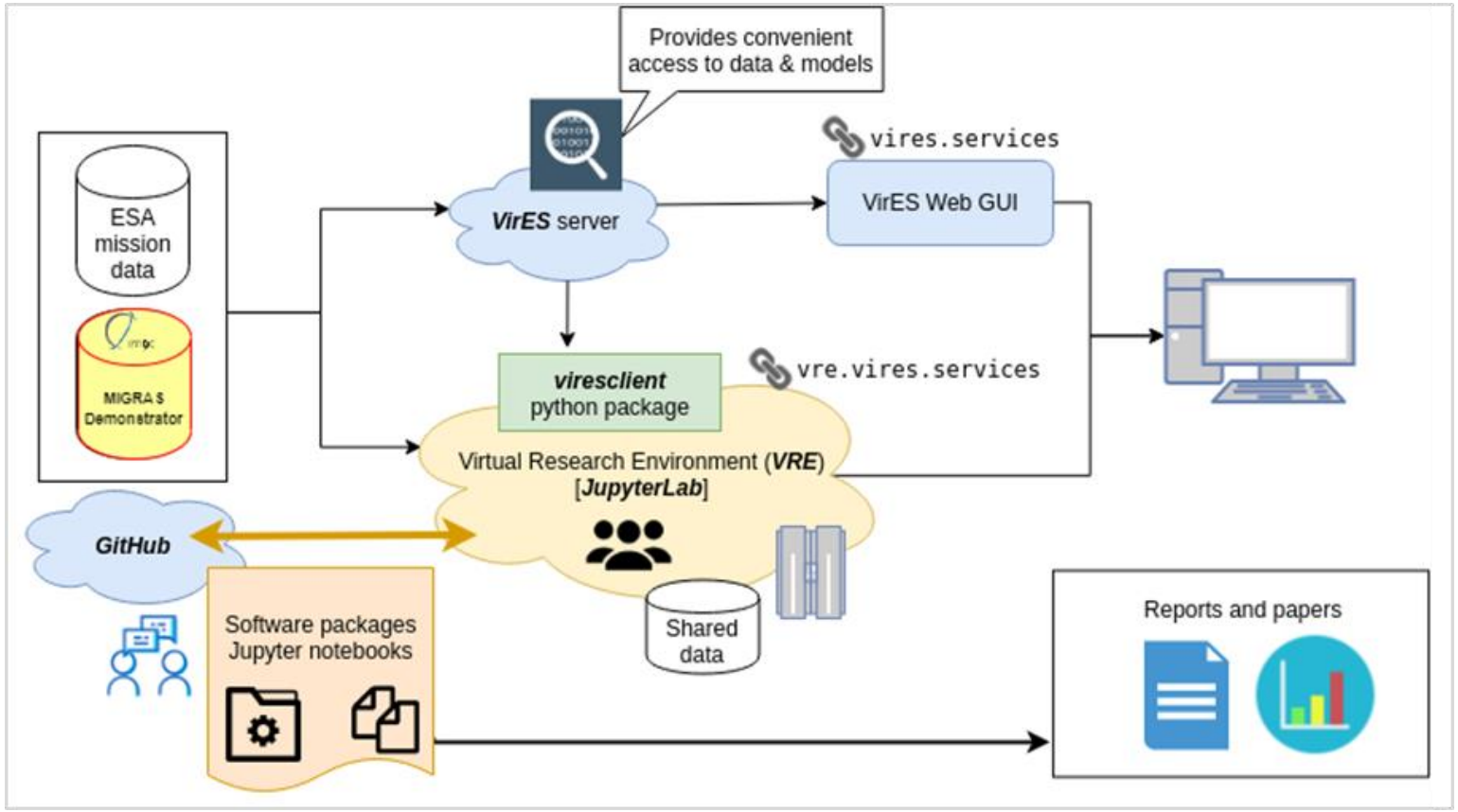
The MIGRAS demonstrator is designed to be compatible with the ViRES ecosystem (as an external data source), thus leveraging data exploration tools that are already available and accepted by a wide user community.

Python Software for TEGIX/NEGIX

- Received software packages
- Code refactoring/benchmarking
- Containerisation with Podman

Implementation of HAPI interface

- Basic interface/routes implemented
- Adaption of TEGIX/NEGIX modules



Summary

- Two new products, namely, TEGIX (Spatial TEC gradients Product) and NEGIX (Spatial Ne gradients Product) have been developed based on Swarm GPS and Langmuir probe observations, respectively.
- Investigation shows that TEGIX and NEGIX correlate very well.
- NEGIX and TEGIX correlate with the ground-based GIX during the St. Patrick's Day storm (17th March 2015) over Europe.
- Use of NEGIX for scintillation modelling shows promising results (utilizing the phase gradient screen approach).
- Availability of MIGRAS products possible via DLR-IMPC at impc.dlr.de

Swarm 10 Year Anniversary & Science Conference 2024