

**Swarm DQW14: 2024**  
**7-11th October in Bucharest**

# **Swarm ionospheric gradient indices TEGIX and NeGIX**

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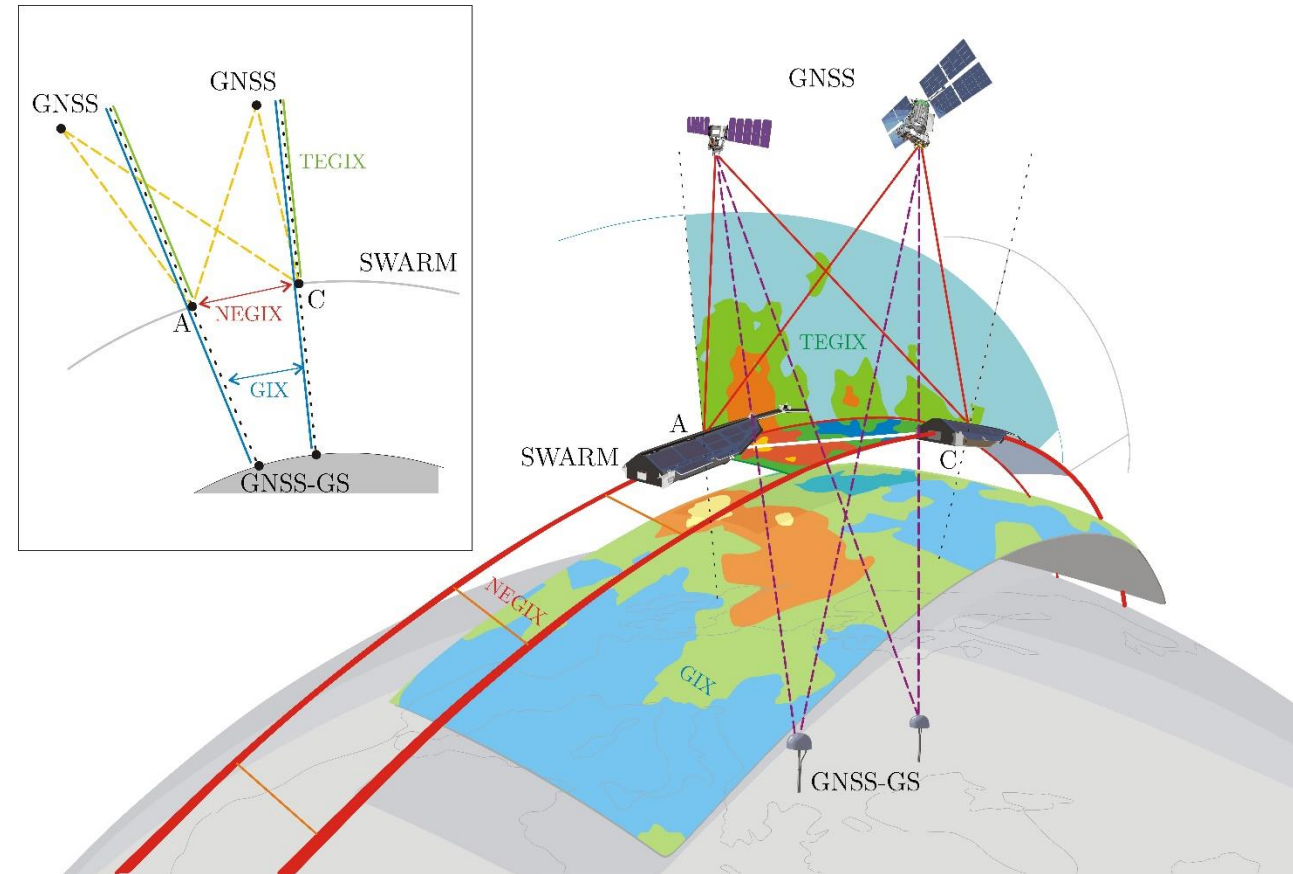
Acknowledgement: Swarm DISC Subcontract SW-CO-DTU-GS-133

# Monitoring of Ionospheric Gradients At Swarm (MIGRAS)

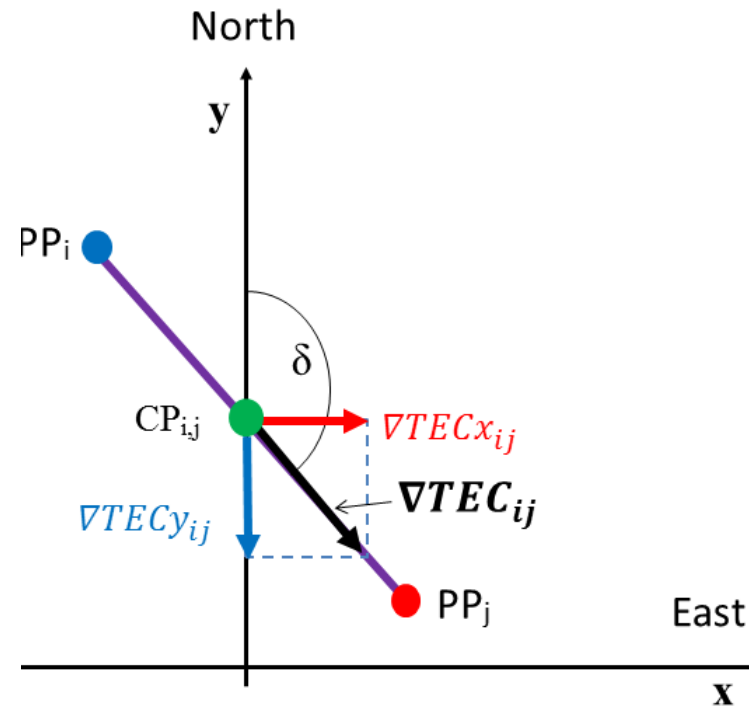
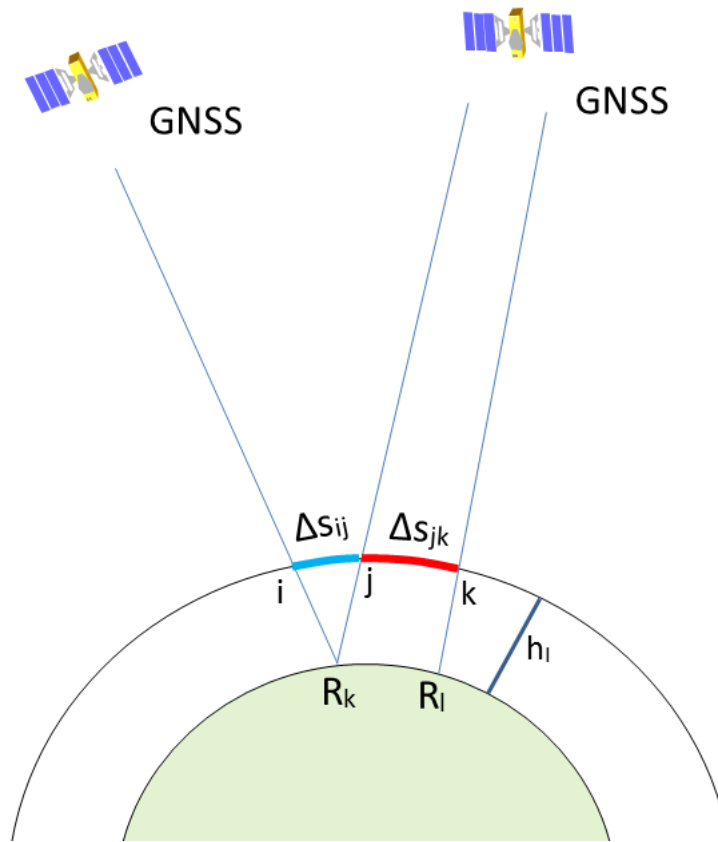
Two new products namely

- TEGIX (Total Electron Content Gradient Index) and
- NeGIX (electron density  $N_e$  Gradient Index)

are developed based on Swarm GPS and Langmuir probe observations, respectively.



# Spatial gradient monitor- Gradient Ionosphere index (GIX)



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

$$\nabla TE C_{x_{ij}} = \nabla TE C_{ij} \cdot \sin \delta$$

$$\nabla TE C_{y_{ij}} = \nabla TE C_{ij} \cdot \cos \delta$$

$$\langle \nabla TE C_x \rangle = \frac{1}{N_c} \sum_{i=1}^{N_c} \nabla TE C_{x_{ij}}$$

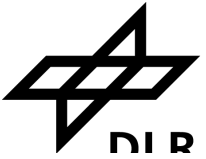
$$\langle \nabla TE C_y \rangle = \frac{1}{N_c} \sum_{i=1}^{N_c} \nabla TE C_{y_{ij}}$$

$$GIX = \langle \nabla TE C \rangle = \sqrt{\langle \nabla TE C_x \rangle^2 + \langle \nabla TE C_y \rangle^2}$$

$$GIXS \equiv \sigma(\nabla TE C) = \sqrt{(\langle \nabla TE C^2 \rangle - \langle \nabla TE C \rangle^2)}$$

- Standard deviation, 95 percentile
- GIX (derived from ground GNSS data) is able to monitor spatial variations of total electron content (TEC)

# Total Electron Content Gradient Index- TEGIX

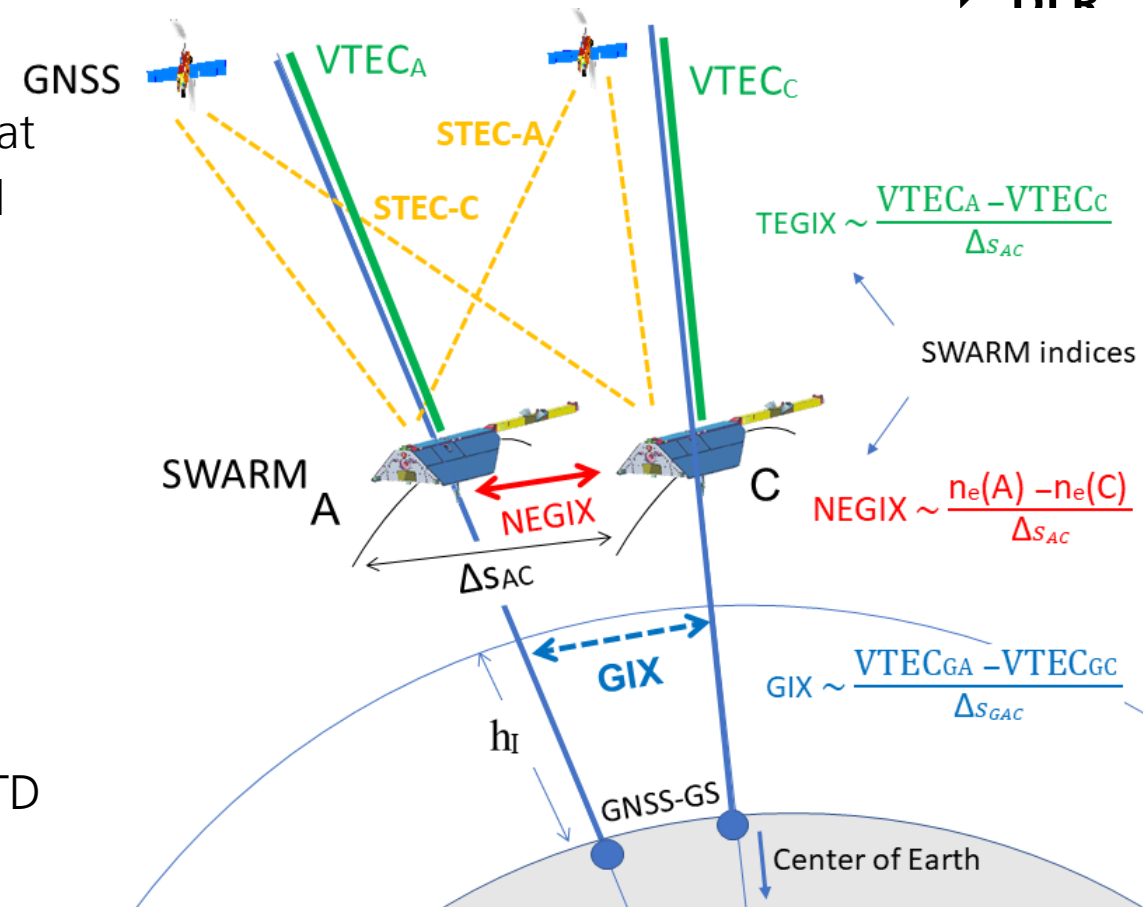


**Definition:** Mean value of TEC gradients (TEGIX), and corresponding standard deviation (STD) and 95 percentile that characterize the overall topside TEC structure over a selected area ( $0.5^\circ$  latitude bin) above the Swarm orbit ( $\sim 660$  km).

**Input:** Vertical Total Electron Content (VTEC) obtained from POD data of Swarm -A and Swarm-C satellites (Level-2 data TECATMS\_2F, 1 Hz data).

## Output:

- TEGIX\_Total, TEGIX\_X, TEGIX\_Y (mean TEC gradients, west-east, north-south comp.)
- TEGIX\_Total\_Sigma, TEGIX\_X\_Sigma, TEGIX\_Y\_Sigma (STD of TEC gradients)
- TEGIX\_Total\_P95, TEGIX\_X\_P95, TEGIX\_Y\_P95 (95 percentile of TEC gradients)



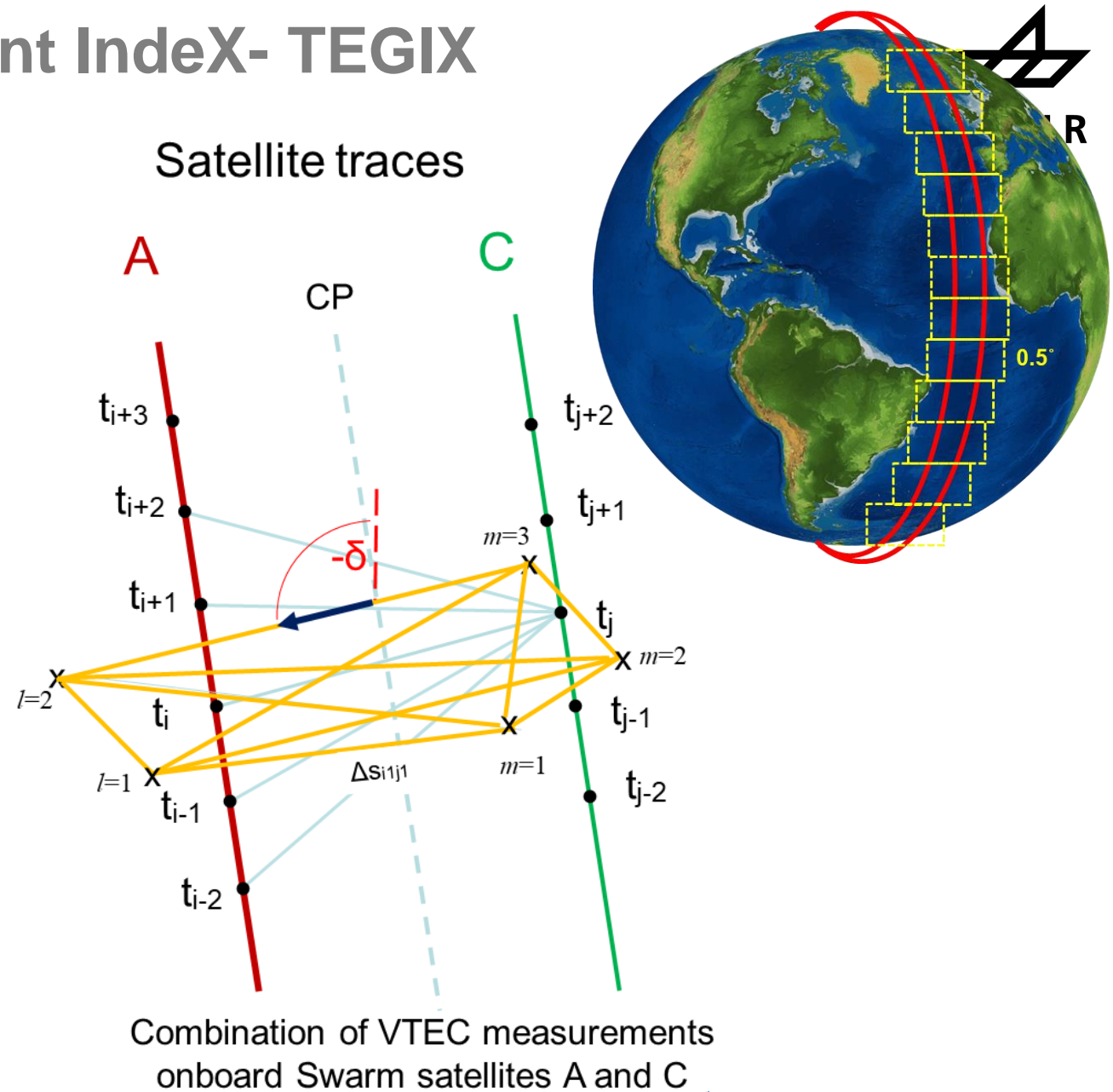
# Total Electron Content Gradient Index- TEGIX

**Definition:** Mean value of TEC gradients (TEGIX), and corresponding standard deviation (STD) and 95 percentile that characterize the overall topside TEC structure over a selected area ( $0.5^\circ$  latitude bin) above the Swarm orbit ( $\sim 660$  km).

**Input:** Vertical Total Electron Content (VTEC) obtained from POD data of Swarm -A and Swarm-C satellites (Level-2 data TECATMS\_2F, 1 Hz data).

**Output:**

- TEGIX\_Total, TEGIX\_X, TEGIX\_Y (mean TEC gradients, west-east, north-south comp.)
- TEGIX\_Total\_Sigma, TEGIX\_X\_Sigma, TEGIX\_Y\_Sigma (STD of TEC gradients)
- TEGIX\_Total\_P95, TEGIX\_X\_P95, TEGIX\_Y\_P95 (95 percentile of TEC gradients)



# Electron density Ne Gradient Index- NeGIX

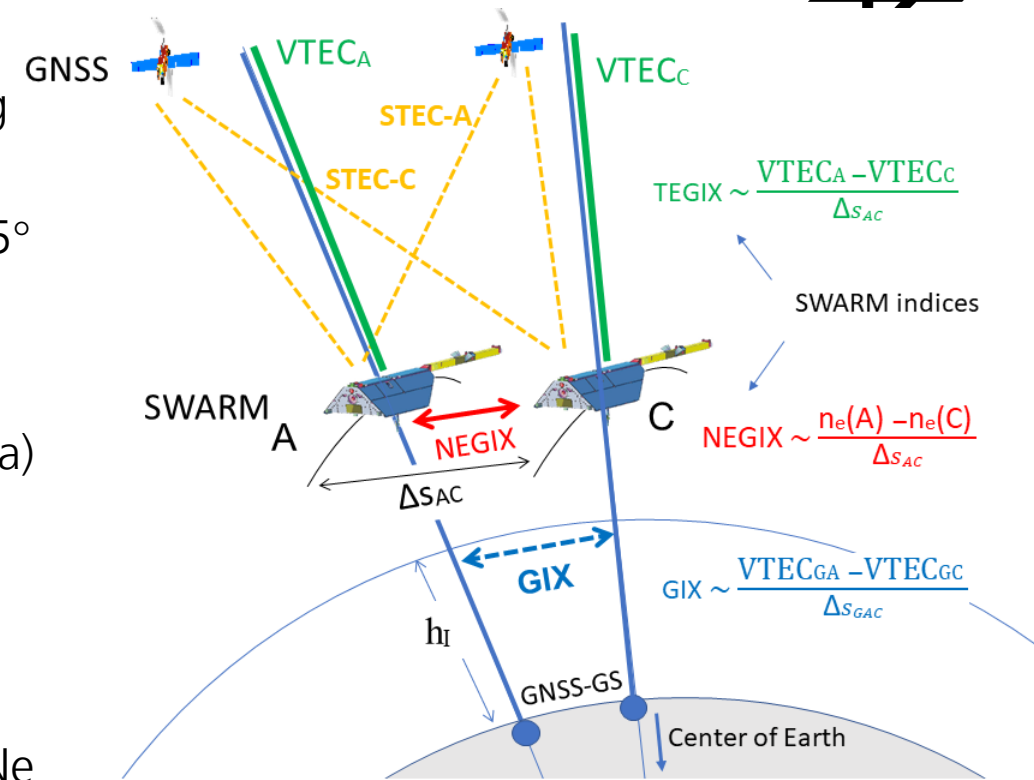


**Definition:** Mean value of Ne gradients (NeGIX), and corresponding standard deviation (STD) and 95 percentile that characterize the electron density structure of the ionosphere over a selected area (0.5° latitude bin) along the Swarm orbit (~460 km).

**Input:** in-situ electron density data from Langmuir probes onboard Swarm A and Swarm C satellites (Level-1 data EFIA\_LP\_1B, 2 Hz data)

**Output:**

- NeGIX\_Total, NeGIX\_X, NeGIX\_Y (mean Ne gradients, west-east, north-south comp.)
- NeGIX\_Total\_Sigma, NeGIX\_X\_Sigma, NeGIX\_Y\_Sigma (STD of Ne gradients)
- NeGIX\_Total\_P95, NeGIX\_X\_P95, NeGIX\_Y\_P95 (95 percentile of Ne gradients)



$$\nabla Ne_{AC} = \frac{(Ne_A - Ne_C)}{\Delta S_{AC}}$$

$$\langle \nabla Nex \rangle = \frac{1}{N_D^{AC}} \sum_{k=1}^{N_D^{AC}} \nabla Nex_k^{AC} \quad \langle \nabla Ney \rangle = \frac{1}{N_D^{AC}} \sum_{k=1}^{N_D^{AC}} \nabla Ney_k^{AC}$$

$$NeGIX_{Total} = \langle \nabla Ne \rangle = \sqrt{\langle \nabla Nex \rangle^2 + \langle \nabla Ney \rangle^2}$$

# Electron density Ne Gradient Index- NeGIX

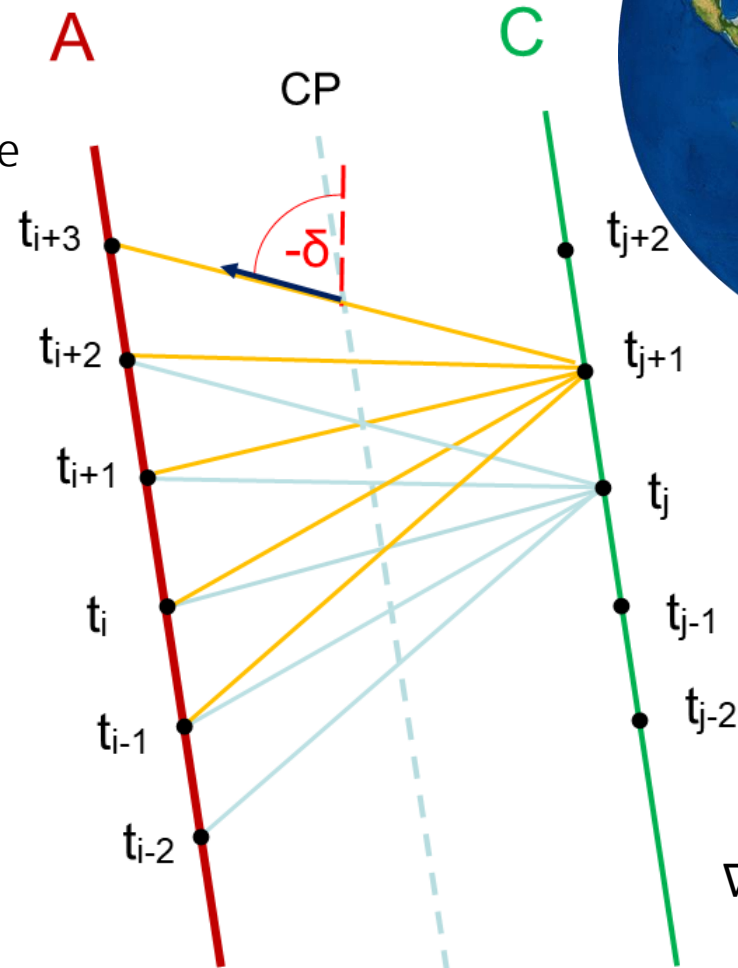
**Definition:** Mean value of Ne gradients (NeGIX), and corresponding standard deviation (STD) and 95 percentile that characterize the electron density structure of the ionosphere over a selected area (0.5° latitude bin) along the Swarm orbit (~460 km).

**Input:** in-situ electron density data from Langmuir probes onboard Swarm A and Swarm C satellites (Level-1 data EFIA\_LP\_1B, 2 Hz data)

**Output:**

- NeGIX\_Total, NeGIX\_X, NeGIX\_Y (mean Ne gradients, west-east, north-south comp.)
- NeGIX\_Total\_Sigma, NeGIX\_X\_Sigma, NeGIX\_Y\_Sigma (STD of Ne gradients)
- NeGIX\_Total\_P95, NeGIX\_X\_P95, NeGIX\_Y\_P95 (95 percentile of Ne gradients)

## Satellite traces

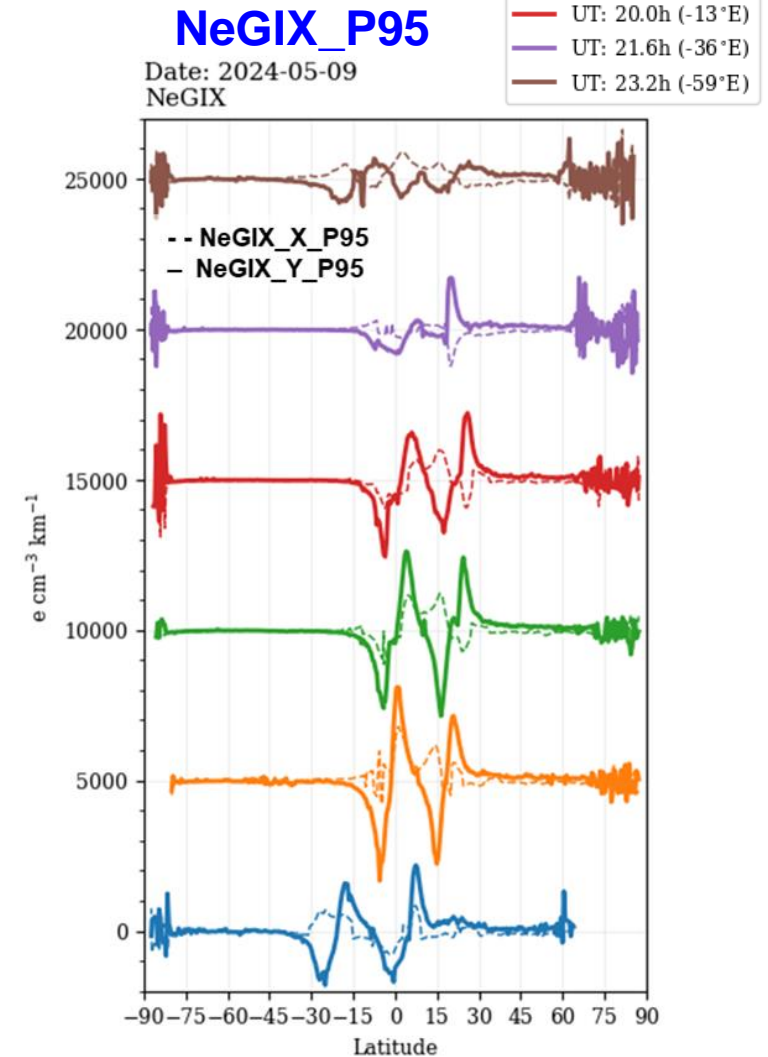
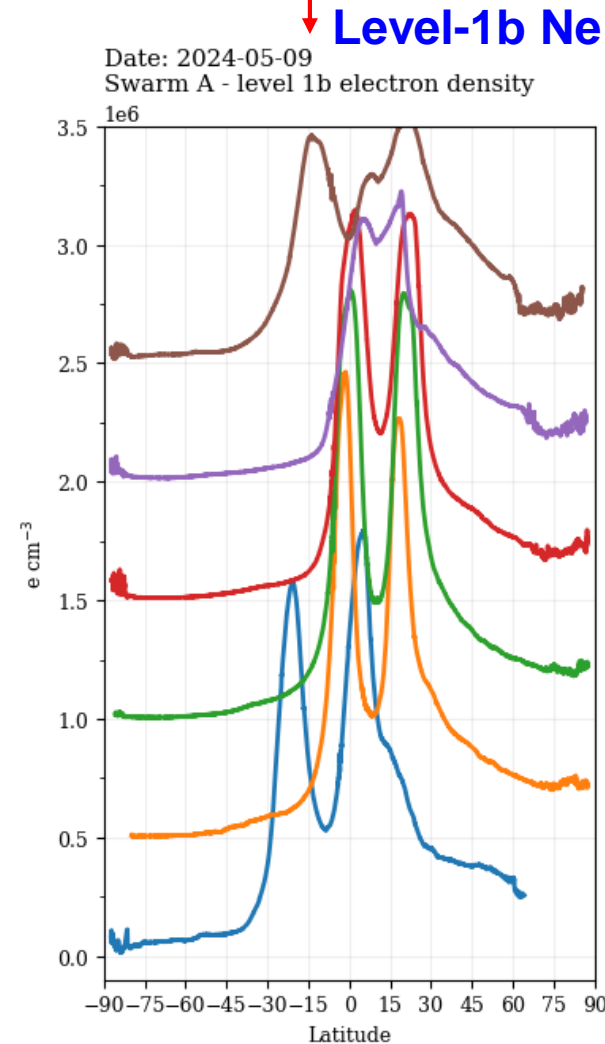
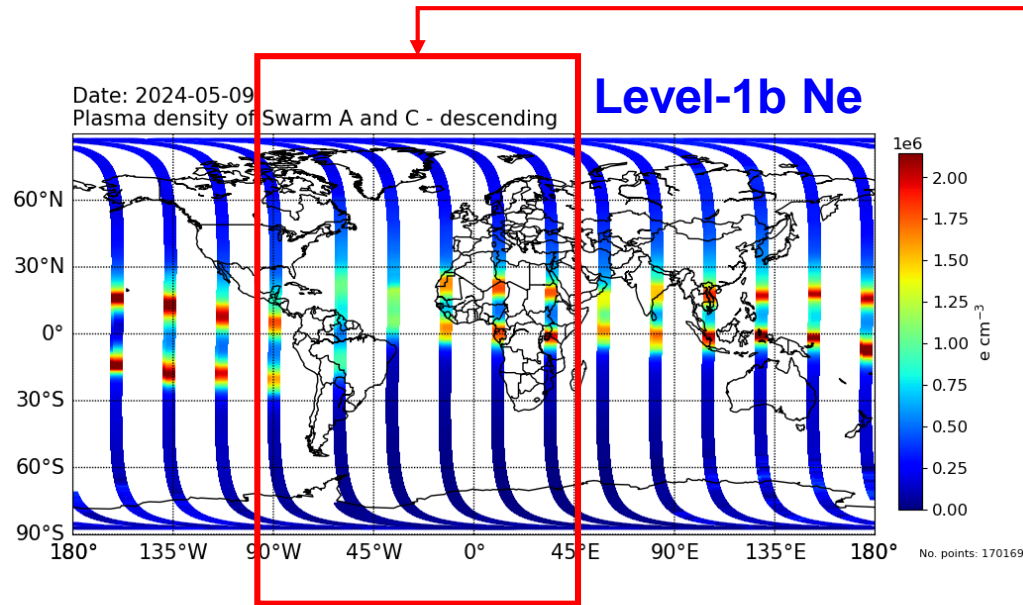


$$\nabla Ne_{AC} = \frac{(Ne_A - Ne_C)}{\Delta s_{AC}}$$

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

# NeGIX during quiet geomagnetic conditions

May 9<sup>th</sup>, 2024 (eq. pass at 19.3h LT)



- For the quiet day of May 9<sup>th</sup>, 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)



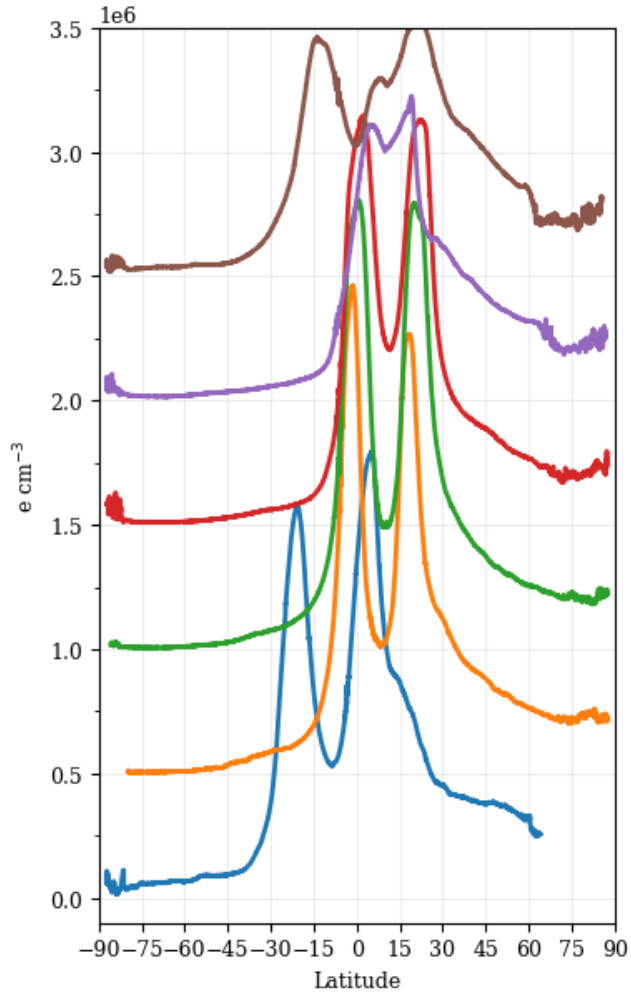
# NeGIX during quiet geomagnetic conditions



May 9<sup>th</sup>, 2024 (eq. pass at 19.3h LT)

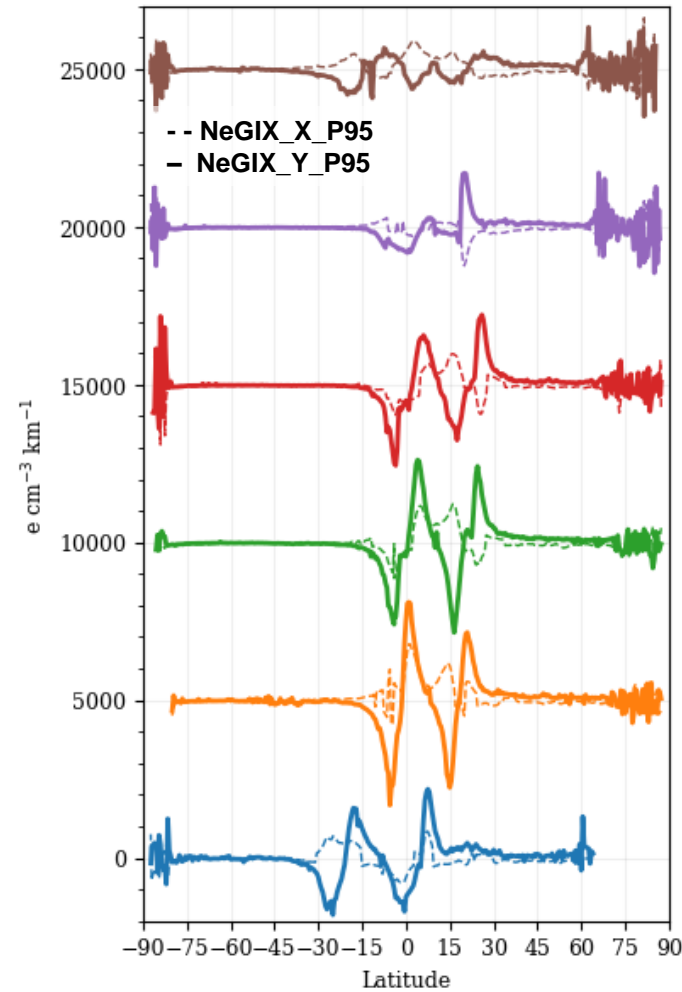
## Level-1b Ne

Date: 2024-05-09  
Swarm A - level 1b electron density



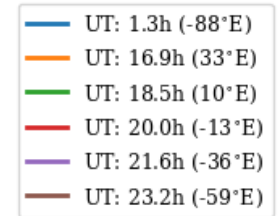
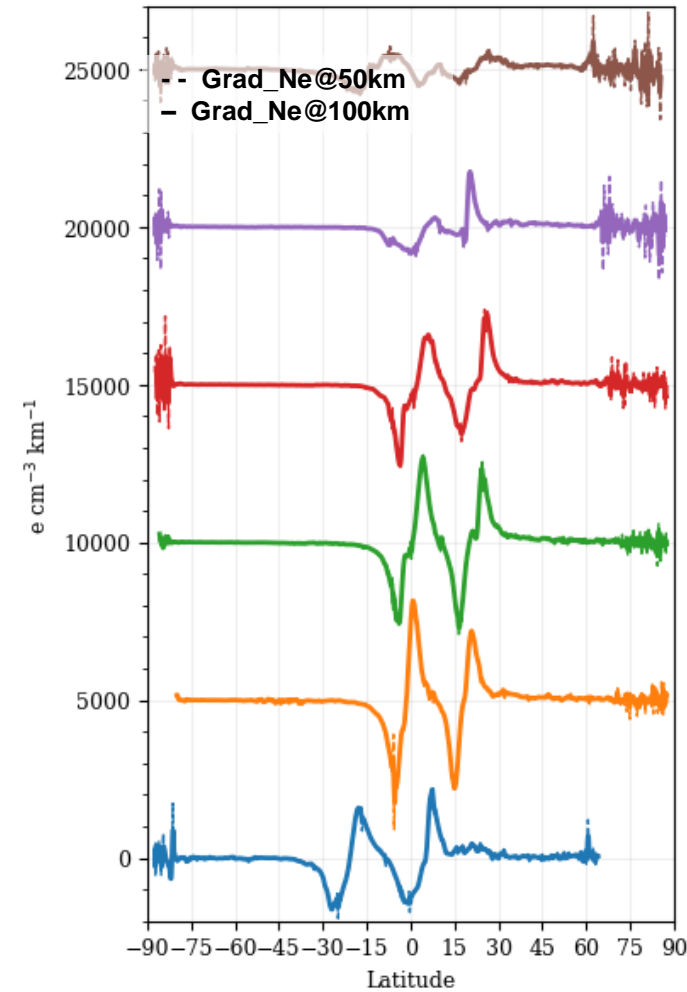
## NeGIX\_P95

Date: 2024-05-09  
NeGIX



## Level-2 IPIR

Date: 2024-05-09  
Swarm A - level 2 IPIR

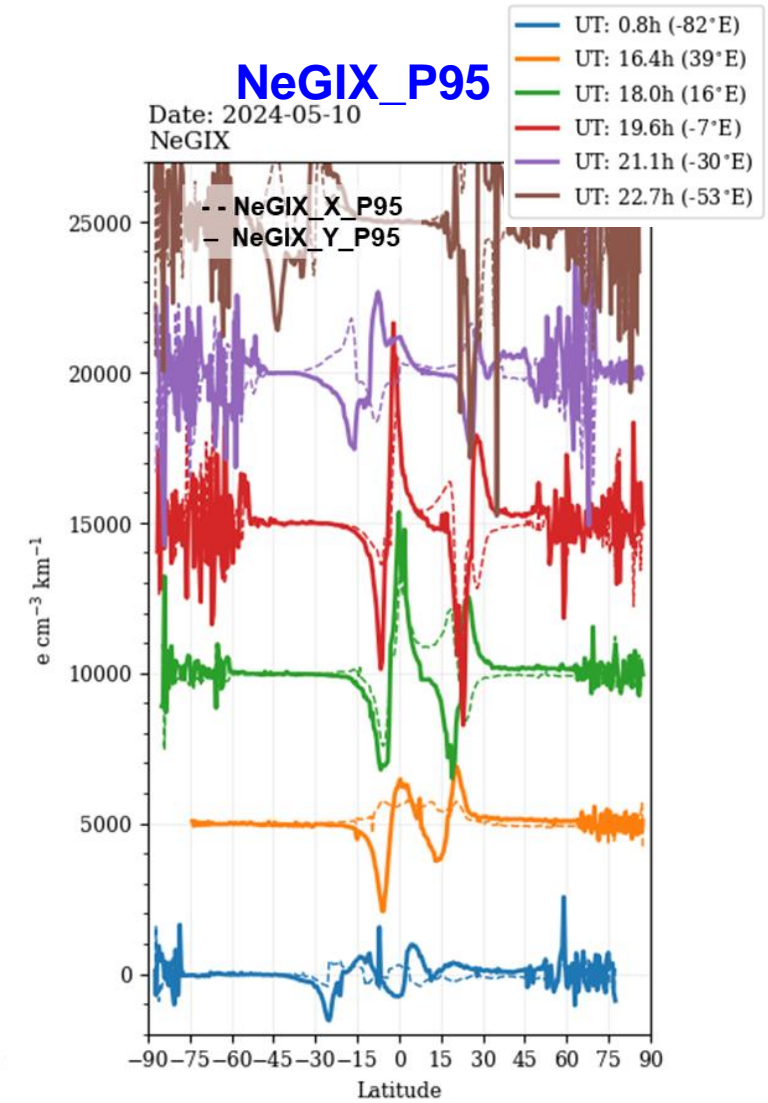
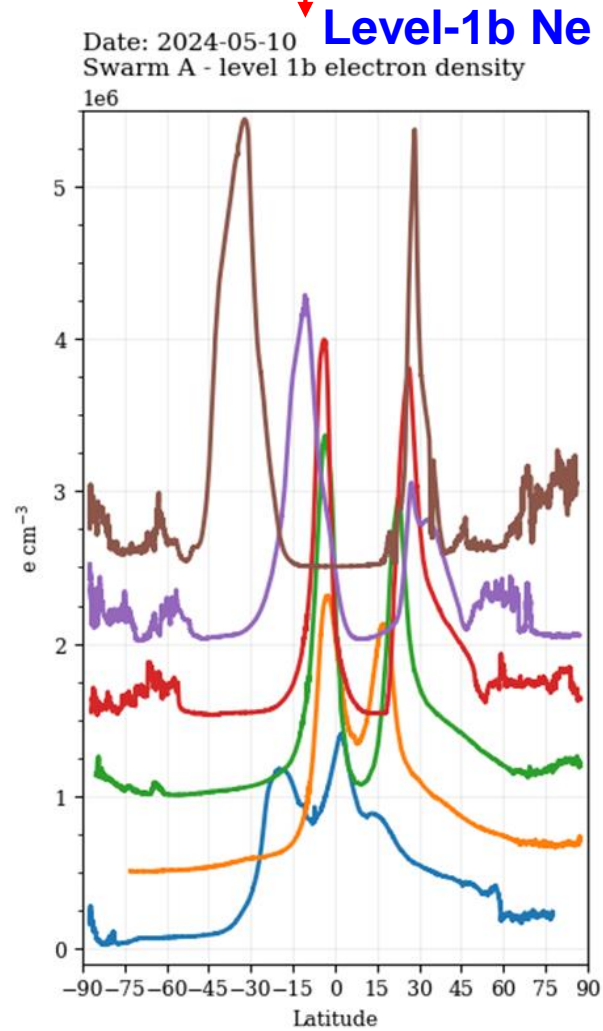
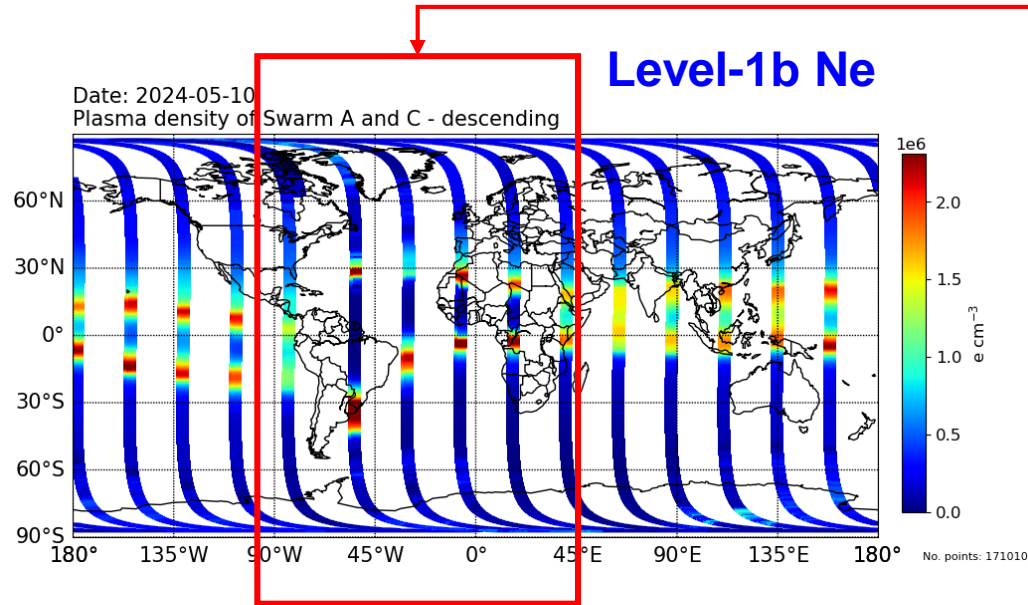


- NeGIX\_Y\_P95 shows similar structure as the gradients of the plasma density fluctuations product IPIR
- NeGIX\_X\_P95 provides additional information in the West-East direction for the characterization of structures from small to mid-scales

# NeGIX during perturbed geomagnetic conditions

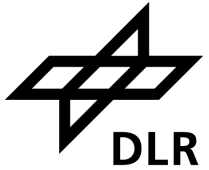


May 10<sup>th</sup>, 2024 (eq. pass at 19.2h LT)



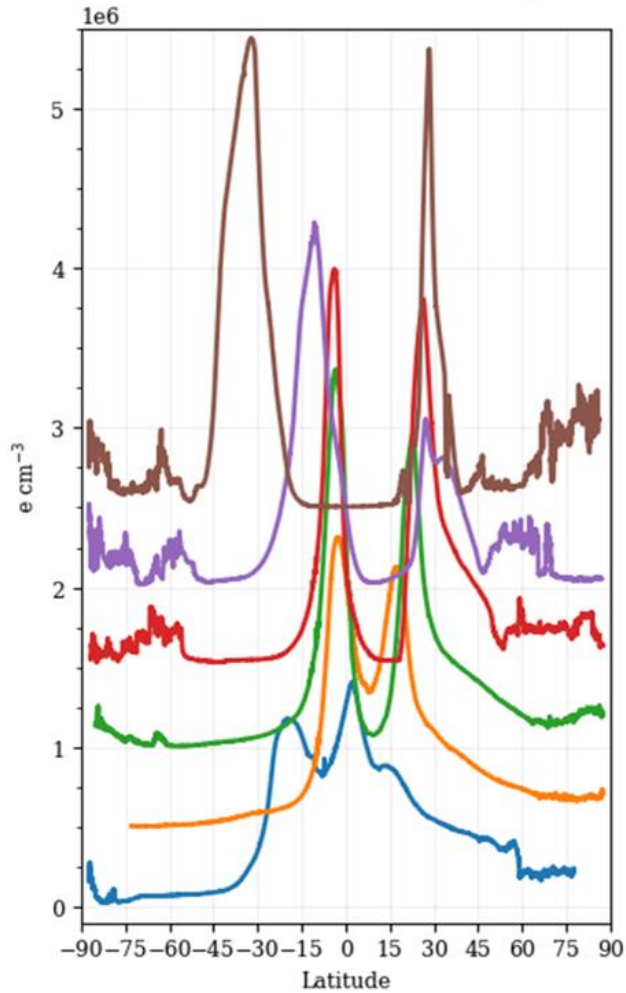
- For the perturbed day of May 10<sup>th</sup>, 2024 (eq. pass at 19.2h LT), NeGIX characterizes the double equatorial structure observed with the Langmuir probe in-situ data as a double positive-negative feature
- In addition to the meridional features, also strong peaks in the zonal component (NeGIX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

# NeGIX during perturbed conditions



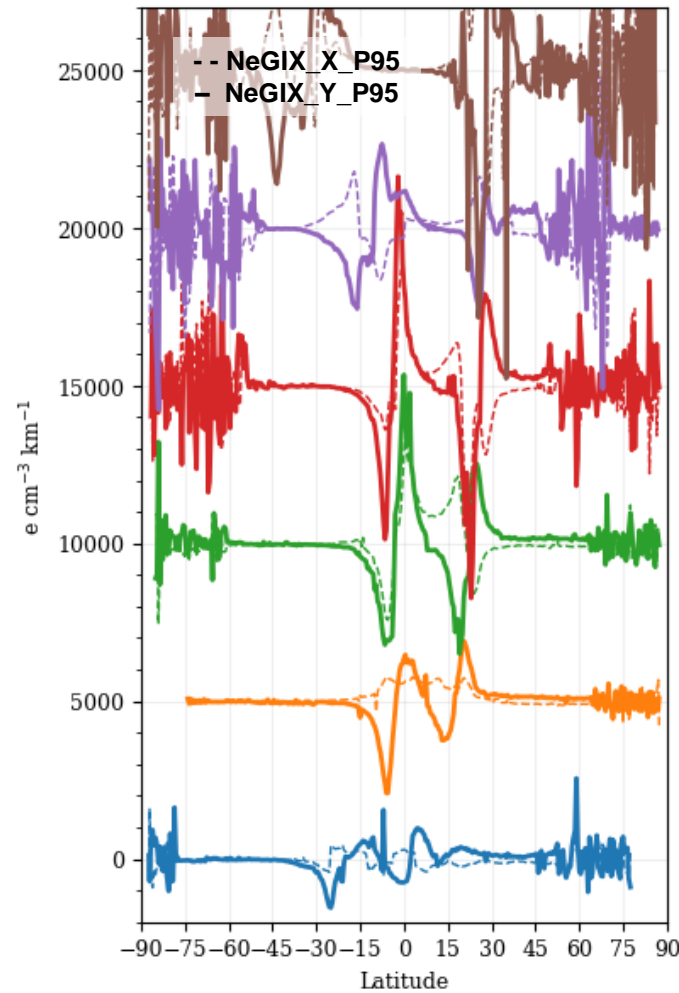
## Level-1b Ne

Date: 2024-05-10  
Swarm A - level 1b electron density



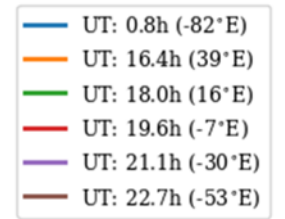
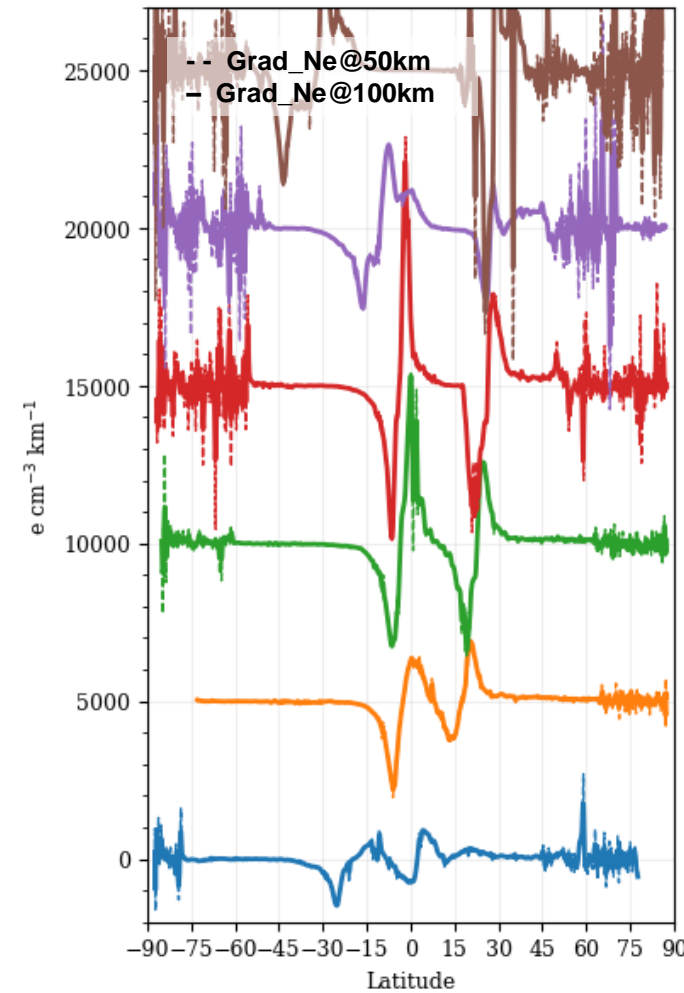
## NeGIX\_P95

Date: 2024-05-10  
NeGIX



## Level-2 IPIR

Date: 2024-05-10  
Swarm A - level 2 IPIR



- NeGIX\_Y\_P95 shows similar structure as the gradients of the plasma density fluctuations product IPIR
- NeGIX\_X\_P95 provides additional information in the West-East direction for the characterization of structures from small to mid-scales

# NeGIX during quiet and perturbed conditions



NeGIX\_X\_P95

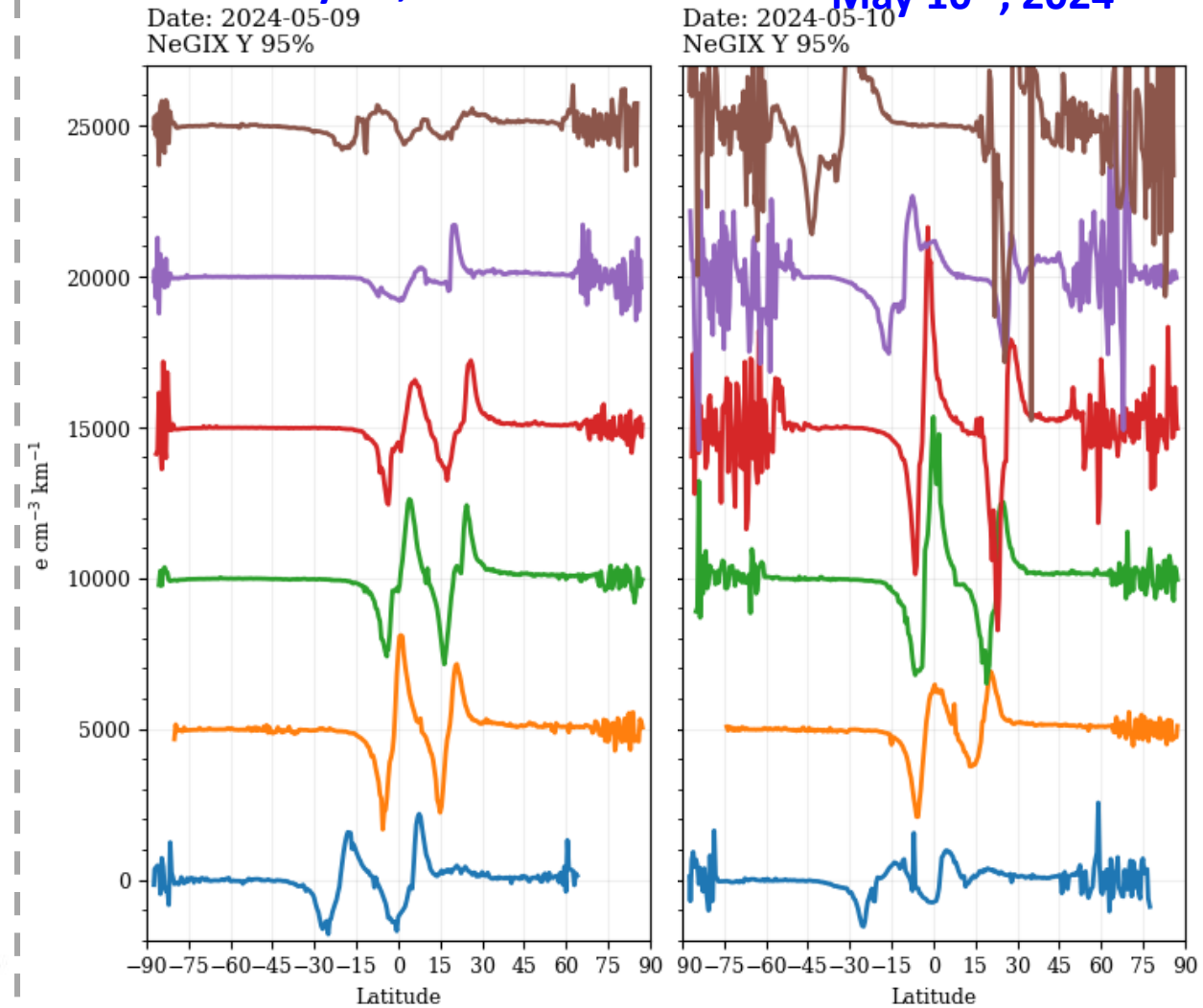
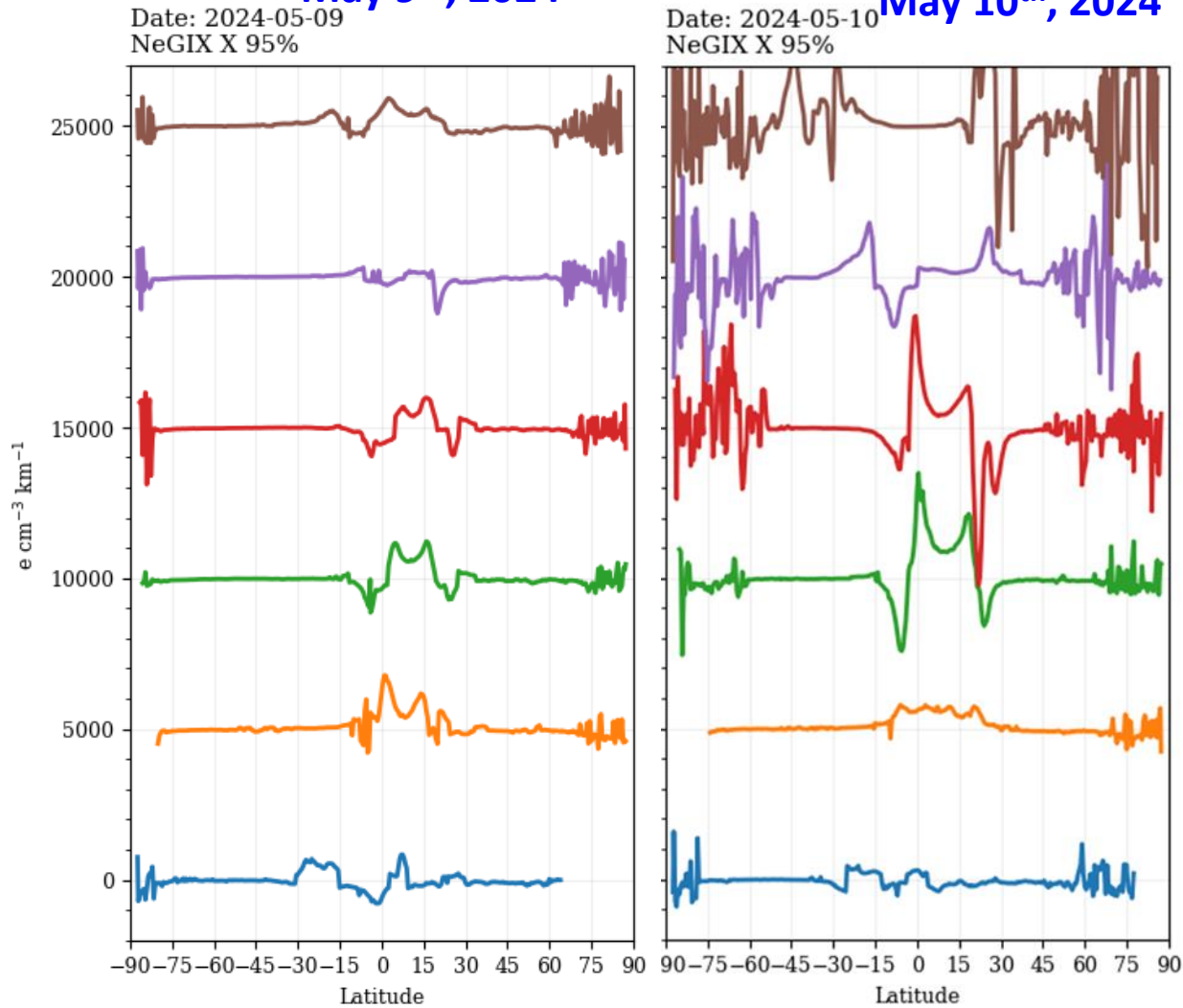
NeGIX\_Y\_P95

May 9<sup>th</sup>, 2024

May 10<sup>th</sup>, 2024

May 9<sup>th</sup>, 2024

May 10<sup>th</sup>, 2024



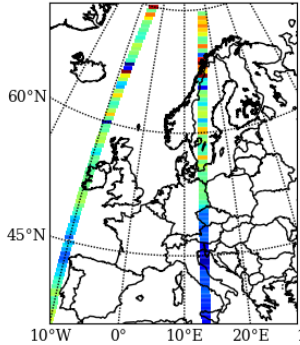
# Comparison of NeGIX and TEGIX with ground-based index GIX over Europe



St. Patrick's Day storm on March 17<sup>th</sup>, 2015 (Swarm eq. pass at 19.8h LT)

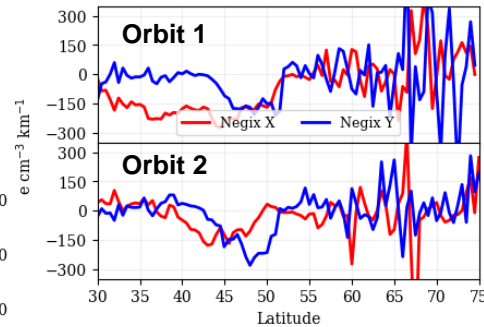
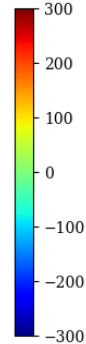
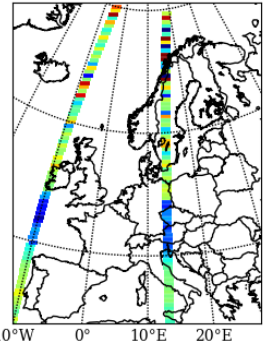
**NeGIX\_X**

Date: 2015-03-17  
Eastward gradient



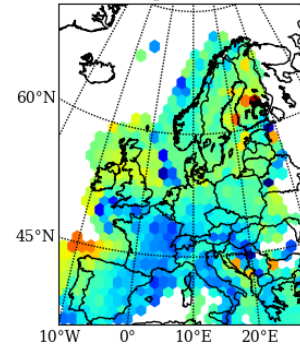
**NeGIX\_Y**

Northward gradient



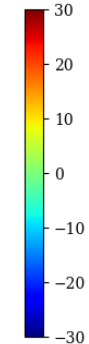
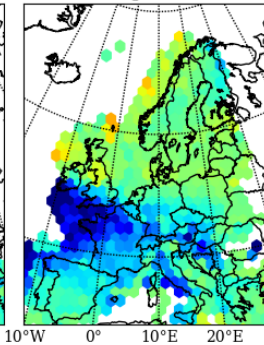
**GIX\_X**

Date: 2015-03-17  
Eastward gradient

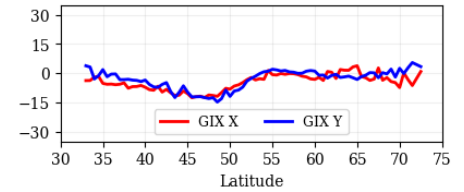


**GIX\_Y**

Northward gradient

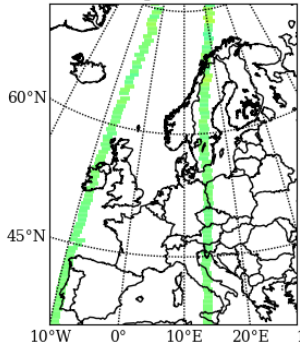


Swarm orbit 1 at UT 19h



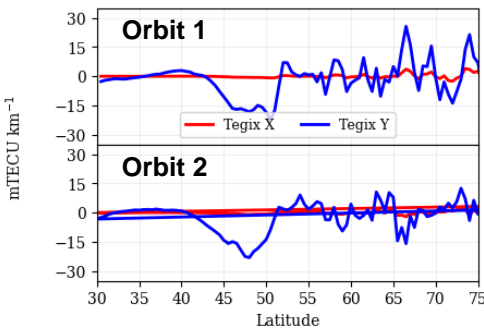
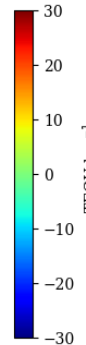
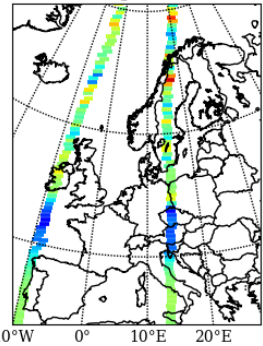
**TEGIX\_X**

Date: 2015-03-17  
Eastward gradient



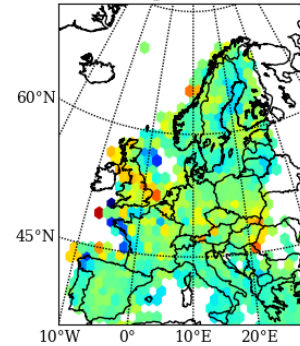
**TEGIX\_Y**

Northward gradient



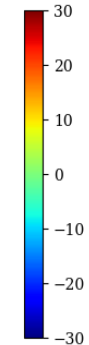
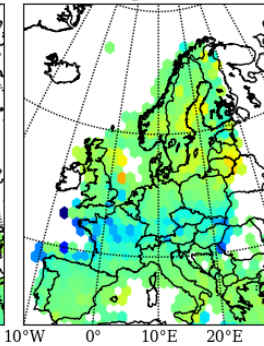
**GIX\_X**

Date: 2015-03-17  
Eastward gradient

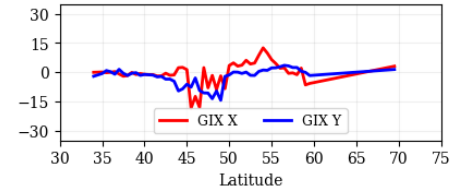


**GIX\_Y**

Northward gradient



Swarm orbit 2 at UT 20.5h

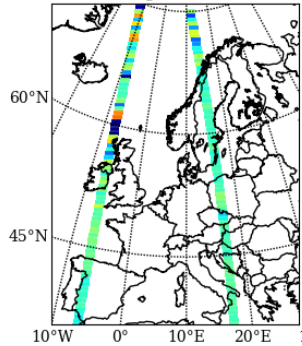


# Comparison of NeGIX and TEGIX with ground-based index GIX over Europe

Mother's Day storm on May 10<sup>th</sup>, 2024 (Swarm eq. pass at 19.2h LT)

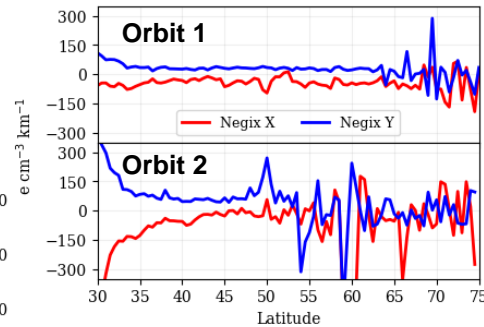
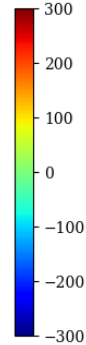
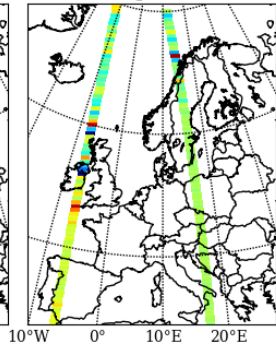
## NeGIX\_X

Date: 2024-05-10  
Eastward gradient



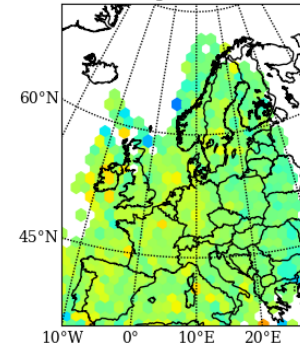
## NeGIX\_Y

Northward gradient



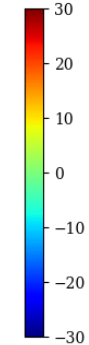
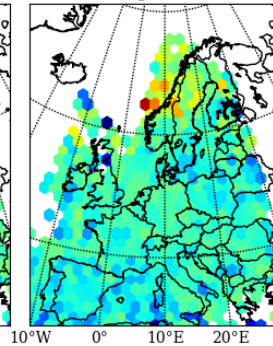
## GIX\_X

Date: 2024-05-10  
Eastward gradient

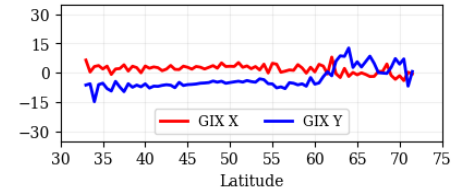


## GIX\_Y

Northward gradient

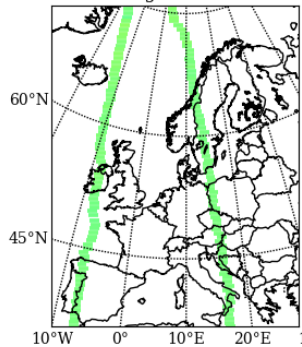


Swarm orbit 1 at UT 17.8h



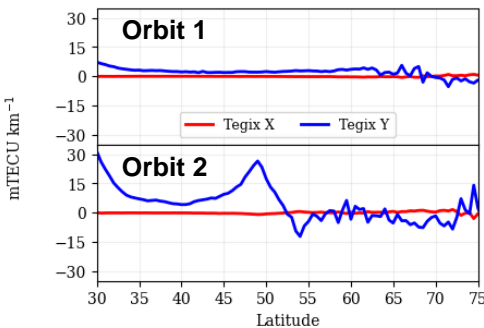
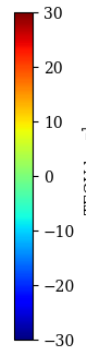
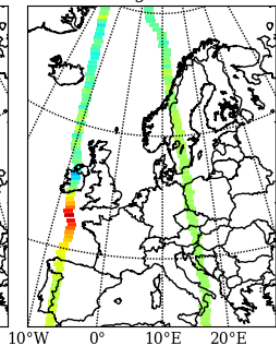
## TEGIX\_X

Date: 2024-05-10  
Eastward gradient



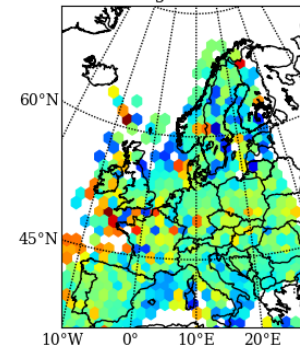
## TEGIX\_Y

Northward gradient



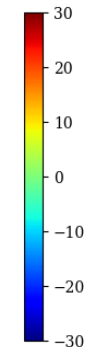
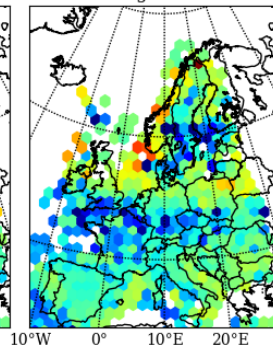
## GIX\_X

Date: 2024-05-10  
Eastward gradient

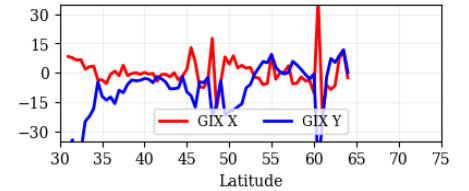


## GIX\_Y

Northward gradient



Swarm orbit 2 at UT 19.3h

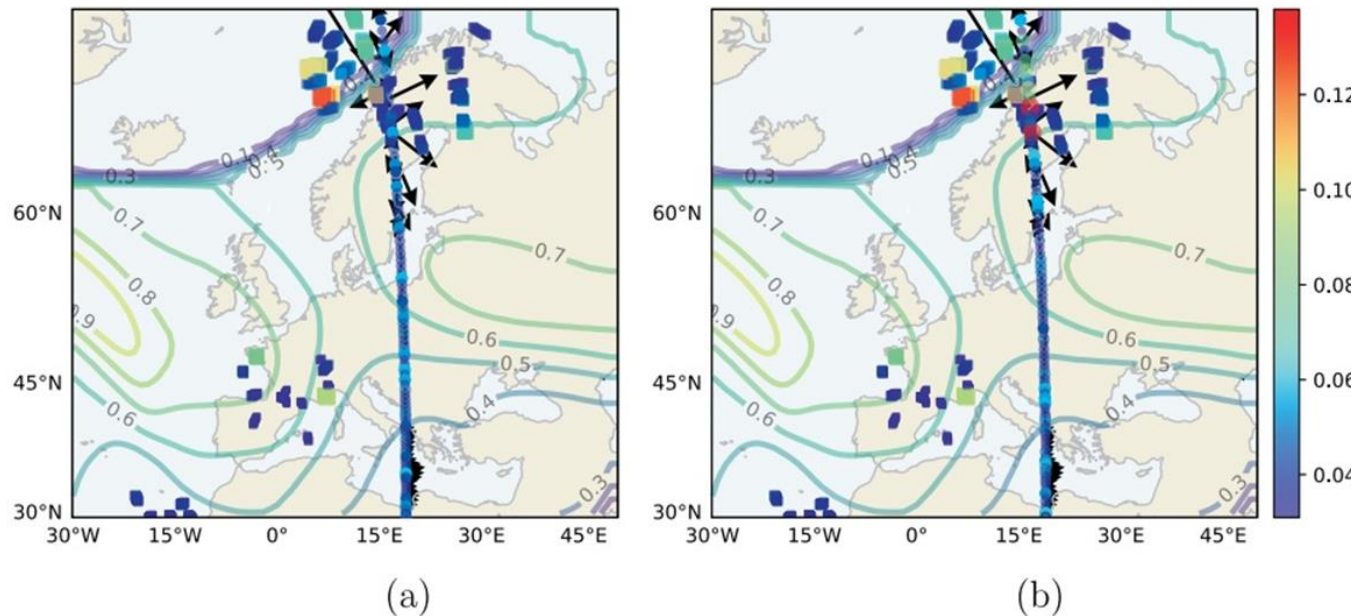


# Applications of NeGIX products

[Scintillation modeling with random phase gradient screens](#)  
([swsc-journal.org](#)) accepted, in press

Date: 2023-04-23 Day Number: 113  
Time: 03:55:00[UTC] Sampling Time:270[sec]

submitted to *Journal of Space Weather and Space Climate*  
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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).

## Scintillation modeling with random phase gradient screens

D. Vasylyev<sup>1,\*</sup>, J. A. Cahuasqui<sup>1</sup>, M. Hoque<sup>1</sup>, N. Jakowski<sup>1</sup>, M. Krieger<sup>1</sup>,  
P. David<sup>1</sup>, Y. Tagargoust<sup>1</sup>, S. C. Buchert<sup>2</sup>, and J. Berdermann<sup>1</sup>

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### ABSTRACT

Multiple studies of scintillation phenomena have shown that, in certain situations, the intense phase fluctuations of trans-ionospheric radio signals are associated with the scattering on strong electron density gradients. The present study provides a theoretical framework for modeling such type of phase fluctuation events. Using the geometrical-optics approximation and retaining the second-order smallness correction in the expansion of the eikonal function, we relate the phase of the transmitted wave not only to the total electron content (TEC) of the ionosphere but also to the spatial gradient of the TEC. The considered correction term is related to the random refraction of signal rays on large-scale ionospheric structures, an effect, that becomes significant in the presence of strong electron density gradients. To conveniently simulate the wave propagation under such conditions, we propose the random phase gradient screen algorithm. For this purpose, we use the novel spatial electron density gradient product (NeGIX) based on in-situ observations of the Swarm Langmuir probe and ground-based TEC and TEC gradient observations. To illustrate the performance of the algorithm, we apply it to simulate a scintillation event over Europe and in the low-latitude region and compare the simulation results with scintillation indices measured

# Summary

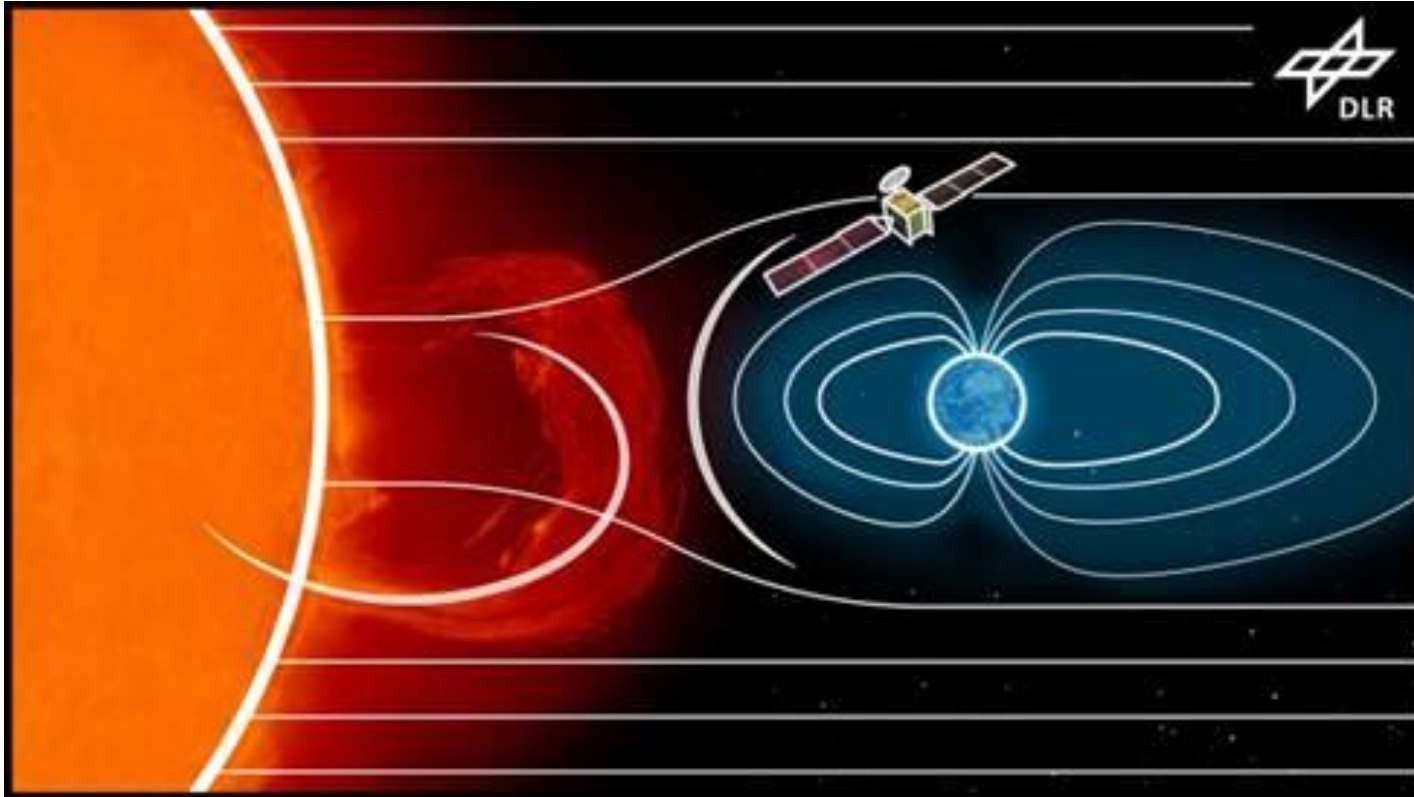


- Two new products namely TEGIX (Spatial TEC gradients Product) and NeGIX (Spatial Ne gradients Product) are developed based on Swarm GPS and Langmuir probe observations, respectively.
- Investigation shows that TEGIX and NeGIX correlate very well
- NeGIX and TEGIX correlate with ground based GIX during St. Patrick Day storm (17<sup>th</sup> March 2015) over Europe
- NeGIX and TEGIX correlate with ground based GIX during Mother's Day storm (9<sup>th</sup> -12<sup>th</sup> May 2024) over Europe
- Use of NeGIX for scintillation modelling shows promising results (utilizing phase gradient screen approach)

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# Thank you!



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