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DLR

Comparative analysis of ground- and space-based ionospheric indices for monitoring the perturbation degree of the ionosphere

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Image by Sara Lundström

Aim & Scope

- **Showcase how ionospheric indices — individually and in combination — characterize the ionosphere's state and dynamics**.
- **Emphasize the role of space-based missions and observations** as essential complements to ground-based monitoring.
- **Promote and communicate the practical value of DLR's ionospheric indices** for both scientific and operational applications.

Images by Dmytro Vasylyev

1. Ionospheric Indices

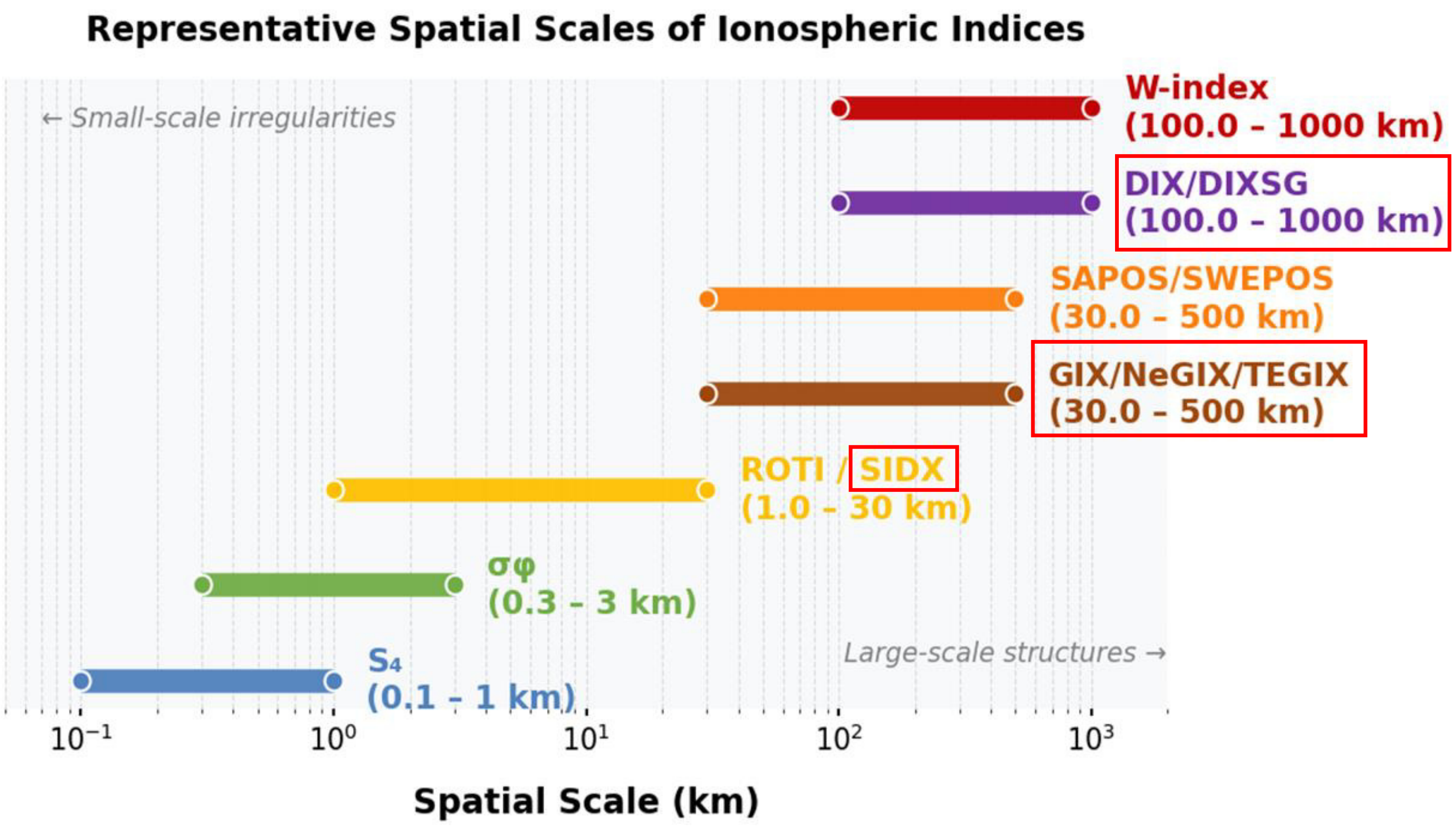
Examples of ionospheric indices capturing processes at different spatial and temporal scales.

Index	Primary sensitivity	Typical spatial / temporal scale	Dominant process or physical meaning
S_4 (Amplitude scintillation index)	Sub-km plasma irregularities	~0.1–1 km	Measures power fluctuations in received GNSS signal amplitude caused by diffraction from small-scale electron-density irregularities. [1]
σφ (Phase scintillation index)	Small- to intermediate-scale irregularities	~0.3–3 km	RMS variation of GNSS carrier phase; sensitive to rapid phase path changes caused by small-scale plasma structures. [2]
ROTI (Rate Of TEC Index)	Mesoscale TEC irregularities / TIDs	~1–30 km along signal path	Quantifies short-term fluctuations in TEC, tracing travelling ionospheric disturbances and plasma irregularities. [3]
SIDX (Sudden Ionospheric Disturbance indeX)	Rapid, flare-induced increase in ionization in the sunlit ionosphere (mainly D/F region)	~1 s–1 h along signal path	Derived from near-real-time GNSS TEC measurements to quantify sudden ionization enhancements caused by solar X-ray and EUV flares. [4]
GIX / NeGIX / TEGIX (space-based) (Gradient Ionospheric indeX)	Regional GNSS-network gradients	~30–500 km	Characterize horizontal TEC gradients and their variability across ground networks, useful for regional disturbance monitoring. [4]
SAPOS / SWEPOS (national warning indices)	Local / regional deviations in the positioning domain	~30-500 km	Easy-to-understand warning systems developed for navigation/positioning applications.
DIX / DIXSG (Disturbance Ionospheric Index)	Regional to continental TEC gradients	~100–1000 km	Quantifies the potential impact of ionospheric perturbation events on radio systems based on GNSS TEC measurements. [5]
W-index (foF2 deviation index)	Continental / global foF2 variability	~100–1000 km	Quantifies ionospheric storm level based on logarithmic deviation of logarithmic deviation of the F2 layer peak plasma density from quiet reference conditions. [6]

References: **1** Yeh & Liu (1982); Aarons (1997); van Dierendonck et al. (1993); **2** Kintner et al. (2007); van Dierendonck & Hua (2001); **3** Pi et al. (1997); Nishioka et al. (2012); **4, 5** Jakowski & Hoque (2019); Nykiel et al. (2024); Cahuasquí et al. (2025); **5** Wilken et al. (2018); **6** Gulyaeva & Stanislawska (2008); Gulyaeva et al. (2013); Stanislawska & Gulyaeva (2015)

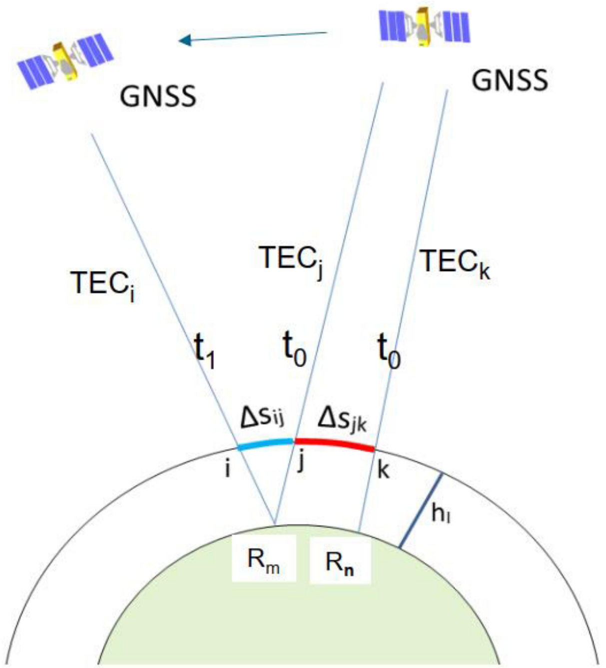
1. Ionospheric Indices

- **DLR** has developed and offers a set of horizontal ionospheric indices focusing **on medium-scale irregularities**.
- Two **new Swarm-based indices** have recently expanded this framework.
- **Together**, these indices complement each other and other existing indices, **enhancing their scientific and practical value**.
- **Ionospheric research, operational monitoring, modeling & forecasting** — especially during geomagnetically disturbed conditions — can **benefit** from combined analyses.



2. Ionospheric Indices at DLR

Scheme of gradient construction



Jakowski and Hoque (2019)

1. Gradient Ionosphere indeX (GIX)

GIX: ΔTEC/Δs – where Δs is the distance between piercing points per epoch

2. Sudden Ionosphere Disturbance indeX (SIDX)

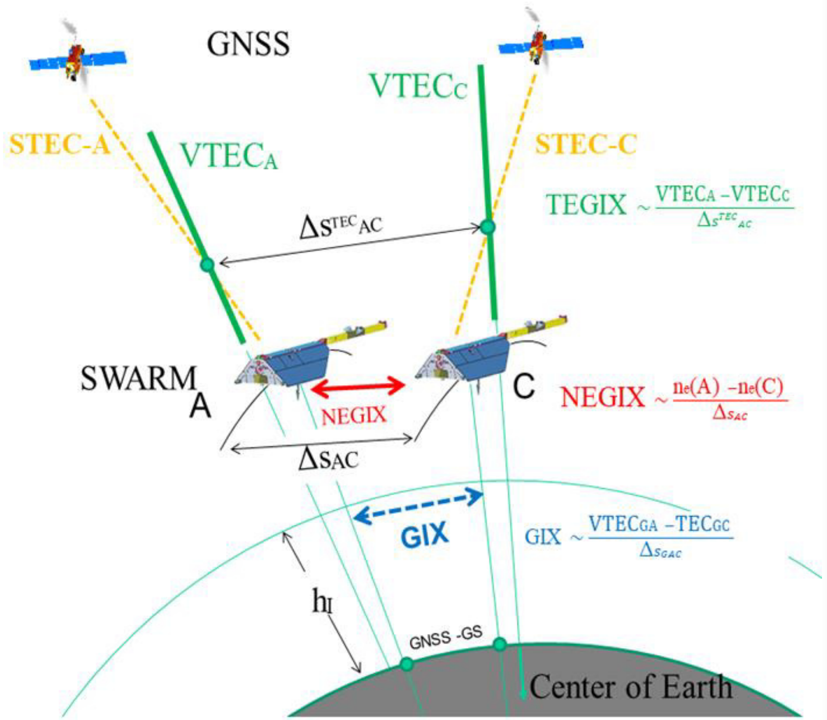
SIDX: ΔTEC/Δt – where $\Delta t = t_1 - t_0$ along the satellite tracks

- Complementary indices designed to separate **spatial and temporal ionospheric perturbations** using GNSS-derived TEC data.
- GNSS-based approach offers:
  - Dense data coverage over key regions
  - High temporal resolution
  - Flexible spatial/temporal scales adaptable to user or application needs
- **Fast computation and low-latency** product generation

- In GIX, the purpose is to **reconstruct the “real” ionospheric vector** out of the large data sample of measurements between IPPs.
- For a certain region, **statistical metrics** (e.g. mean, standard deviation, 95-percentile) for the total ionospheric vector and components **are determined**.
- For **GIX**, **better azimuthal coverage** than along-track approaches are an advantage.

2. Ionospheric Indices at DLR

Scheme of definition of NeGIX and TEGIX with respect to Swarm/GNSS satellites



Cahuasquí et al. (2025) – JSWSC Swarm 10-Year Topical Issue

1. Electron Density Gradient Ionospheric indeX (NeGIX)

NeGIX – derived from **in-situ Langmuir Probe** measurements from Swarm satellites A and C.

2. Total Electron Content Gradient Ionospheric indeX (TEGIX)

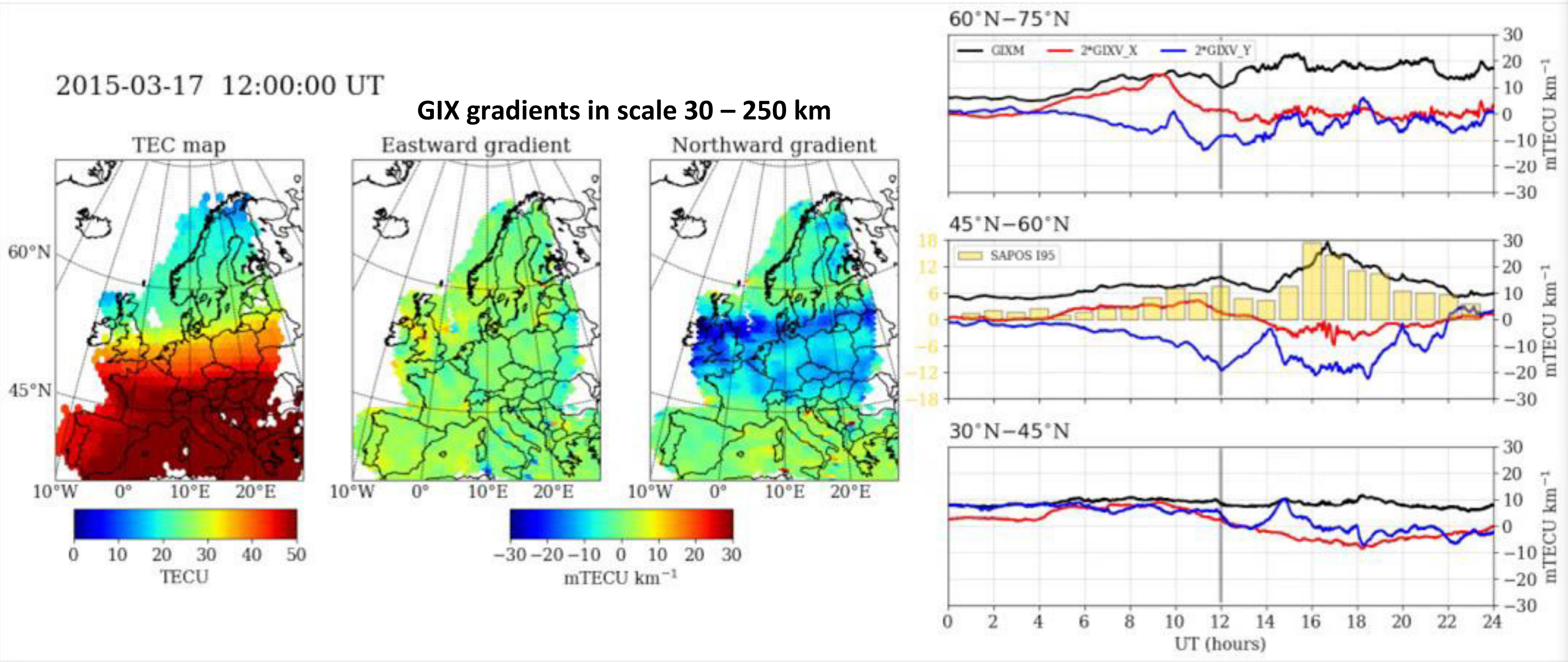
TEGIX – based on **GNSS Precise Orbit Determination (POD)** measurements from Swarm satellites A and C.

- Both indices exploit the near-polar, parallel orbits of Swarm satellites A and C to **provide horizontal gradients over scales of 30 – 200 km**.
- Data from the two spacecraft are combined with a **latitudinal resolution of 0.5°**, increasing robustness and statistical reliability.
- Unlike existing Swarm indices, **NeGIX and TEGIX** provide gradient information in **both meridional** (South–North) **and zonal** (West–East) **directions**.

- Publicly available Level 2 OPER products (TIX_TMS_2F & NIX_TMS_2F) **via Swarm Data Access / DLR-IMPC.**
- **4–5 day latency.**
- Time resolution ca. **8 seconds.**

3. Ionospheric Indices during perturbed conditions

Comparison GIX vs. SAPOS I95



St. Patrick's Day Storm
March 17, 2015

G4 severe geomagnetic storm with a Kp index of 8 and Dst of -223 nT. Storm main phase 16 – 22 UT.

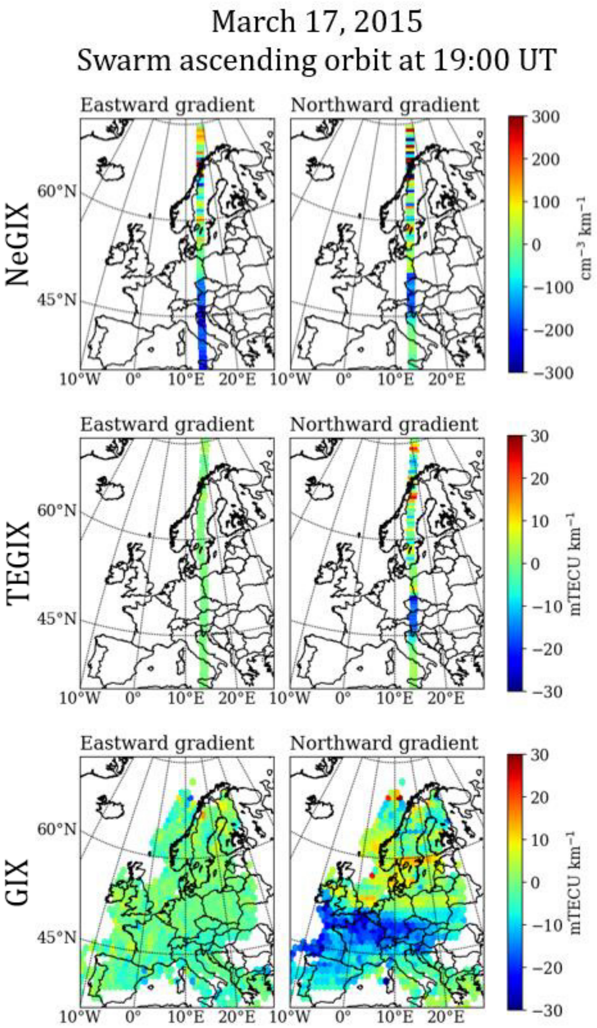
- **GIX ⟺ SAPOS I95**

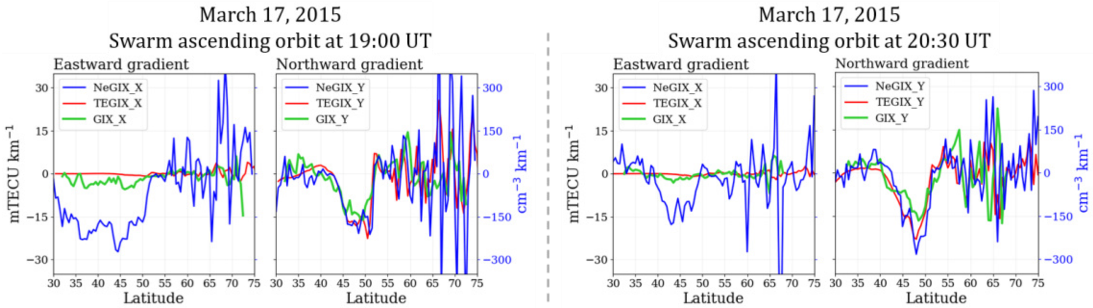
I95 – operational indicator of disturbed ionospheric conditions **impacting RTK/PPP accuracy** in the German GNSS network.

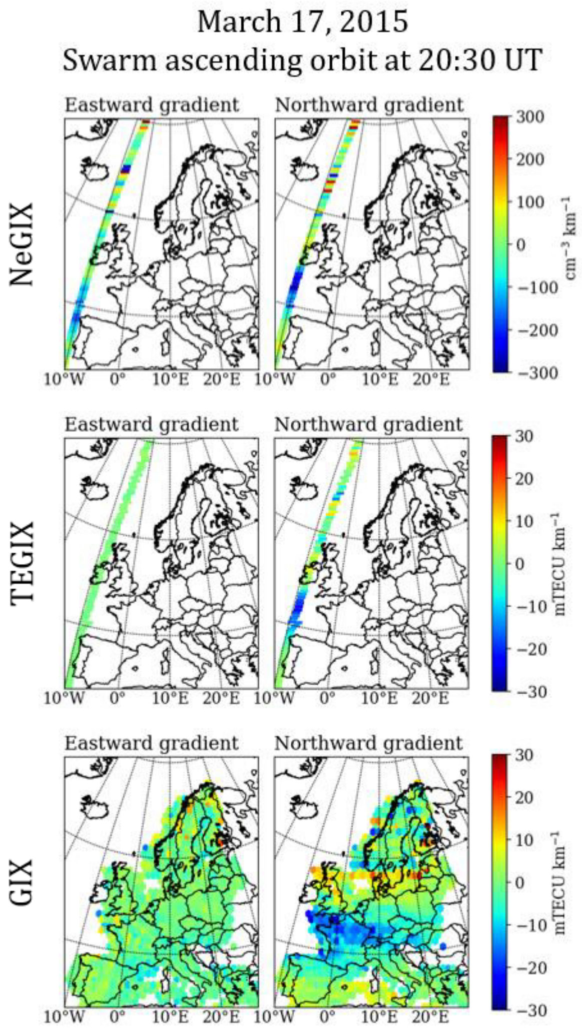
GIX and I95 show a great correlation – ionospheric disturbed conditions have direct impact on precise positioning and navigation applications

3. Ionospheric Indices during perturbed conditions

Comparison GIX vs. NeGIX vs. TEGIX







St. Patrick's Day Storm
March 17, 2015

G4 severe geomagnetic storm with a Kp index of 8 and Dst of -223 nT.
Storm main phase 16 – 22 UT.

- **GIX ⟺ NeGIX ⟺ TEGIX (spatial scales 30 – 200 km)**

Strong agreement is seen between the **ground- and space-based indices**, especially for the meridional component.

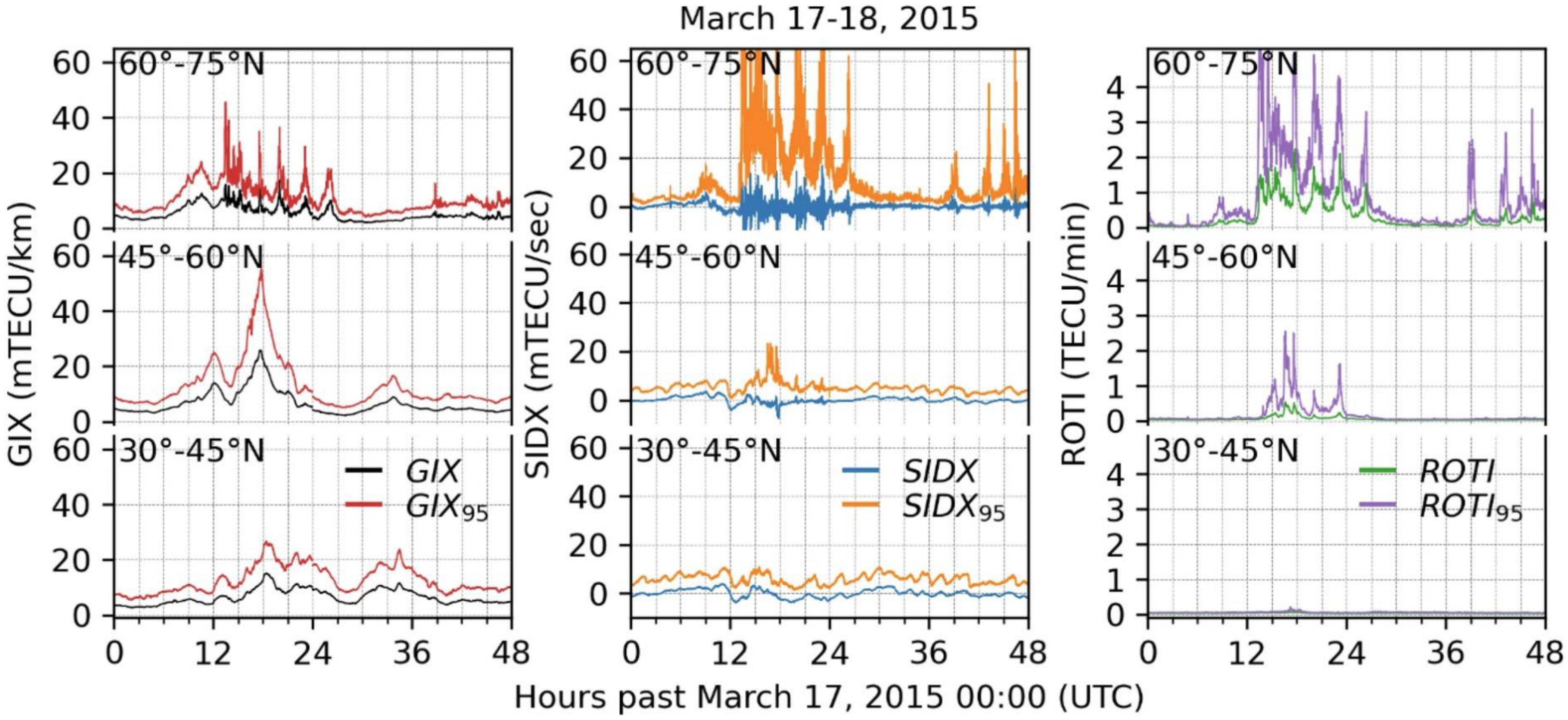
Differences may be due to their different **technical definition** and geometrical distribution of **measurements**.

A **combined/complimentary** use may provide insights into **altitude** dependencies and extend coverage over **oceans & remote regions**.

Cahuasquí et al. (2025) – JSWSC Swarm 10-Year Topical Issue

3. Ionospheric Indices during perturbed conditions

Comparison GIX vs. SIDX vs. ROTI



Nykiel et al. (2024)

St. Patrick's Day Storm
March 17, 2015

G4 severe geomagnetic storm with a Kp index of 8 and Dst of -223 nT. Storm main phase 16 – 22 UT.

- **GIX ⟺ SIDX ⟺ ROTI**

At high-latitudes – strong peaks, small-scale changes, particle precipitation.

At mid-latitudes – strong peak clearly demonstrating spatial gradients.

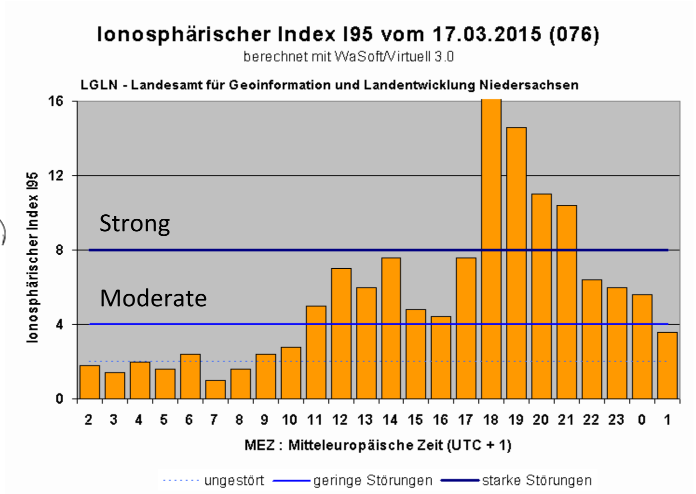
At low-latitudes – GIX has moderate gradients, while SIDX and ROTI show no significant variations.

3. Ionospheric Indices during perturbed conditions

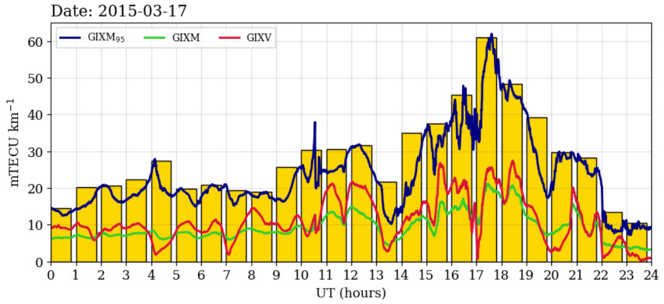
Comparison GIX vs. SAPOS I95 vs. SWEPOS Monitoring

DLR

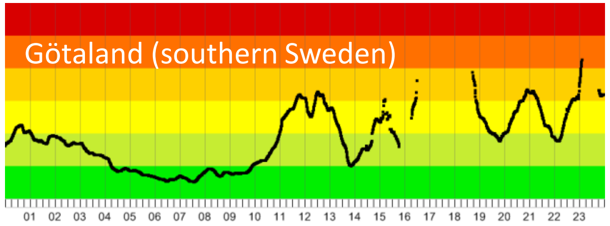
SAPOS®



GIX



SWEPOS



St. Patrick's Day Storm
March 17, 2015

G4 severe geomagnetic storm with a Kp index of 8 and Dst of -223 nT. Storm main phase 16 – 22 UT.

- ❑ **GIX ⟺ SAPOS I95 ⟺ SWEPOS Ionosphere Monitor**

GIX aligns well with existing indicators of disturbed GNSS conditions, such as the **German SAPOS** and **Swedish SWEPOS** networks.

It shows strong potential as a **regional proxy and early-warning indicator** of ionospheric disturbances.

Scaling and combined analyses will further enhance **interoperability** among different ionospheric indices.

3. Ionospheric Indices during perturbed conditions

Comparison GIX vs. ROTI – Mother's Day storm

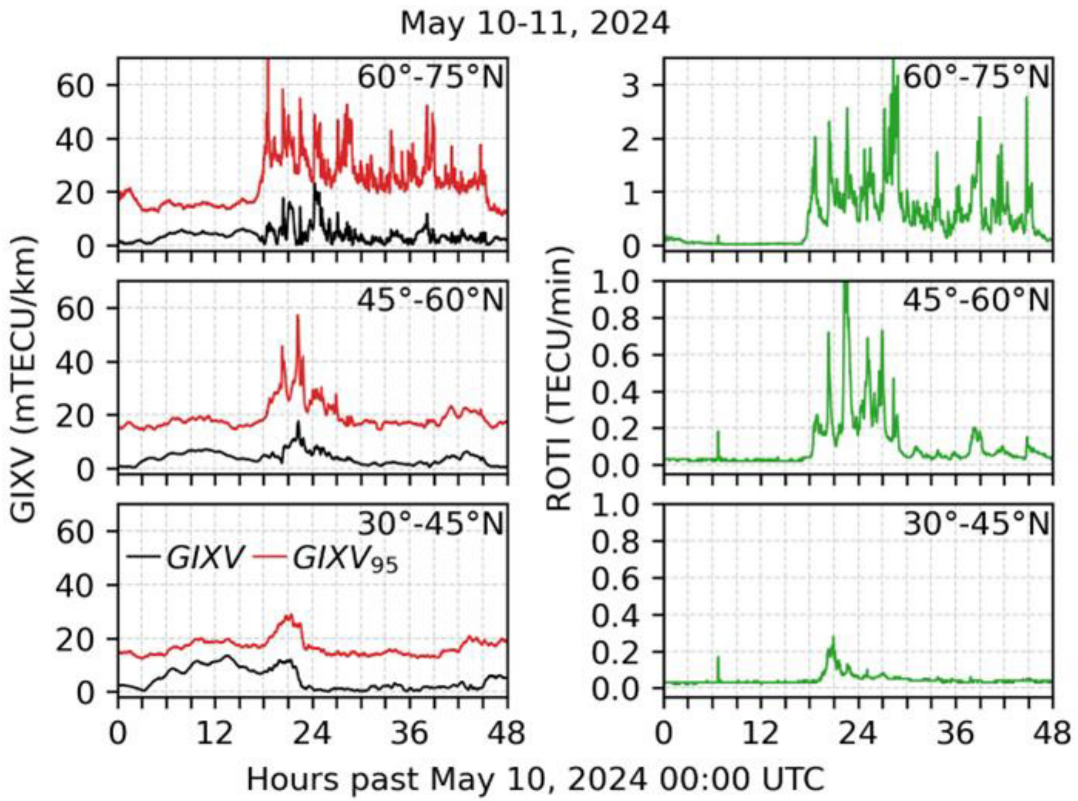


Figure provided by Grzegorz Nykiel

Mother's Day Storm
May 10 – 11, 2024

G5-level superstorm with a Kp index of 9 and Dst of -412 nT. Storm main phase 17 – 3 UT (May 11).

❑ **GIX ⟺ ROTI**

Both indices characterize ionospheric perturbations but in a different manner.

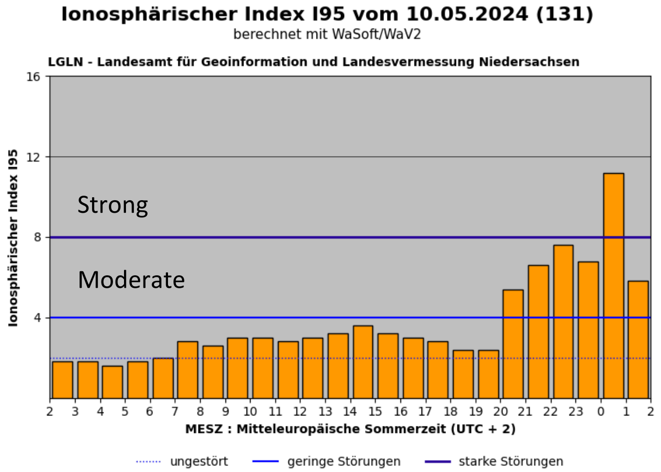
At high-latitudes – strong peaks, small-scale changes, particle precipitation.

At mid-latitudes – strong peaks demonstrating larger spatial gradients.

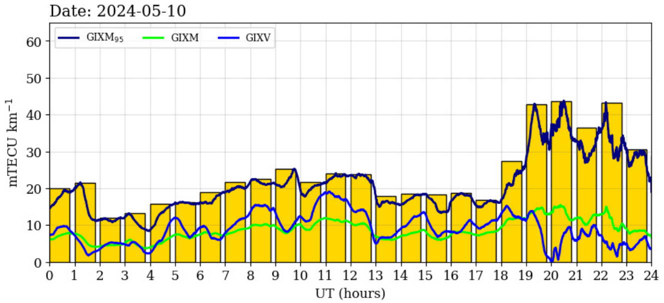
At low-latitudes – GIX has a moderate peak, and a weak peak is also detected by ROTI.

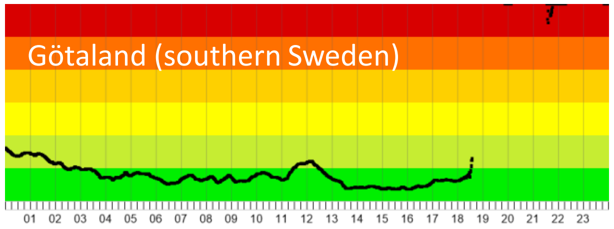
3. Ionospheric Indices during perturbed conditions

Comparison GIX vs. SAPOS I95 vs. SWEPOS Monitoring



GIX





Mother's Day Storm
May 10, 2024

G5-level superstorm with a Kp index of 9 and Dst of -412 nT. Storm main phase 17 – 3 UT (May 11).

- GIX ⟺ SAPOS I95 ⟺ SWEPOS Ionosphere Monitor

GIX aligns well with the German **SAPOS** and Swedish **SWEPOS** monitoring indices.

It confirms its **strong potential** as a **regional proxy and early-warning indicator** of ionospheric disturbances.

Scaling and combined analyses will further **enhance interoperability** among different ionospheric indices.

4. Conclusions

- **Complementary ionospheric indices** capture processes across different spatial and temporal scales.
- **Joint ground- and space-based analyses** improve understanding of ionospheric dynamics and effects on GNSS.
- **Scaling relations between indices** strengthen interoperability and practical use.
- **Indices as early-warning tools** can complement national systems in the navigation/positioning domain.
- **DLR indices (GIX, SIDX, NeGIX, TEGIX)** address medium-scale gradients and have the potential to support near-real-time services.
- **NeGIX (NIX)** and **TeGIX (TIX)** Swarm products are publicly available via https://swarm-diss.eo.esa.int.
- **DLR IMPC** provides operational and scientific products via www.impc.dlr.de.

Thank you!

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