IONOSPHERIC INDICES GIX AND SIDX AND RELATED PERTURBATION SCALES

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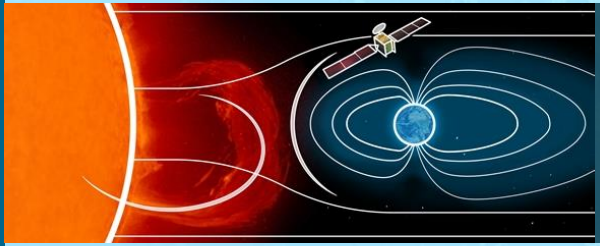

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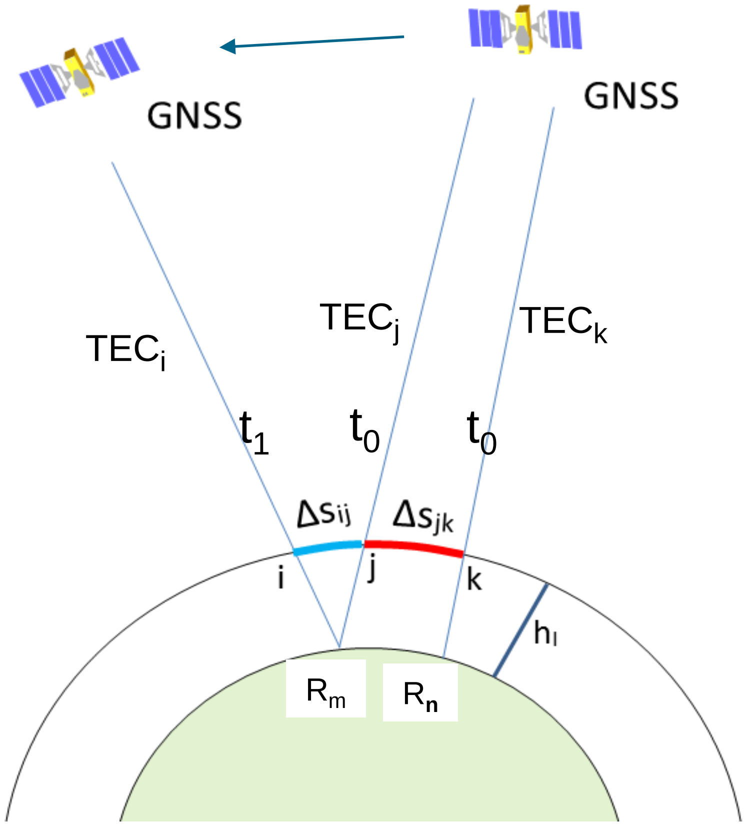
Outline

- Introduction
- Definition of index approaches GIX and SIDX
- Application of indices in GNSS positioning
- Discussion of application related scales
- Summary and Conclusions

Introduction

- Ionospheric research and space based technologies such as telecommunication, navigation and remote sensing require an objective measure of the ionospheric perturbation degree on global scale.
- Topic is addressed in ISWAT group G2B-04 (https://iswat-cospar.org/G2B-04)
- Developing indices and related scales must consider the following criteria:
  - Objective measure, free from instrumental impact
  - Global data coverage around the clock
  - Characterization of the state of the ionosphere in near real time
  - Robust approach, nevertheless, reliable and sufficiently accurate
  - Easy and fast computation and interpretation
  - Pragmatic scale, certified and accepted by customers
- Different perturbation indices for research and for technical applications possible
- Indices and related scales require international acceptance (standardization)

Gradient Ionosphere indeX (GIX) and Sudden Ionosphere Disturbance indeX (SIDX)



- Attempt to separate temporal and spatial perturbations by GIX and SIDX
- Index approaches based on GNSS data
  - Good data coverage over main application areas
  - High temporal resolution (≈ 1s) possible
  - Data close to user needs
- Fast computation, low latency of products

- GIX: ΔTEC/Δs   Δs: distance between piercing points at t_0
- SIDX: ΔTEC/Δt $\Delta t = t_1 - t_0$ at satellite tracks

Jakowski, N. and M. M. Hoque (2019), Estimation of spatial gradients and temporal variations of the total electron content using ground based GNSS measurements, Space Weather, doi: 10.1029/2018SW002119

Sudden Ionosphere Disturbance Index (SIDX)

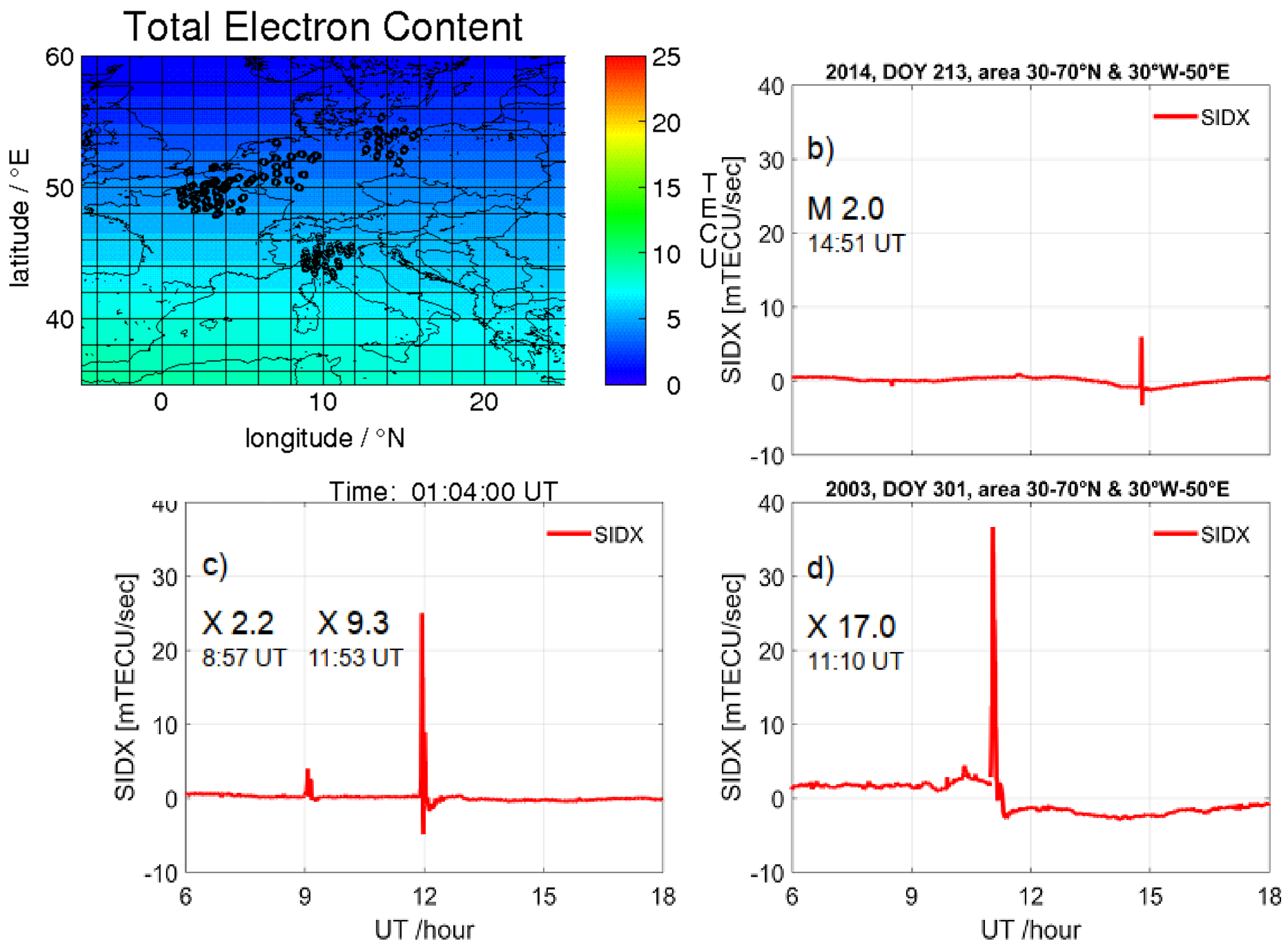
- SIDX - basic approach:
  average rate of TEC rate of change
  at all PPs in a selected area

$$\frac{\partial TEC}{\partial t} = \frac{\Delta STEC}{M\,\Delta t} - \frac{\partial TEC}{\partial u} v$$

$$\left\langle\frac{\partial TEC}{\partial t}\right\rangle \approx \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\Delta STEC}{M\,\Delta t}\right)_i$$

$$\boldsymbol{SIDX} = \left\langle\frac{\partial TEC}{\partial t}\right\rangle$$

$$\boldsymbol{SIDXS} = \sqrt[2]{\left(\left\langle\frac{\boldsymbol{\partial TEC^2}}{\boldsymbol{\partial t}}\right\rangle - \left\langle\frac{\boldsymbol{\partial TEC}}{\boldsymbol{\partial t}}\right\rangle^2\right)}$$



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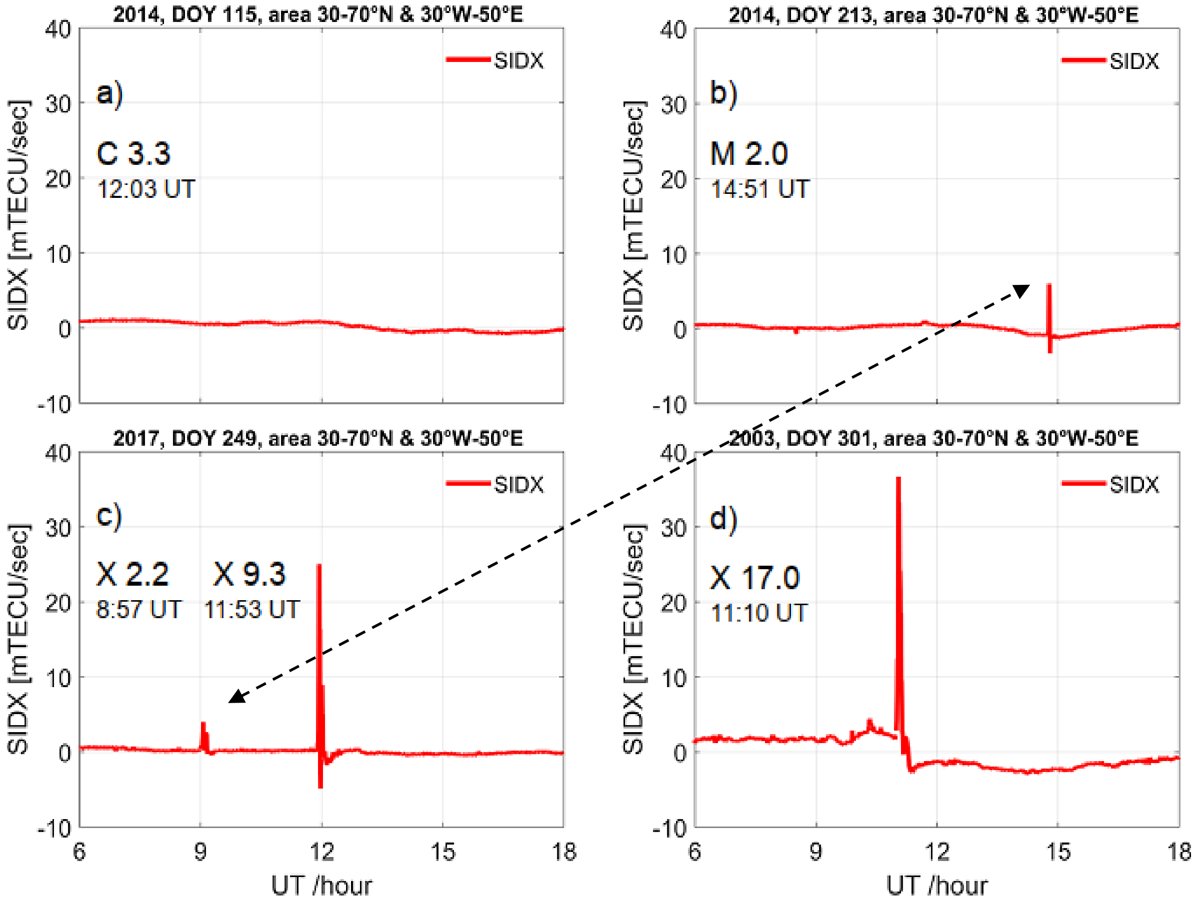
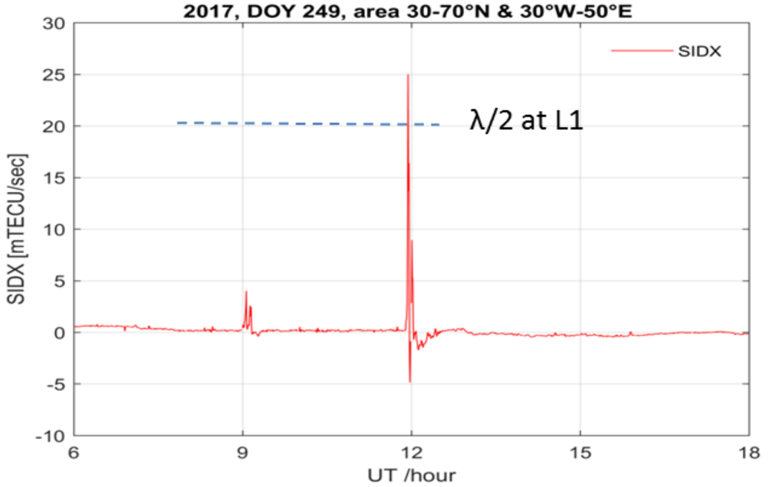
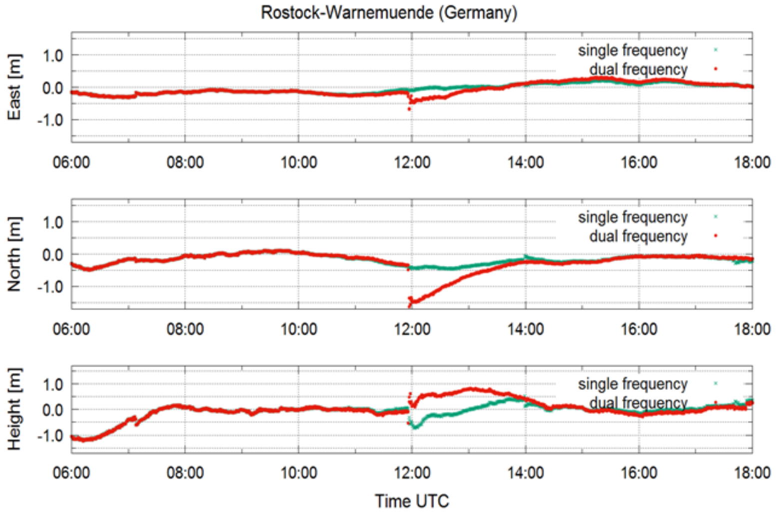


SIDX response to solar flares may differ from X ray classification due to spectral dependence of ionization

Application of SIDX in positioning

SIDX Sept 6, 2017 – solar flare impact



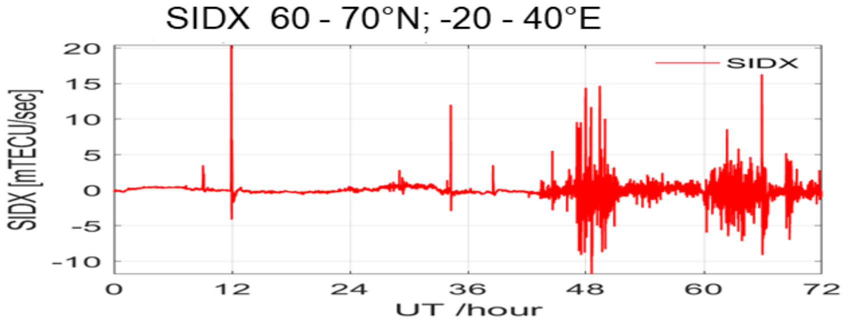


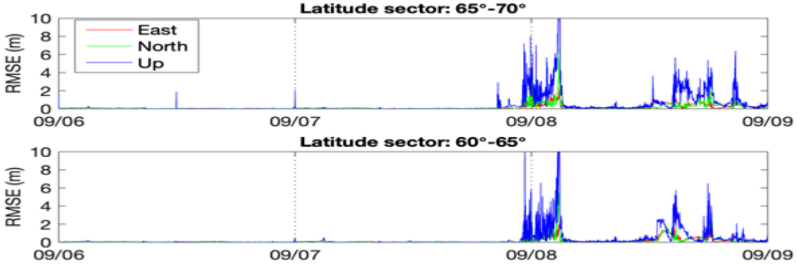
- Enhanced SIDX values due to rapid changes of ionospheric ionization correlate with GNSS positioning errors
- Rapid changes of ionospheric ionization may be caused by solar flares and precipitation of energetic particles

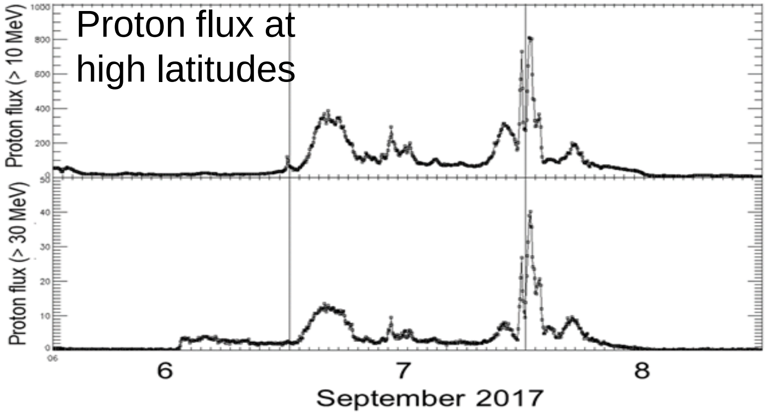
→ detectable by SIDX

- Definition of a scale useful for customers needs numerous measurement samples.

SIDX Sept 7, 2017 – particle precipitation



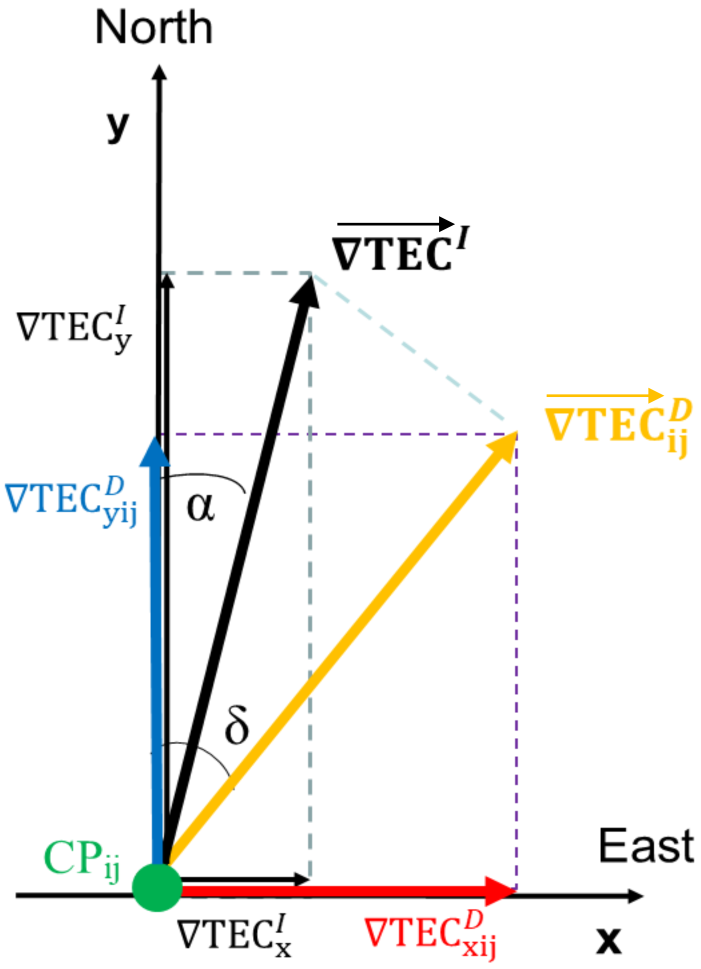




Berdermann et al. (**2018**) Space Weather, 16. https://doi.org/10.1029/2018SW001933

Jakowski et al., COSPAR 2021, Athens

Gradient Ionosphere Index (GIX) ➡ GIXM + GIXV



Vertical TEC data at N ionospheric piercing points (IPPs)

$N_D \leq N(N-1)/2$ Number of different IPP links (dipoles)

N: number of piercing points PP_i and PP_j

Cpij : Central point of dipole, location of the measured gradient vector $\overrightarrow{\nabla TEC}_{ij}^D$

Δs_{ij}: distance between piercing points

$$\mathrm{GIXM} = \langle \nabla TEC^D \rangle = \frac{1}{N_D} \sum_{\mathrm{k}=1}^{N_D} \left| \nabla \mathrm{TEC}_{\mathrm{k}}^D \right|$$

∇TEC_{ij}^D: measured gradient value between PP_i and PP_j

$\nabla TECx_{ij}^D$: measured gradient component in East direction

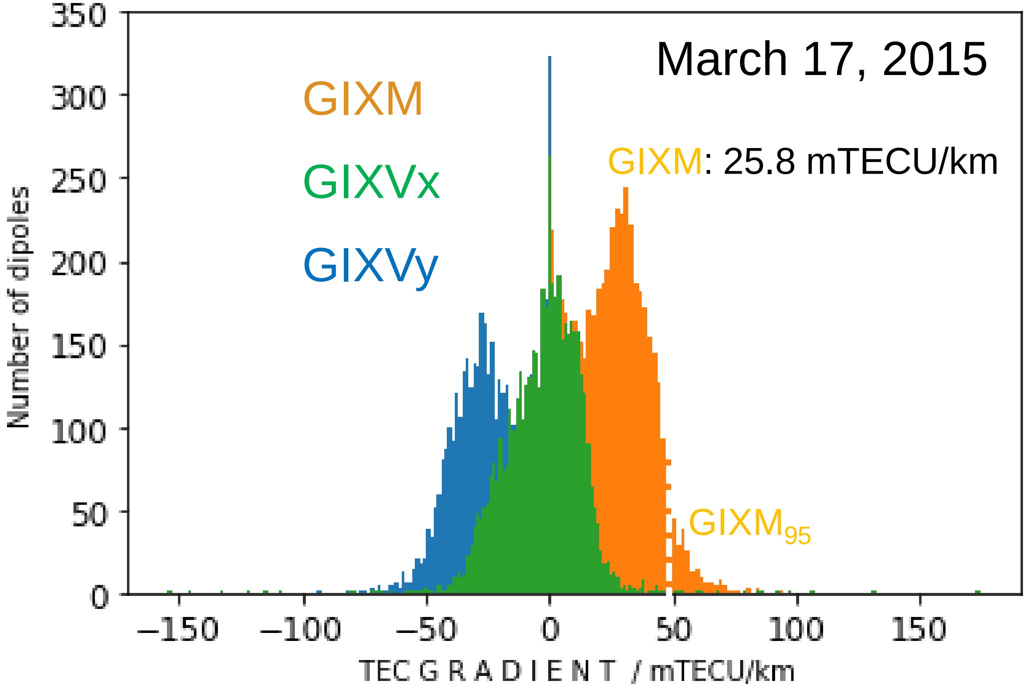
$\nabla TECy_{ij}^D$: measured gradient component in North direction

$$\mathrm{GIXV} = \langle \nabla TEC^I \rangle = 2 \cdot \sqrt[2]{\langle \nabla TECx^D \rangle^2 + \langle \nabla TECy^D \rangle^2}$$

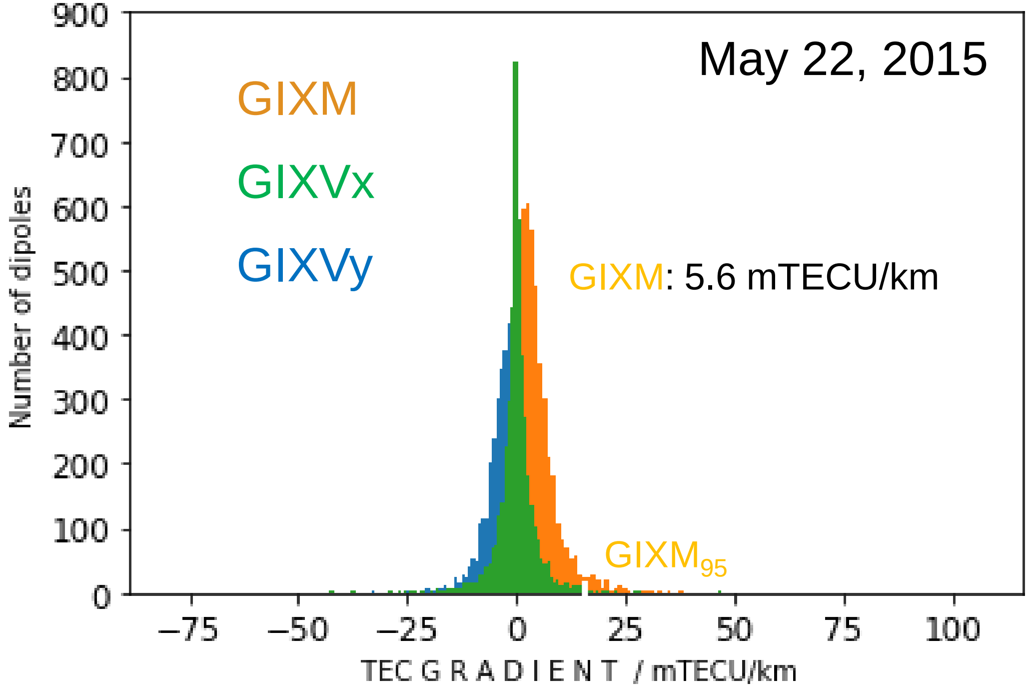
$$\alpha = \mathrm{atan}\left(\langle \nabla TECx^D \rangle \,/\, \langle \nabla TECy^D \rangle \right)$$

Distribution functions of GIXVx, GIXVy and GIXM on March 17, 2015 and May 22, 2015 at 18:00 UT

Ionospheric gradient vector: 38.6 mTECU/km
Azimuth of ionospheric gradient vector: 187.3°

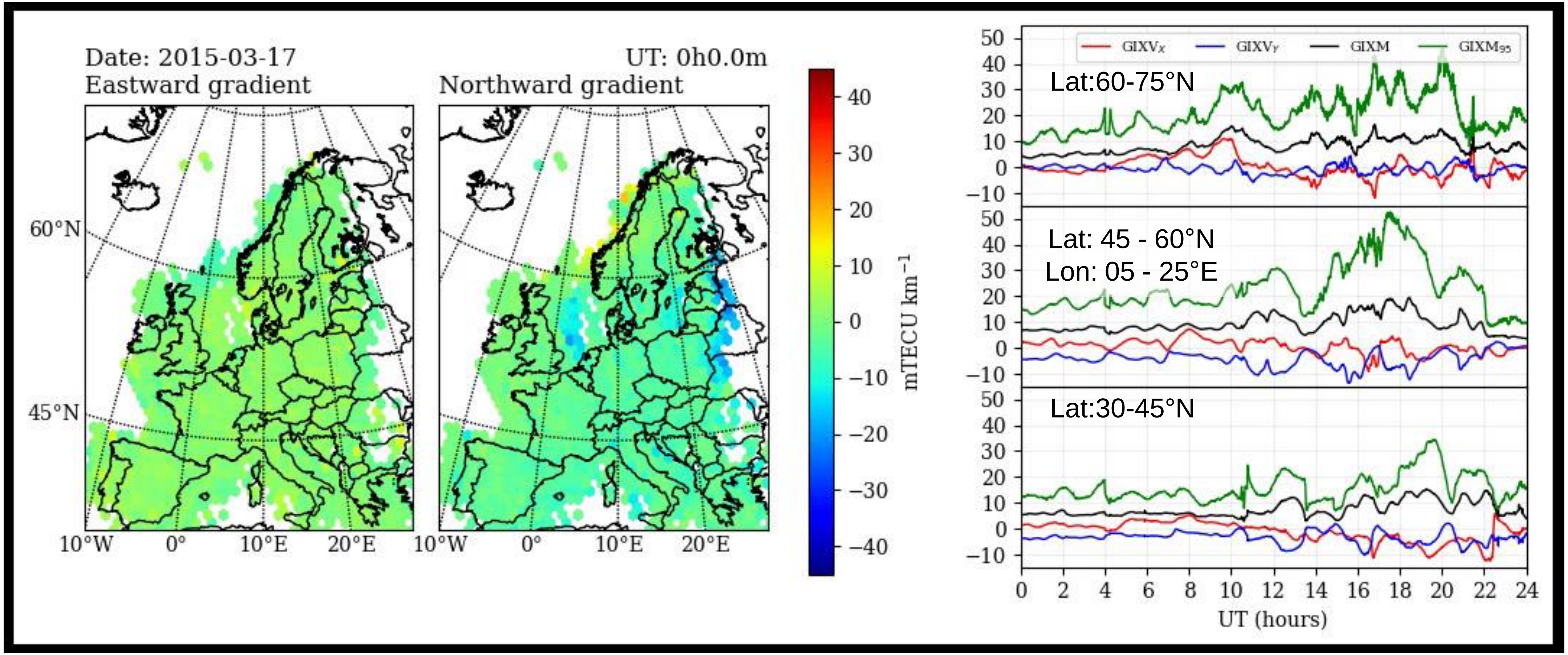


Ionospheric gradient vector: 4.8 mTECU/km
Azimuth of ionospheric gradient vector: 181.1°

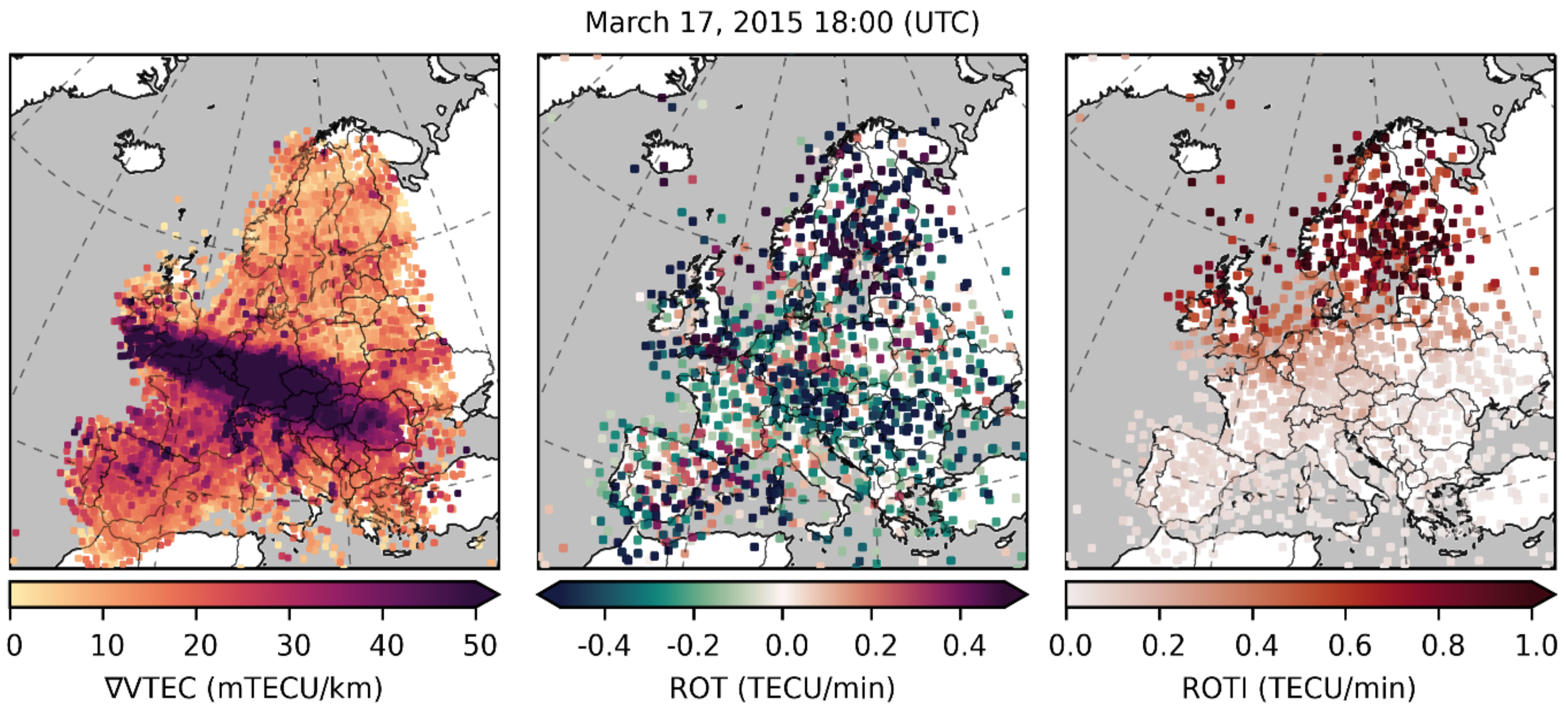


- ISWAT G2B-04 initiated a „Coordinated Ionosphere Study on Scales and Indices" (CISSI)
- Goal: comparison of different index approaches at disturbed and quiet periods (reference)

Propagation of perturbations on St. Patrick's Day storm at March 17, 2015



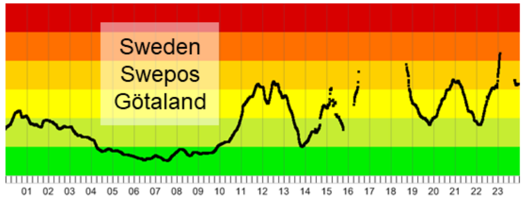
Comparison of GIXV and ROTI over Europe on St. Patricks storm day

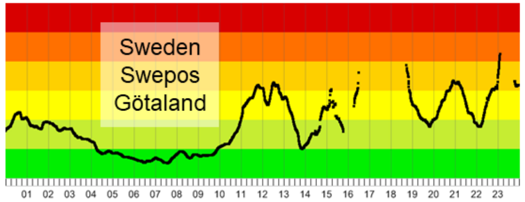


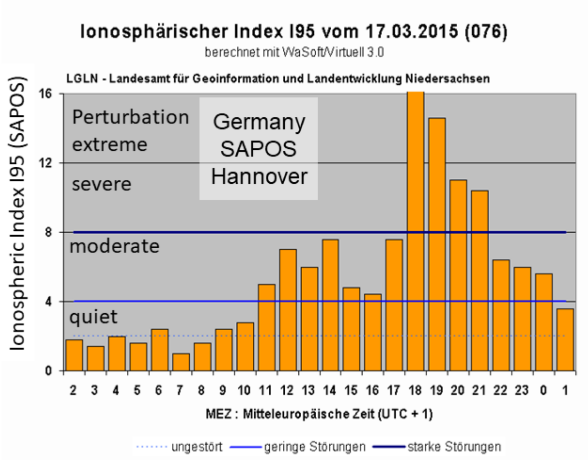
Cf. Nykiel, G. *et al.* Relationship between GIX, SIDX, and ROTI ionospheric indices and GNSS precise positioning results under geomagnetic storms. *GPS Solut* **28**, 69 (2024). https://doi.org/10.1007/s10291-023-01611-5

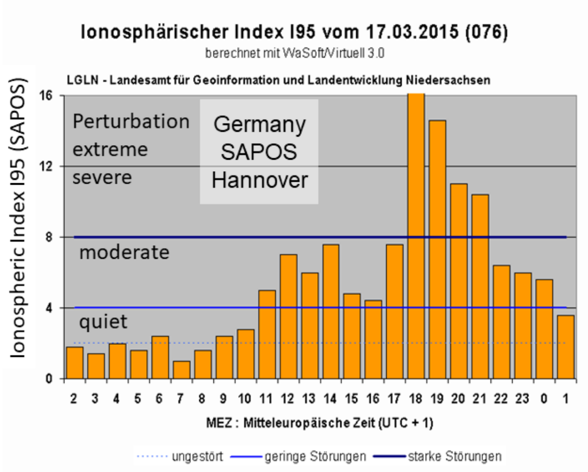
- GIXV indicates mid- to large-scale gradients in midlatitudes (50-500km)
- ROTI focuses on indicating small to mid-scale perturbations (here high latitudes)

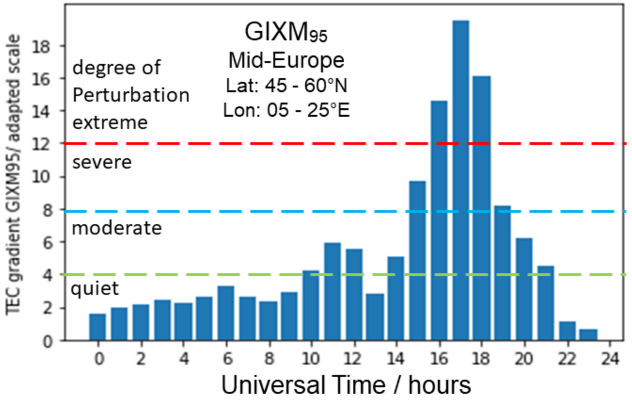
GIXM /GIXM95 scaling for GNSS positioning
Sample day: March 17, 2015

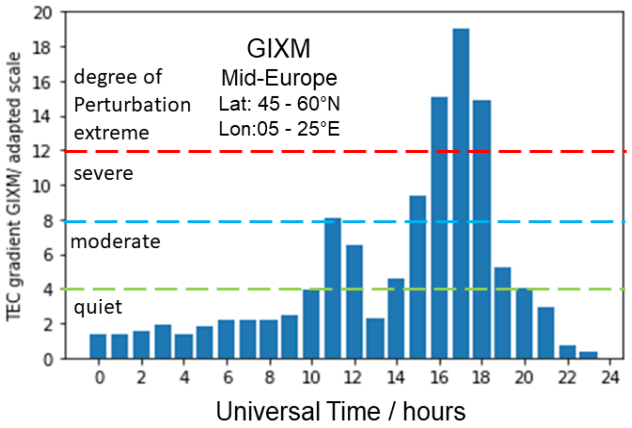










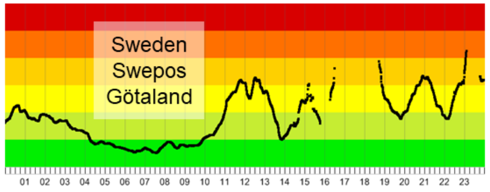


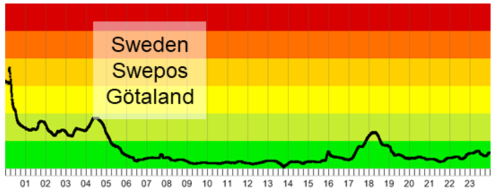
- Comparison of index approaches with user estimates of residual errors
- Top: SWEPOS
  - Service for high accurate GNSS positioning in Sweden
  - Operates Swedish national reference system
  - https://www.l5navigation.se/jonosfarsmonitor/

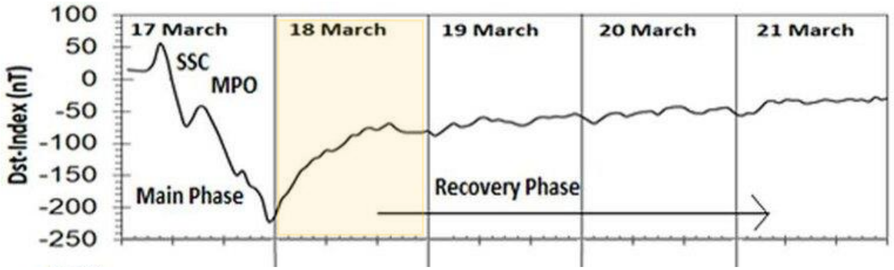
https://www.l5navigation.se/jonosfarsmonitor/

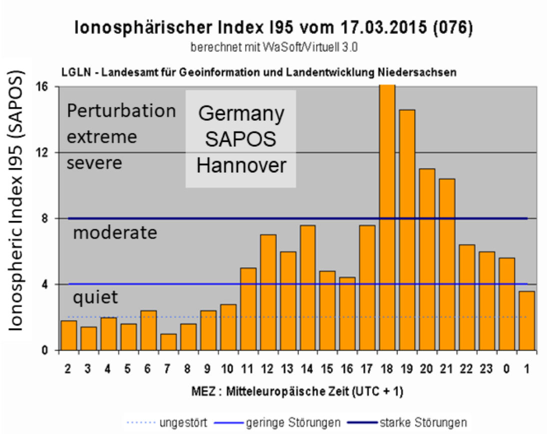
- Middle: SAPOS
  - Service for high-accurate GNSS measurements in Germany
  - Operates German GNSS reference network
  - https://www.lgln.niedersachsen.de/sapos/ionosphaerischer-index-i95-51389.html
- Comparison GIXM95 and GIXM
  - Bottom left: adapted GIXM95 scale
  - Bottom right: adapted GIXM scale
- Adapted indizes GIXM95 and GIXM behave similarly, GIXM somewhat better

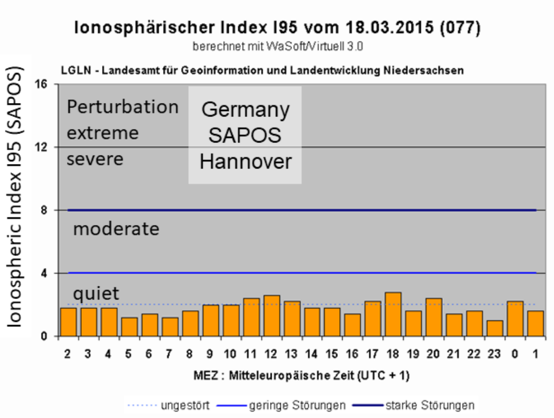
GIXM scaling adapted to GNSS positioning approach (I95)
Sample days: March 17 and 18, 2015





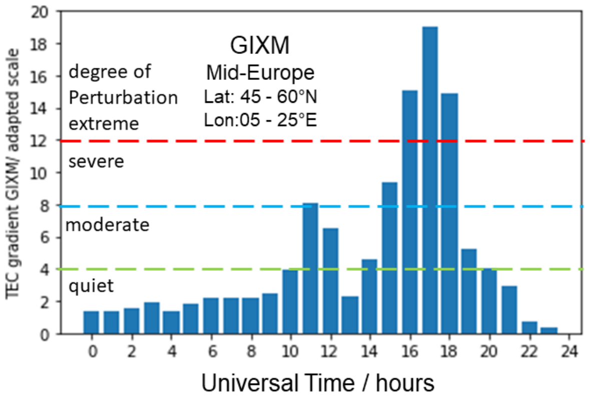


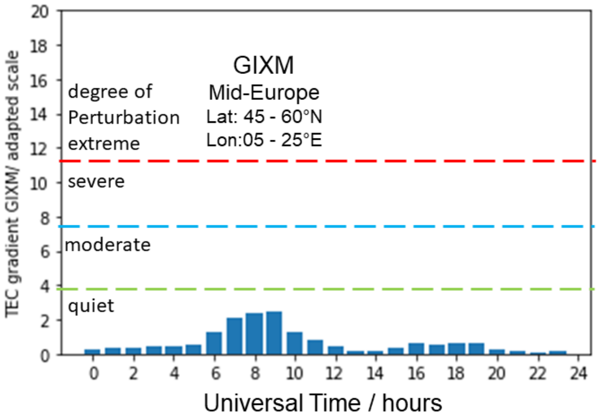




GIXM on March 17 and 18, 2015
Bottom left: March 17, 2015
Bottom right: March 18, 2015

Ionospheric storm effects disappear on March 18, 2015 at all scales



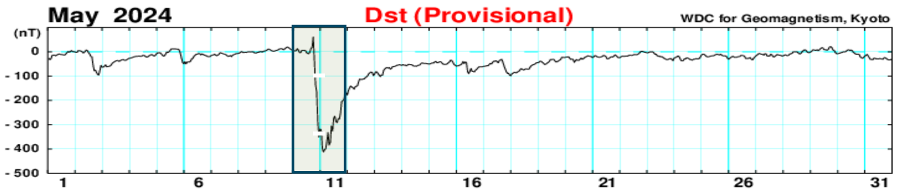


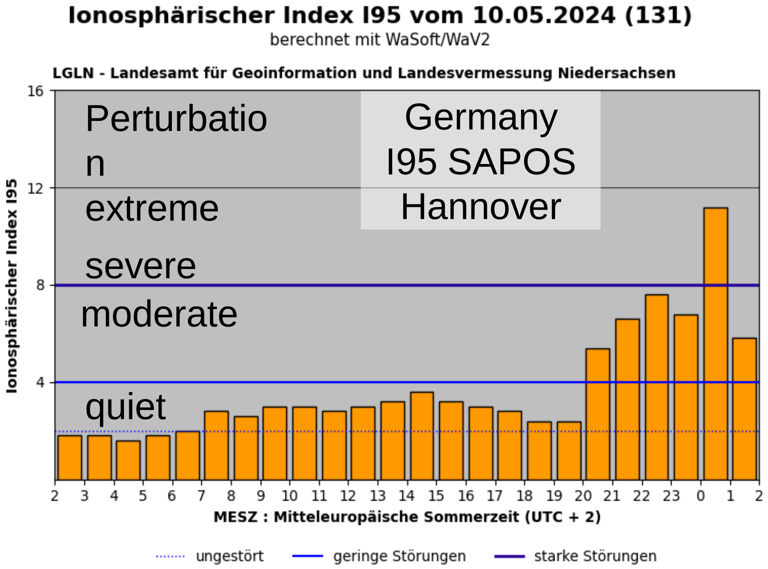
Dst mostly < -100 nT on March18, 2015 during the recovery phase of the geomagnetic storm

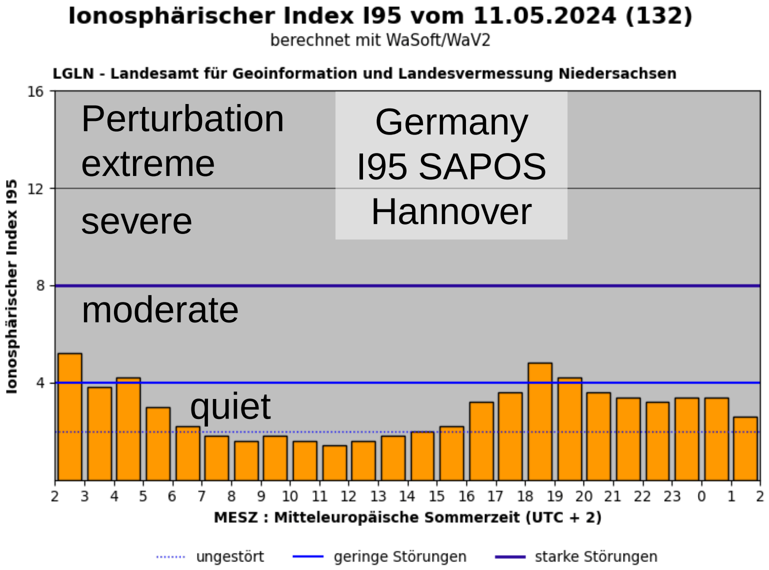
Dst values not suited to estimate the perturbation degree of the ionosphere

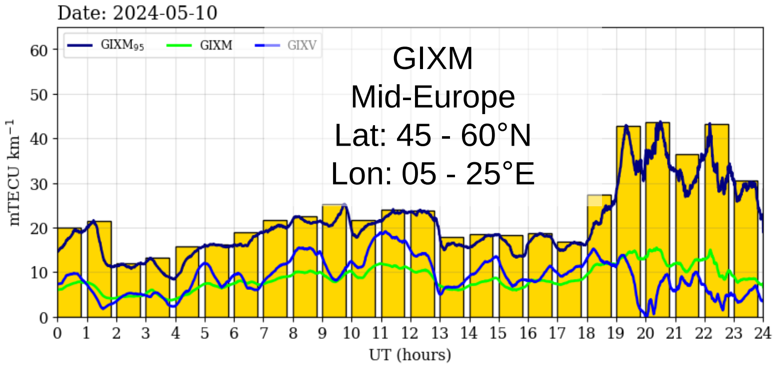
GIXM comparison with I95 from SAPOS

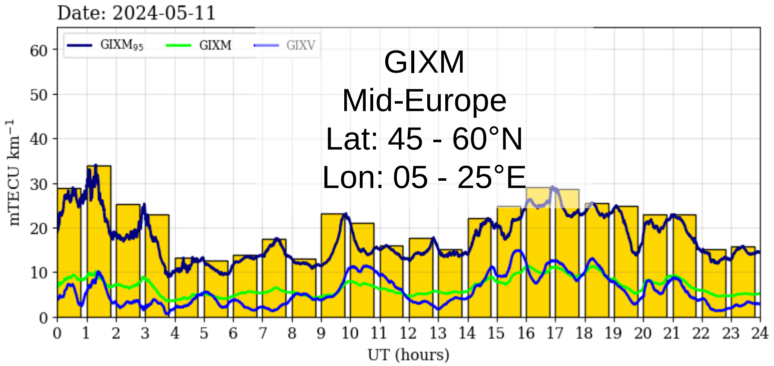
Sample days: May 10 and 11, 2024







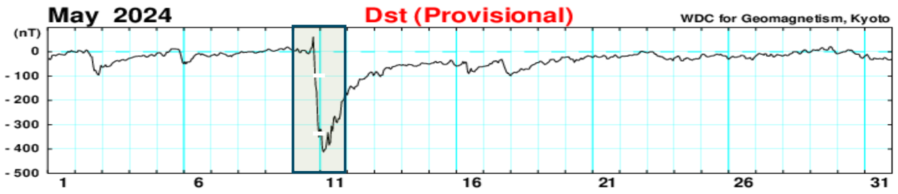


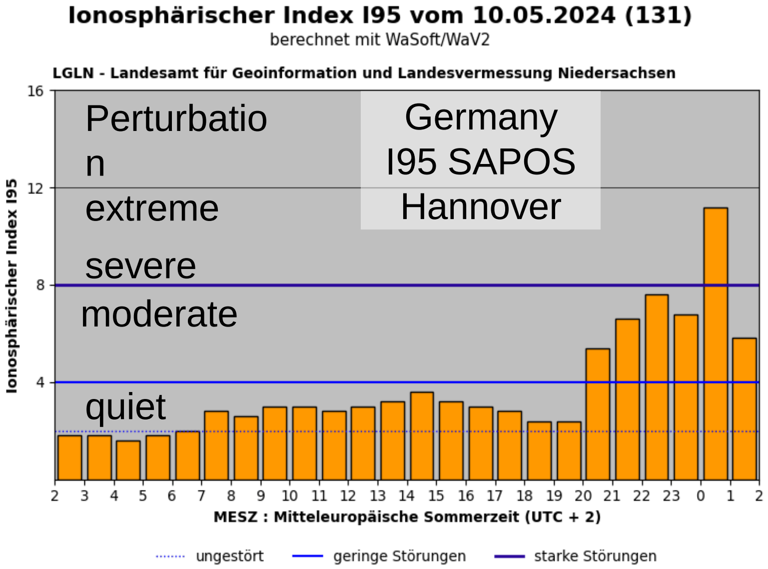


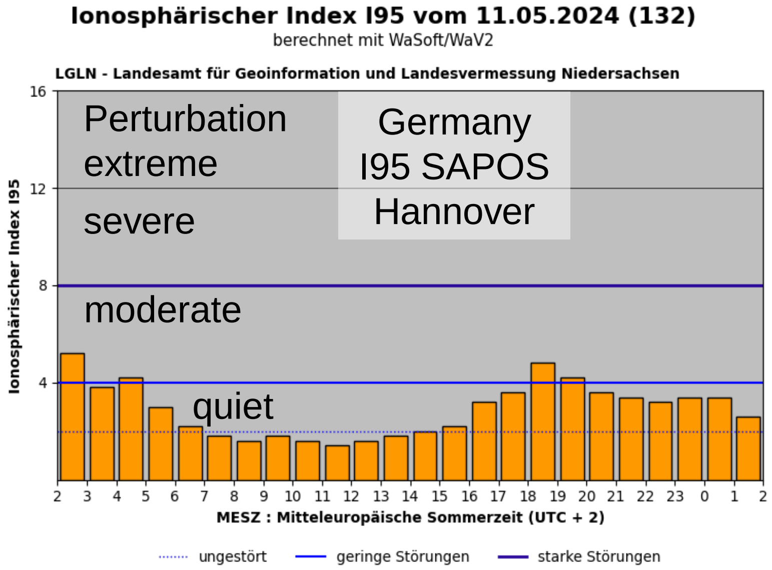
- GIXM and I95 from SAPOS/Germany show similar behaviour over recent storm days on May 10 and 11, 2024.
- Two main options for defining a trans-ionospheric SW scale:
  - user adapted scale

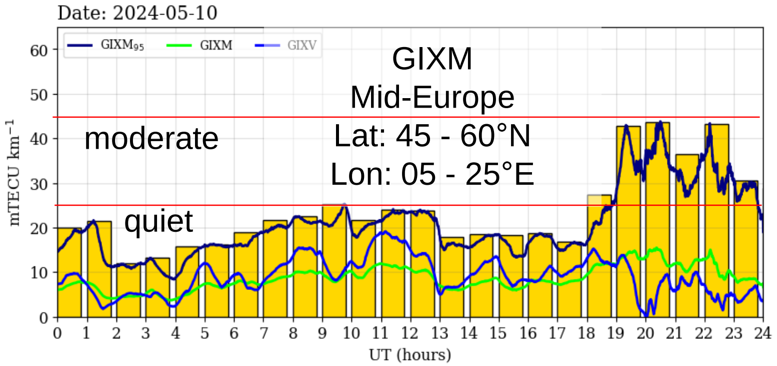
    (seen in the previous slide)

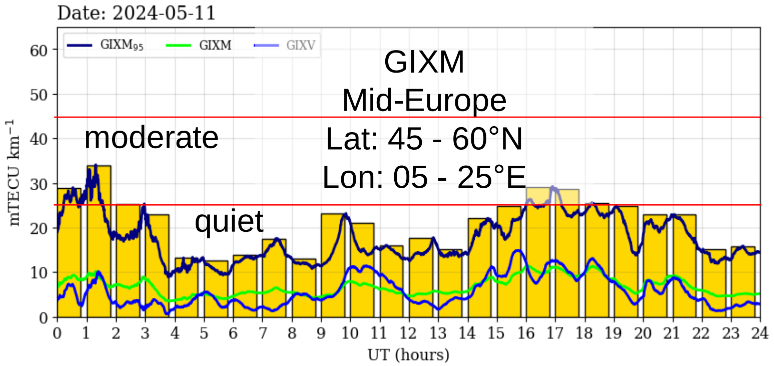
GIXM comparison with I95 from SAPOS
Sample days: May 10 and 11, 2024











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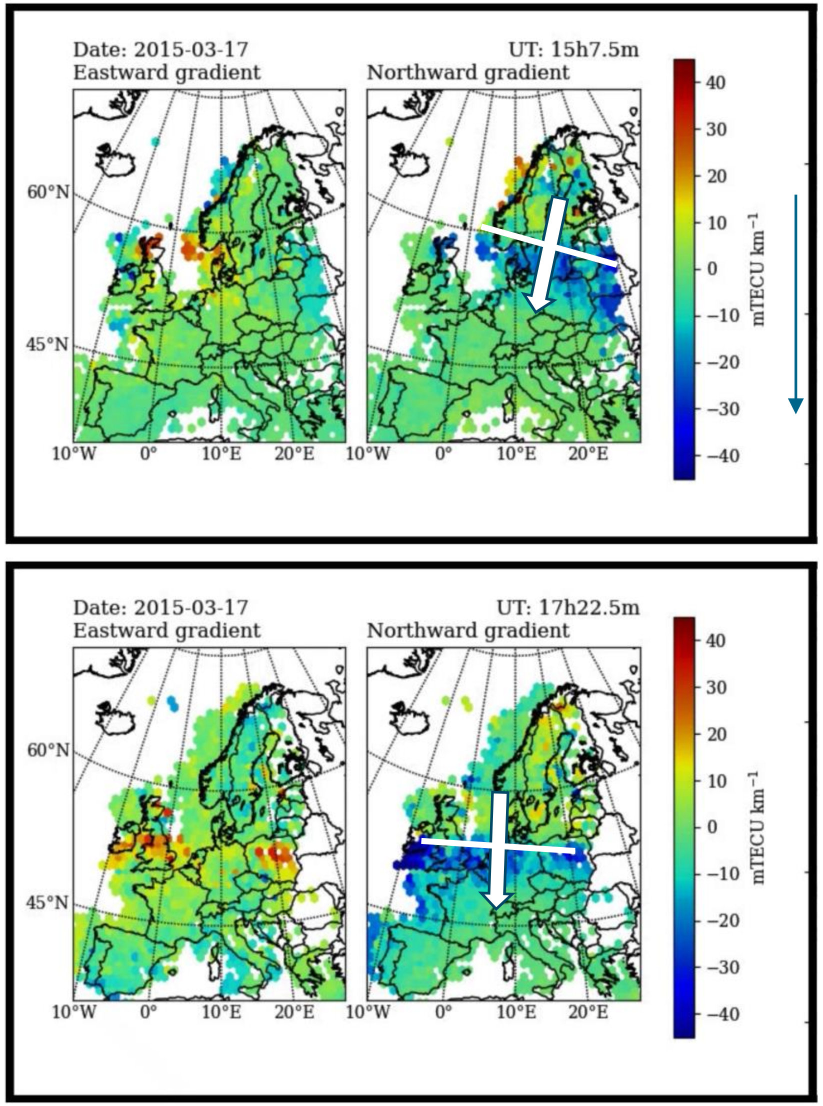
  - physics based definition including units Thresholds defined from users point of view

Forecast of perturbation propagation using GIXV



Early detection of the propagating ionization front

strength	see color scale
velocity	≈ 55 m/s *
direction	≈188°

Forecast for lower latitudes

Permanent control of the ionization front parameters corresponding correction forecast for lower latitudes based on the estimation of the direction and velocity of the ionisation front.

Control of ionization front parameters at application area
Forecast for lower latitudes
Comparison of gradient values with positioning results at application areas, conclusions to further improve the prediction algorithms

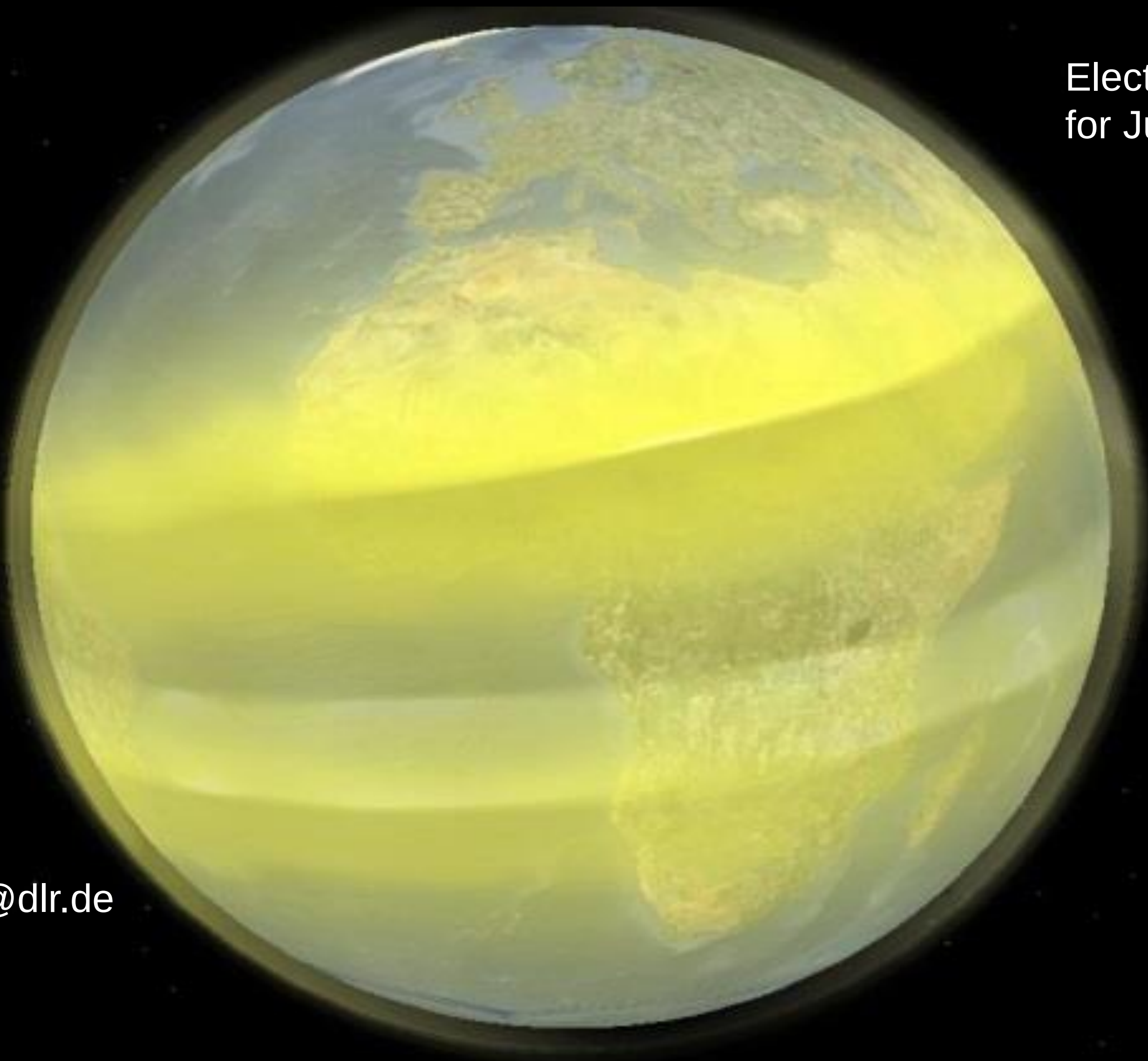
* Propagation velocity estimated between 15:08 and 17:23 UT

Summary and conclusions

- GIX indicates spatial TEC structures over a selected area in near real time with high temporal resolution 1s ≤ Δt
- SIDX indicates rapid change rates of TEC over a selected area with a time resolution Δt depending on the sampling rate of measurements (Δt > 1/0.1Hz)
- Two different perturbation scales suggested
  - For science (use ionospheric parameters, solar wind relationships, comparative studies)
  - For applications (adapted to customer needs, easy and understandable use by customers)
- Customers are mainly interested in forecasts – two options to warn users:
  - Ionospheric observations at high latitudes used to estimate strength and dynamics of perturbation
  - Relationships between solar wind and indices are used to estimate dynamics of perturbation
- Close dialogue with user community required

Ionosphere from space

Electron density reconstruction at DLR
for July 23, 2011, 14:00 UT



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Thank you !