IONOSPHERIC INDICES FOR CHARACTERIZING IONOSPHERIC PERTURBATIONS AND WARNING USERS OF TRANS-IONOSPHERIC RADIO SYSTEMS

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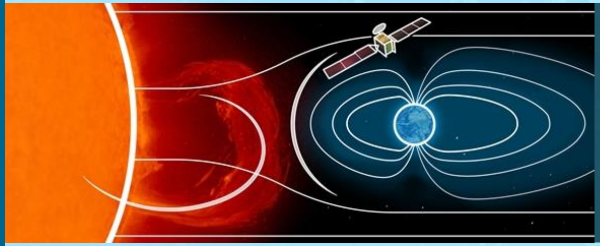

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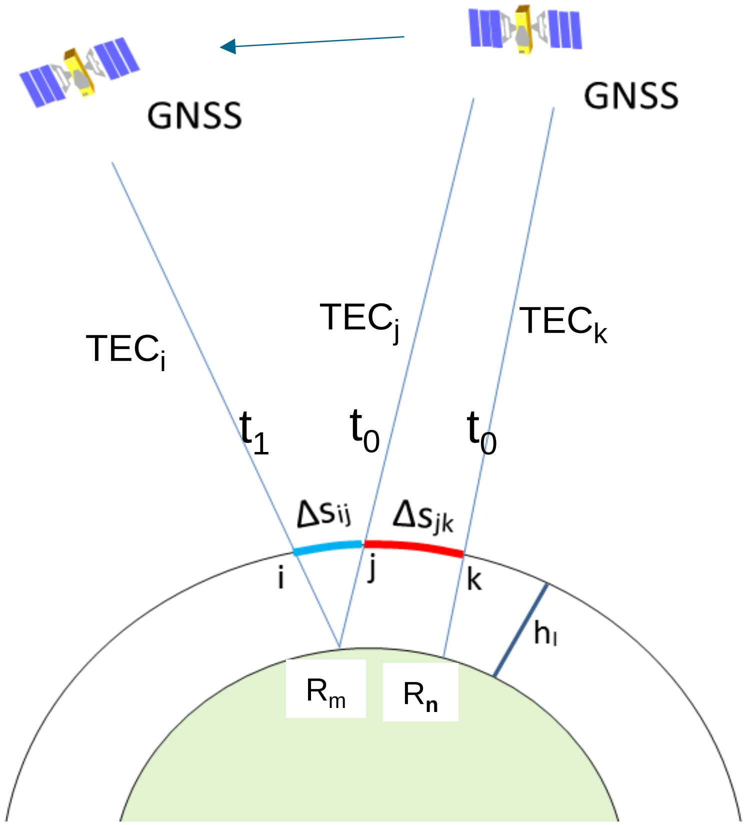
Outline

- Introduction
- Ionospheric index approaches GIX and SIDX
- Use 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.
- 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, accepted by customers
  - Forecast capability
- Indices and related scales require international acceptance, efforts to standardize well accepted approaches (ISWAT group G2B-04 - https://iswat-cospar.org/G2B-04)

Gradient **I**onosphere inde**X** (GIX) and **S**udden **I**onosphere **D**isturbance inde**X** (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

GNSS*: Global Navigation Satellite System

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)

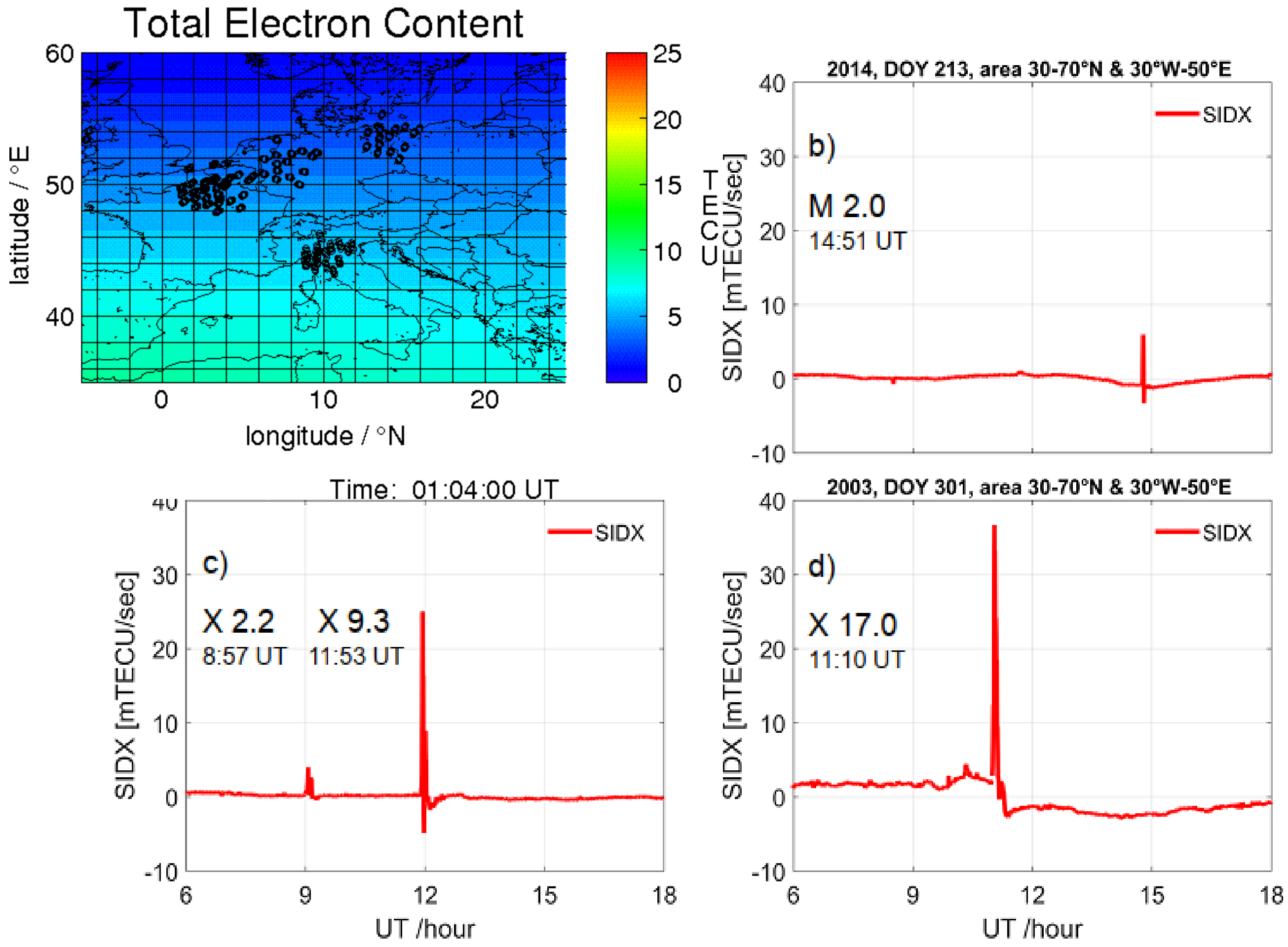
- SIDX - basic approach:
  average rate of TEC rate of change
  at all PPs in a selected area

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

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

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

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



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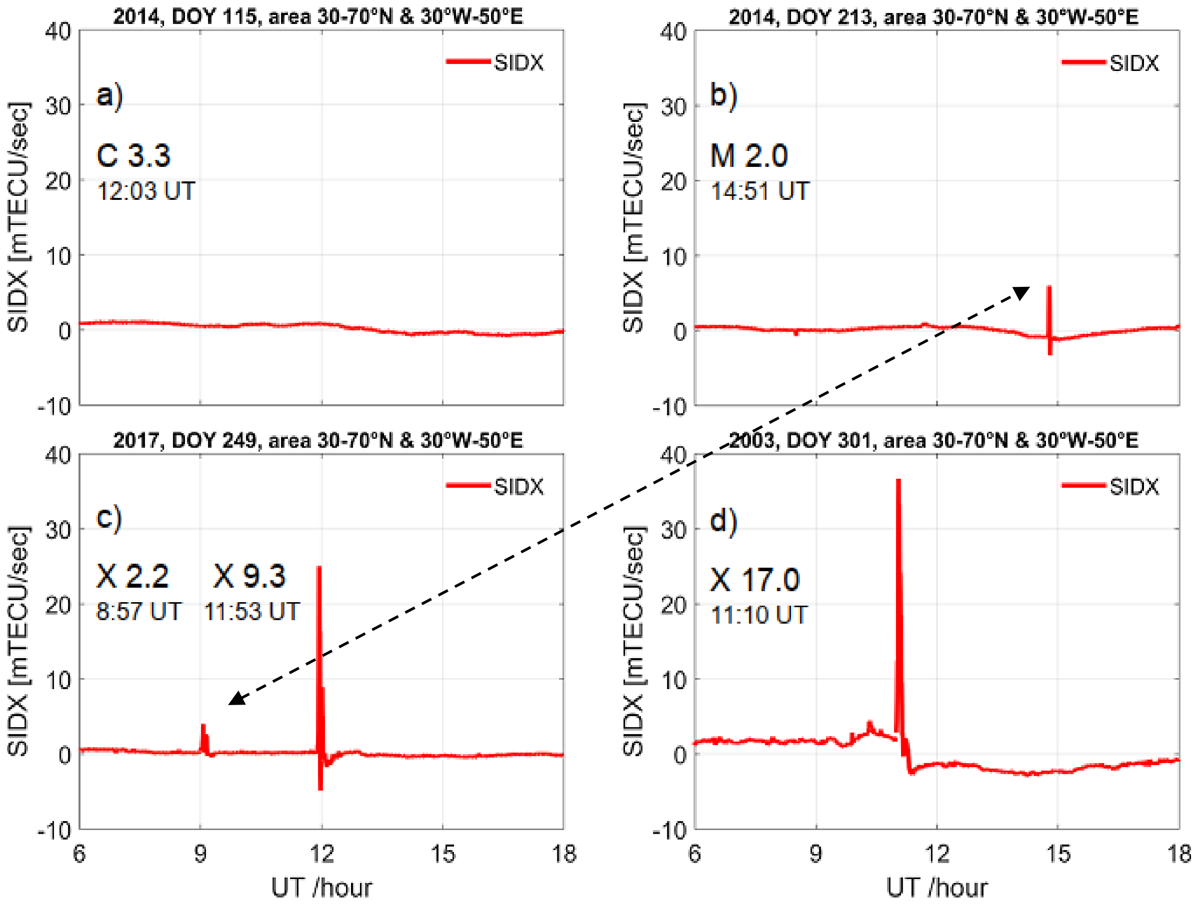
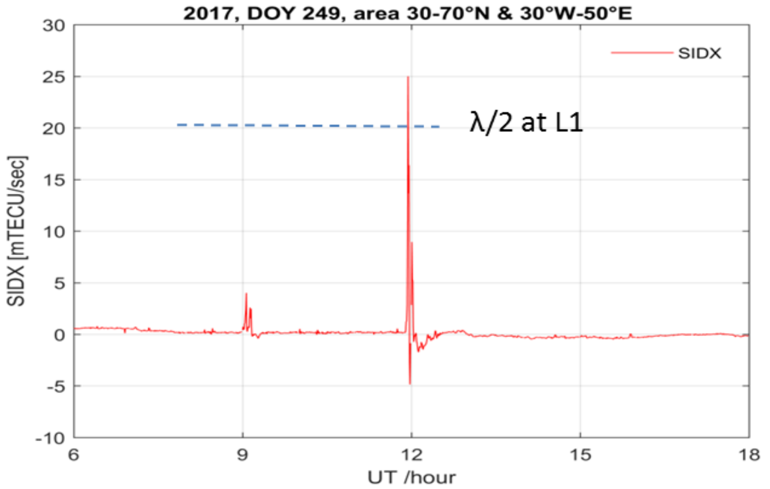
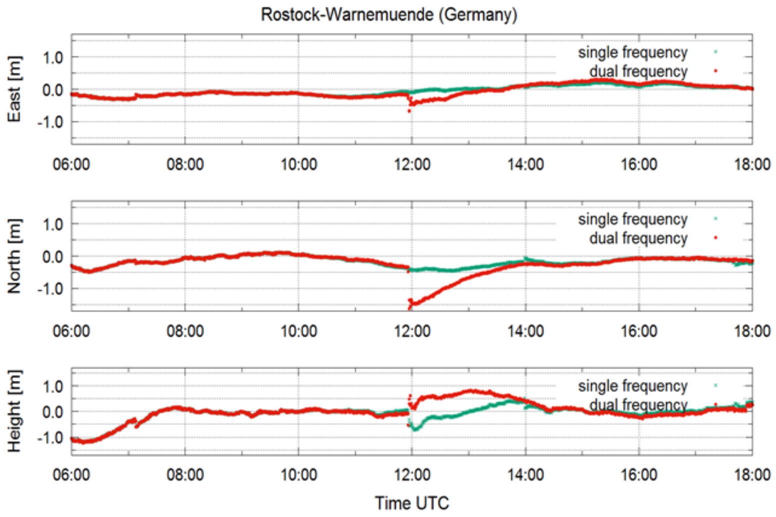


SIDX response to solar flares may differ from X ray classification due to spectral dependence of ionization

Application of SIDX in positioning

SIDX Sept 6, 2017 – solar flare impact





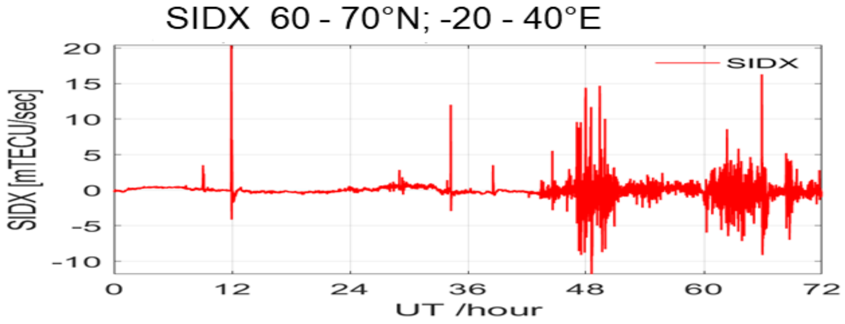
*Berdermann et al. (**2018**) Space Weather, 16.*
https://doi.org/10.1029/2018SW001933

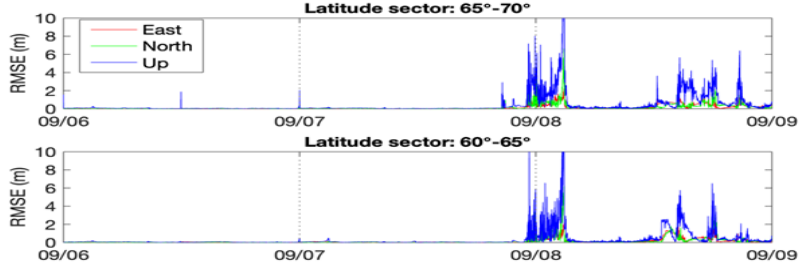
- Enhanced SIDX values due to rapid changes of ionospheric ionization correlate with GNSS positioning errors
- Rapid changes of ionospheric ionization may be caused by solar flares and precipitation of energetic particles

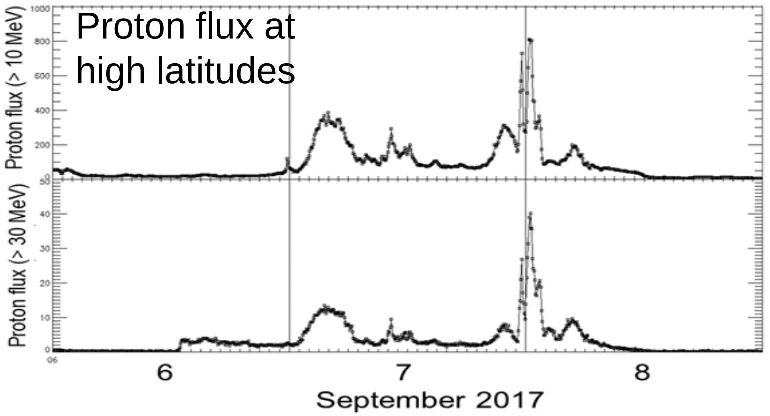
→ detectable by SIDX

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

SIDX Sept 7, 2017 – particle precipitation





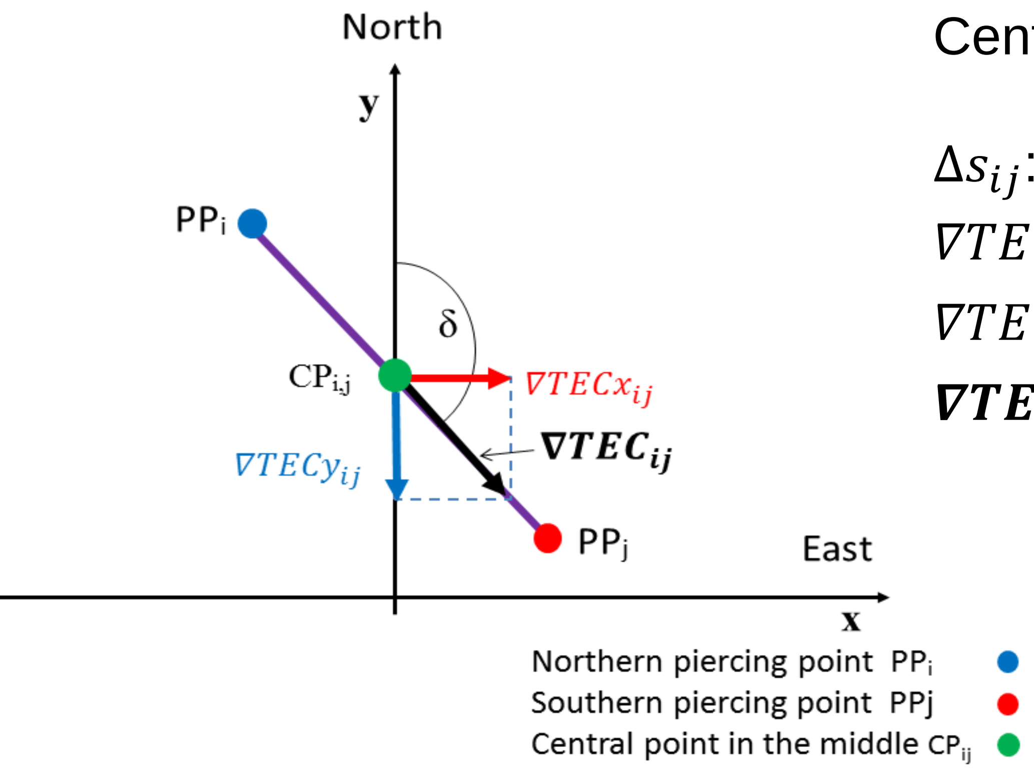


Jakowski et al., COSPAR 2021, Athens

Spatial perturbation degree by the Gradient Ionosphere indeX GIX

N: number of piercing points PP_i and PP_j
Central point Cpij

Δs_{ij}: distance between piercing points
$\nabla TECx_{ij}$: gradient East direction
$\nabla TECy_{ij}$: gradient in North direction
$\boldsymbol{\nabla TECx_{ij}}$: total gradient between PP_i and PP_j



Gradient Ionosphere indeX

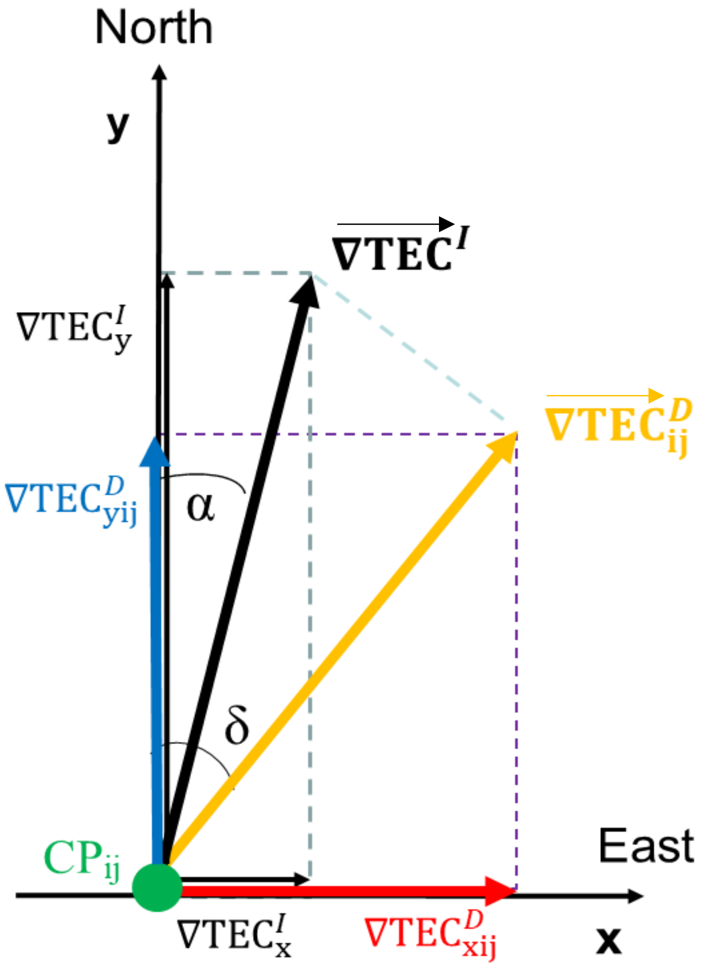
Data base:

Vertical TEC data at N piercing points $PP_{i,j}$.

ND = N(N-1)/2 maximal number of different PPs usable for gradient computation

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

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 $\overrightarrow{\nabla TEC^D_{ij}}$

Δs_{ij}: distance between piercing points

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

∇TEC^D_{ij}: measured gradient value between PP_i and PP_j

$\nabla TECx^D_{ij}$: measured gradient component in East direction

$\nabla TECy^D_{ij}$: measured gradient component in North direction

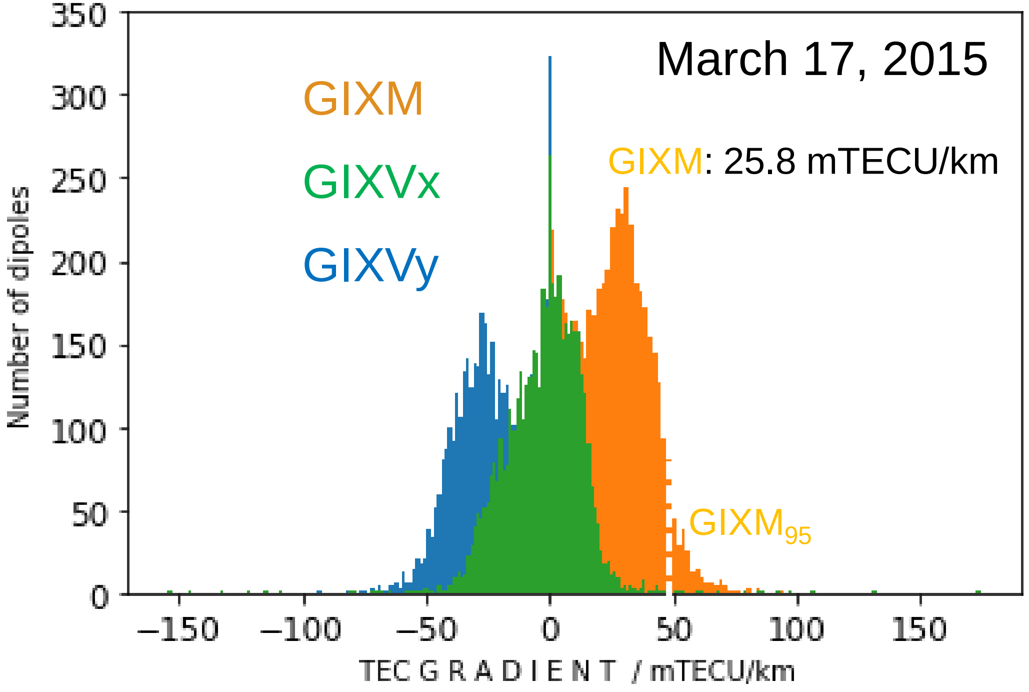
$$\mathrm{GIXV} = \langle \nabla TEC^I \rangle = \sqrt[2]{\langle \nabla TECx^D \rangle^2 + \langle \nabla TECy^D \rangle^2}$$

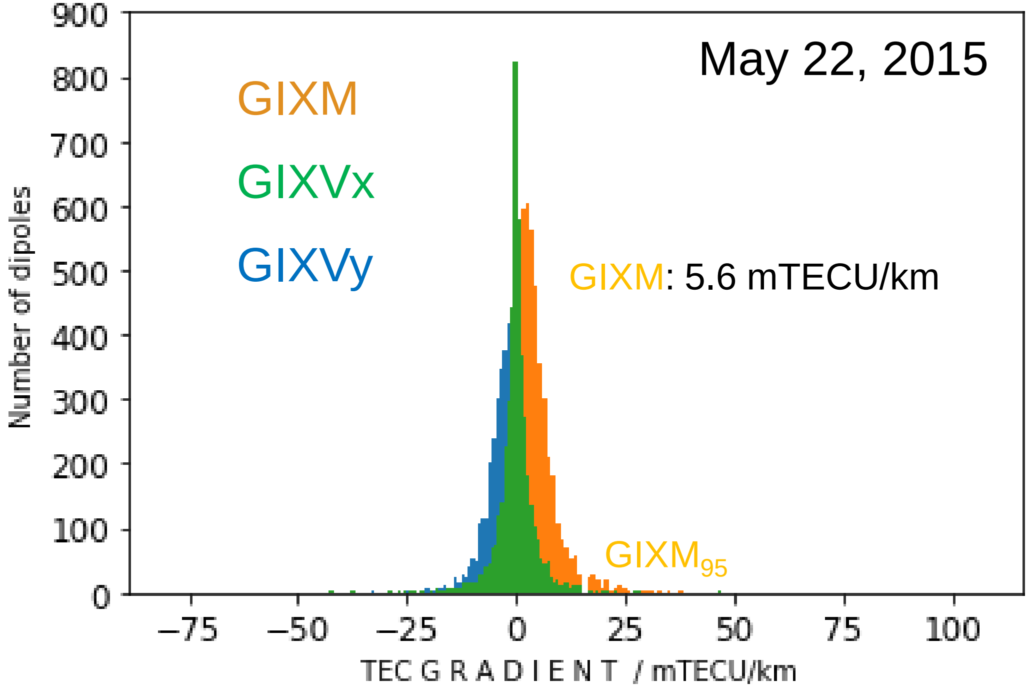
$$\alpha = \mathrm{atan}\left(\langle \nabla TECx^D \rangle / \langle \nabla TECy^D \rangle \right)$$

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°

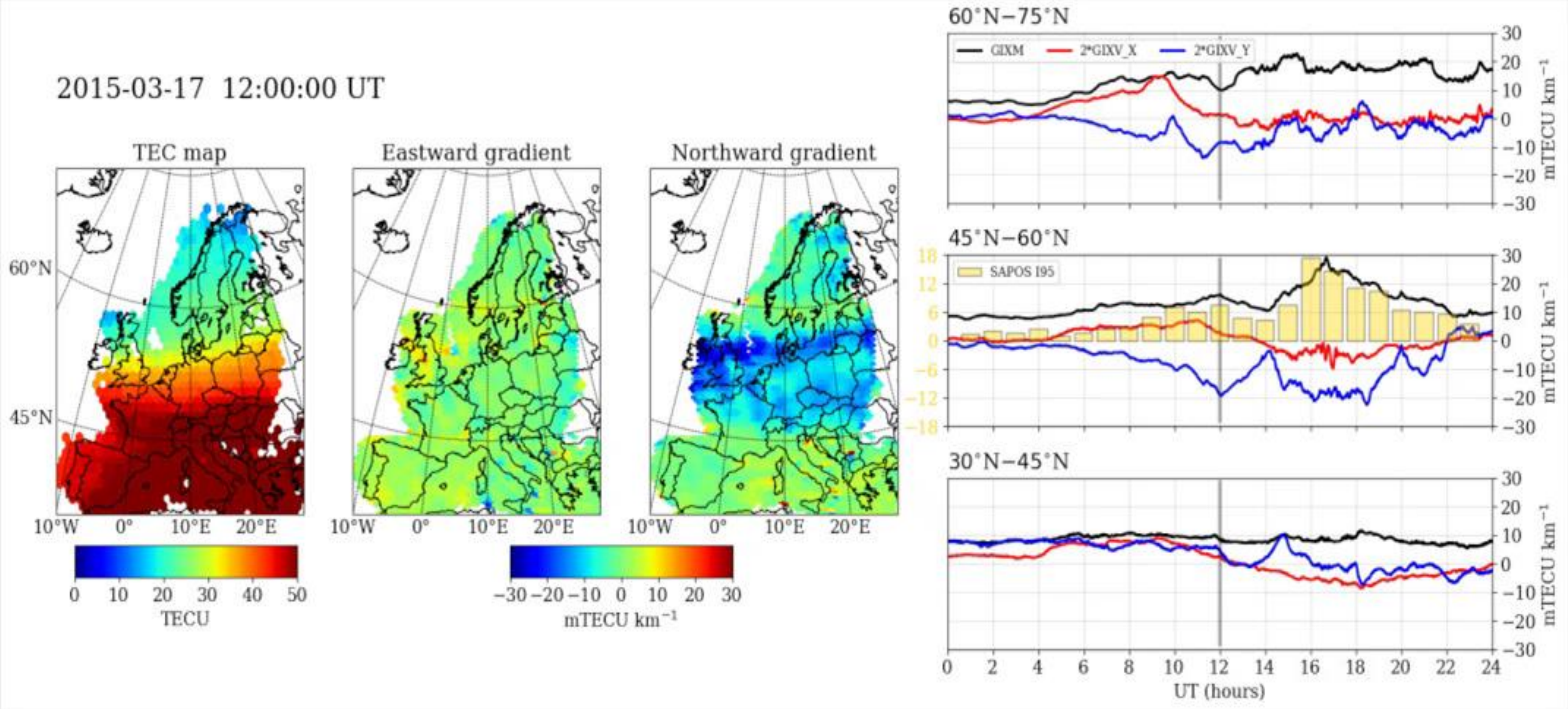
Ionospheric gradient vector: 4.8 mTECU/km
Azimuth of ionospheric gradient vector: 181.1°



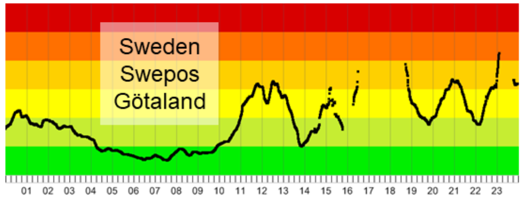


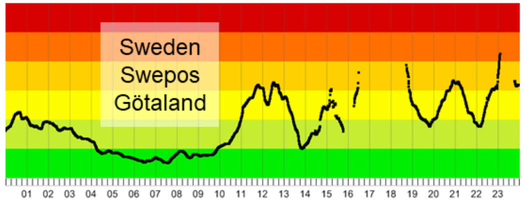
- ISWAT G2B-04 initiated a „Coordinated Ionosphere Study on Scales and Indices” (CISSI)
- Goal: comparison of different index approaches at disturbed and quiet periods (reference)

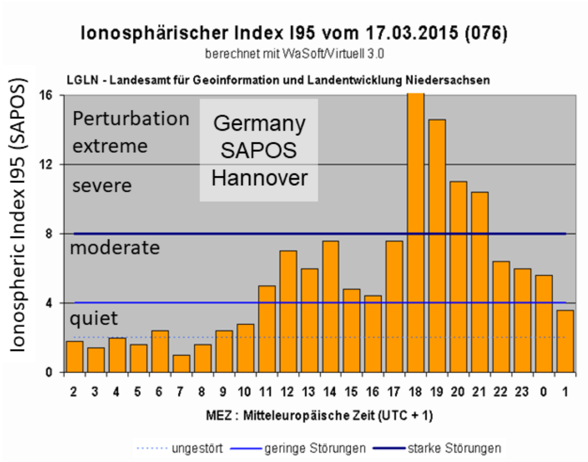
Propagation of perturbations on St. Patrick's Day storm at March 17, 2015

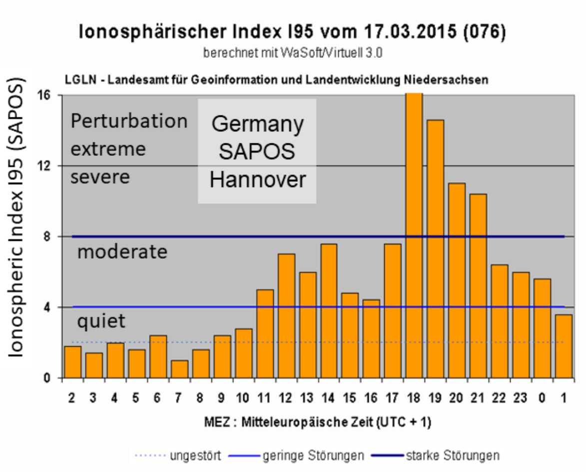


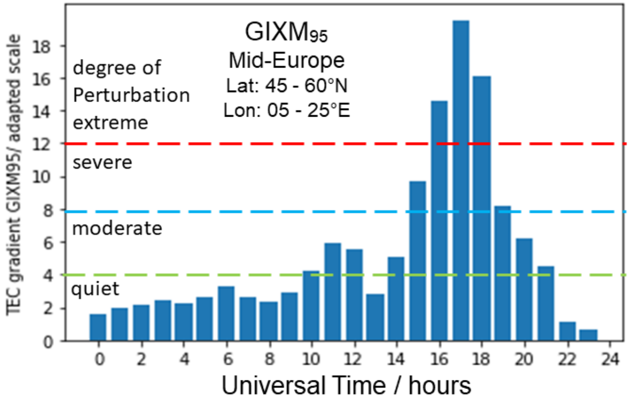
GIXM /GIXM95 scaling for GNSS positioning
Sample day: March 17, 2015

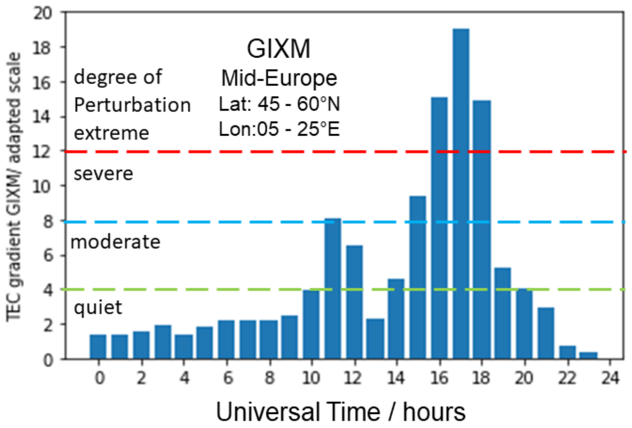










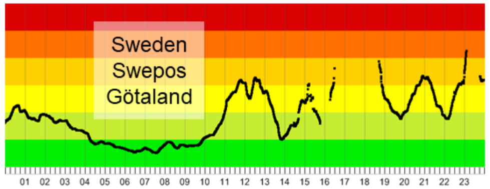


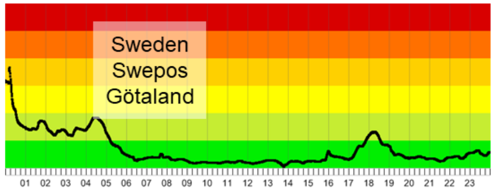
- Comparison of index approaches with user estimates of residual errors
- Top: SWEPOS
  - Service for high accurate GNSS positioning in Sweden
  - Operates Swedish national reference system
  - https://www.l5navigation.se/jonosfarsmonitor/

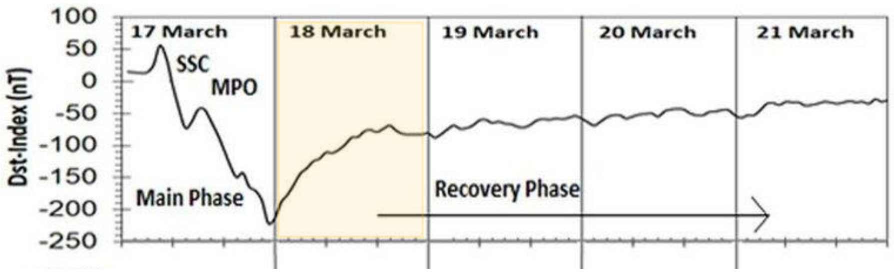
https://www.l5navigation.se/jonosfarsmonitor/

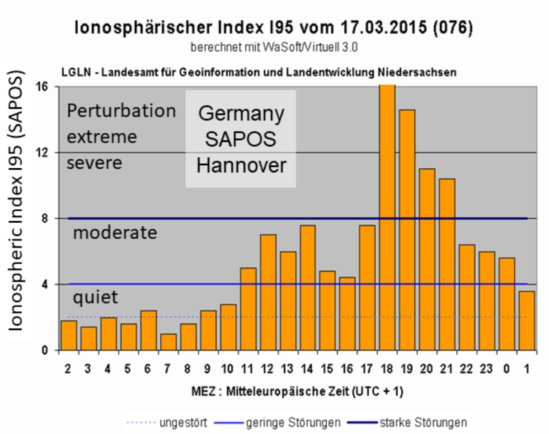
- Middle: SAPOS
  - Service for high-accurate GNSS measurements in Germany
  - Operates German GNSS reference network
  - https://www.lgln.niedersachsen.de/sapos/ionospaerischer-index-i95-51389.html
- Comparison GIXM95 and GIXM
  - Bottom left: adapted GIXM95 scale
  - Bottom right: adapted GIXM scale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

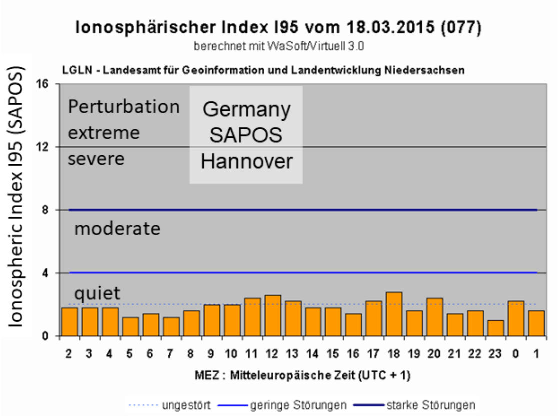
GIXM scaling adapted to GNSS positioning approach (I95)
Sample days: March 17 and 18, 2015

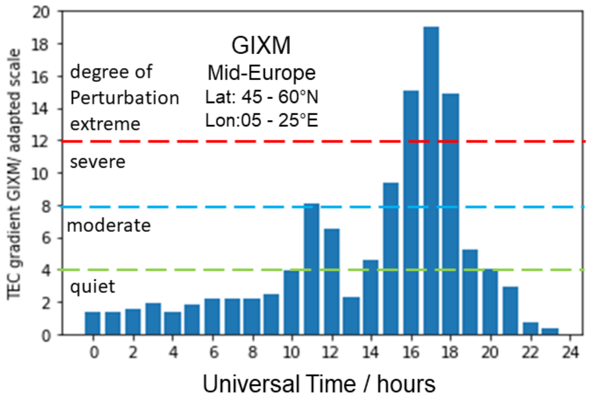


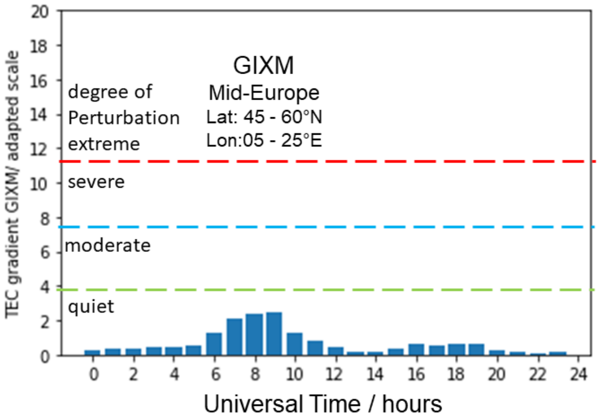












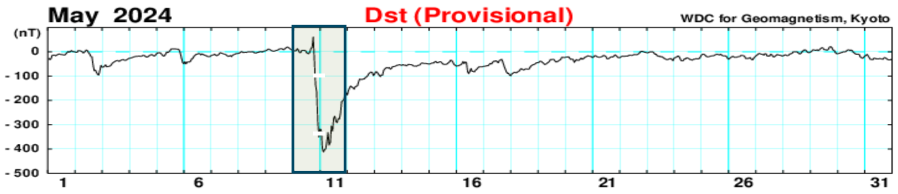
GIXM on March 17 and 18, 2015
Bottom left: March 17, 2015
Bottom right: March 18, 2015

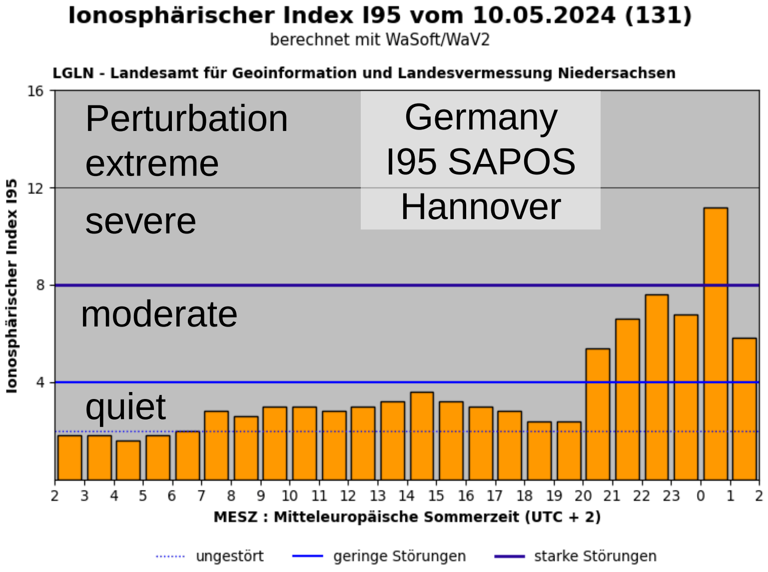
Ionospheric storm effects disappear on March 18, 2015 at all scales

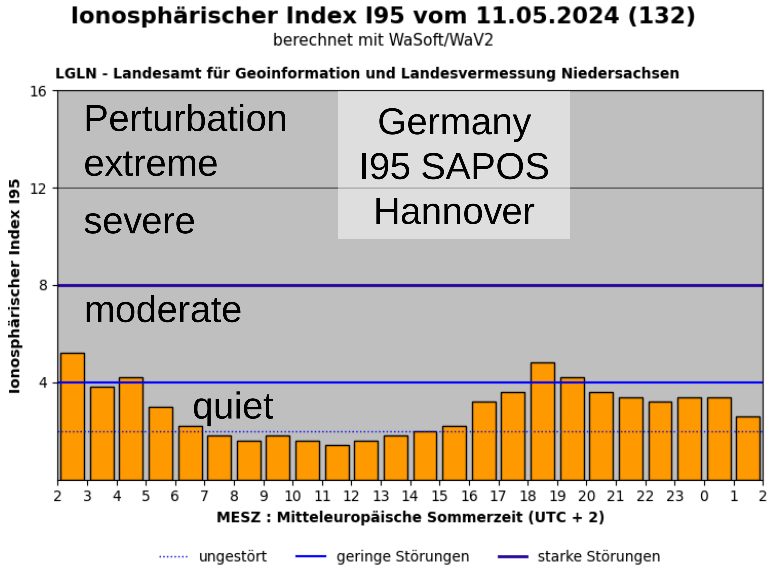
Dst mostly < -100 nT on March18, 2015 during the recovery phase of the geomagnetic storm

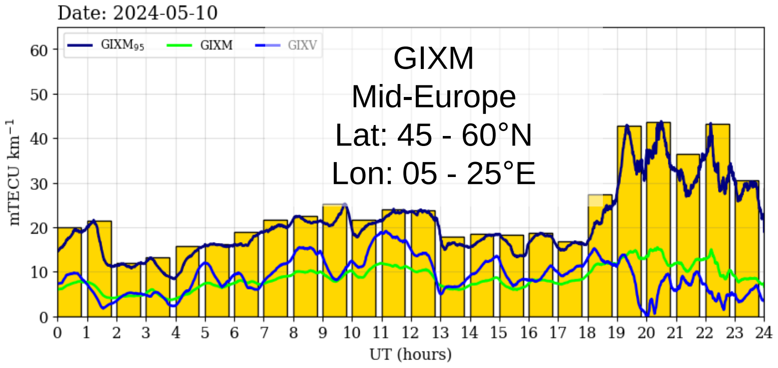
Dst values not suited to estimate the perturbation degree of the ionosphere

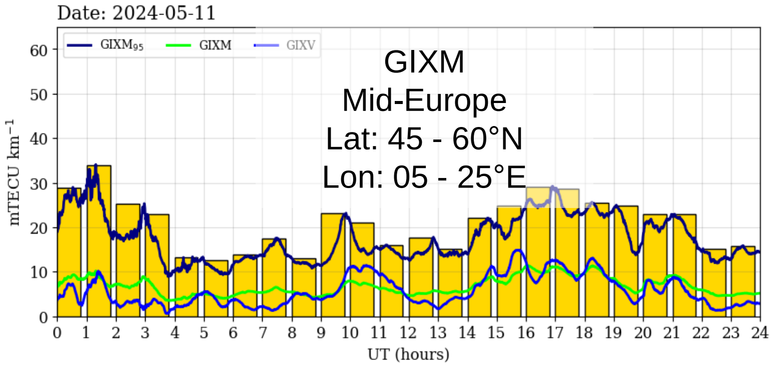
GIXM comparison with I95 from SAPOS
Sample days: May 10 and 11, 2024











- 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)

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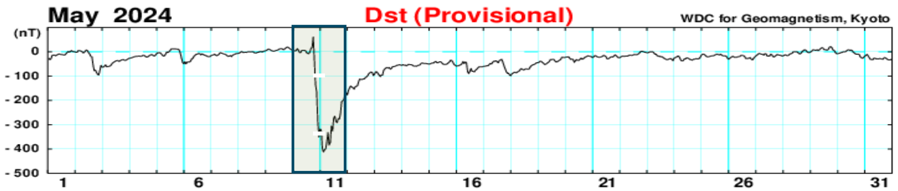

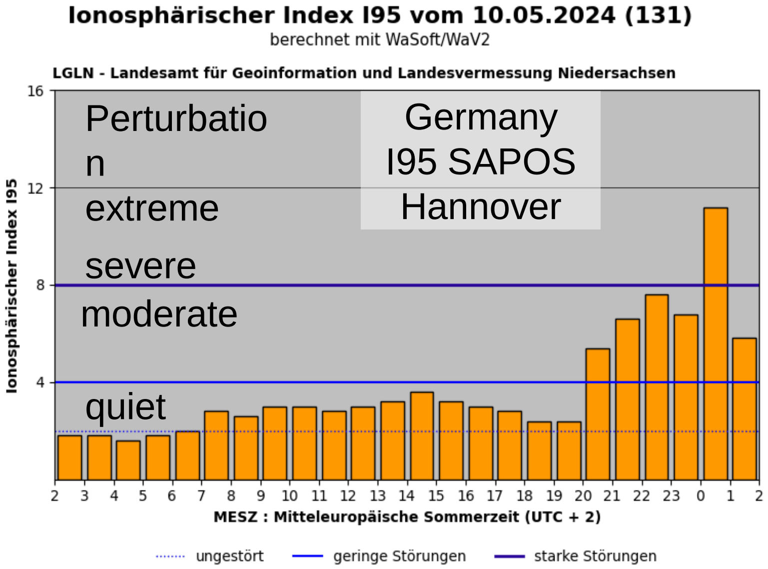

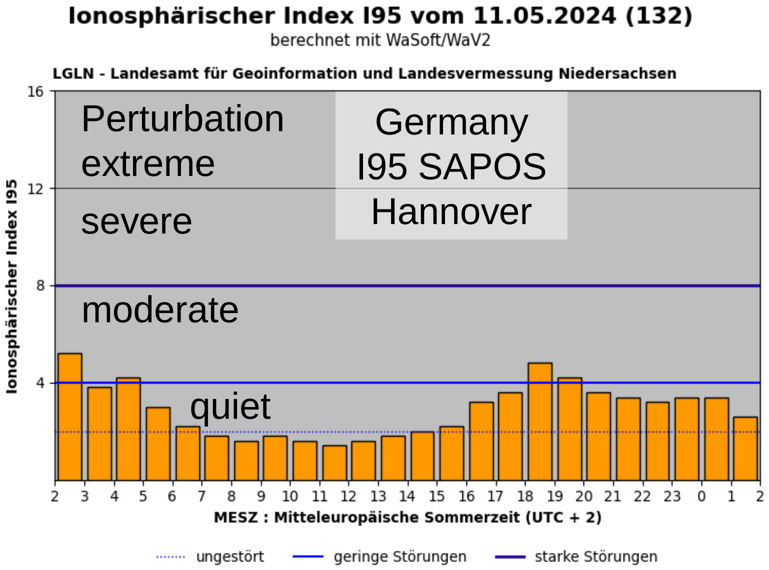

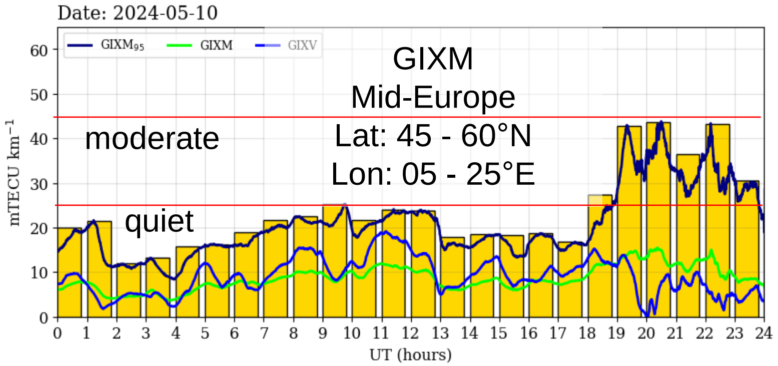

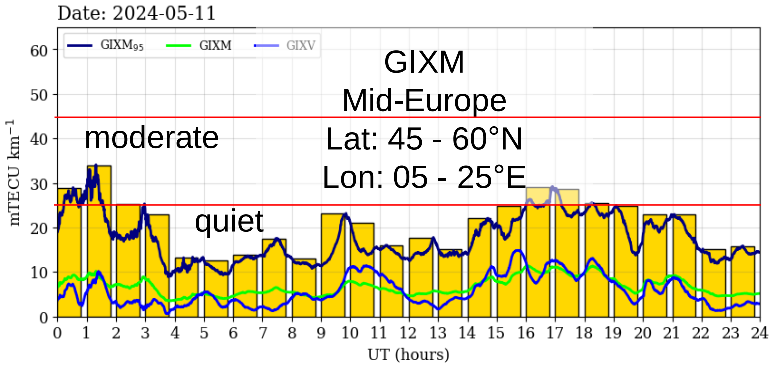

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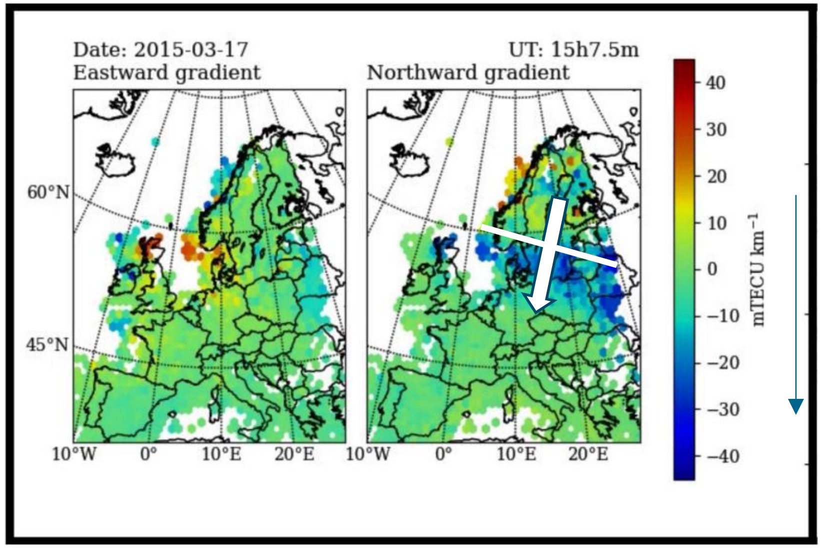
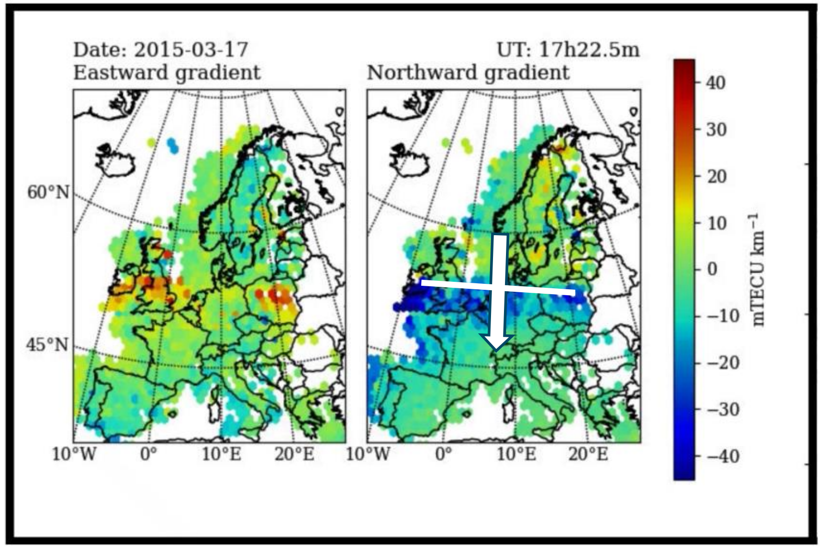
    (seen in the previous slide)
  - physics based definition including units
    Thresholds defined from users point of view

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

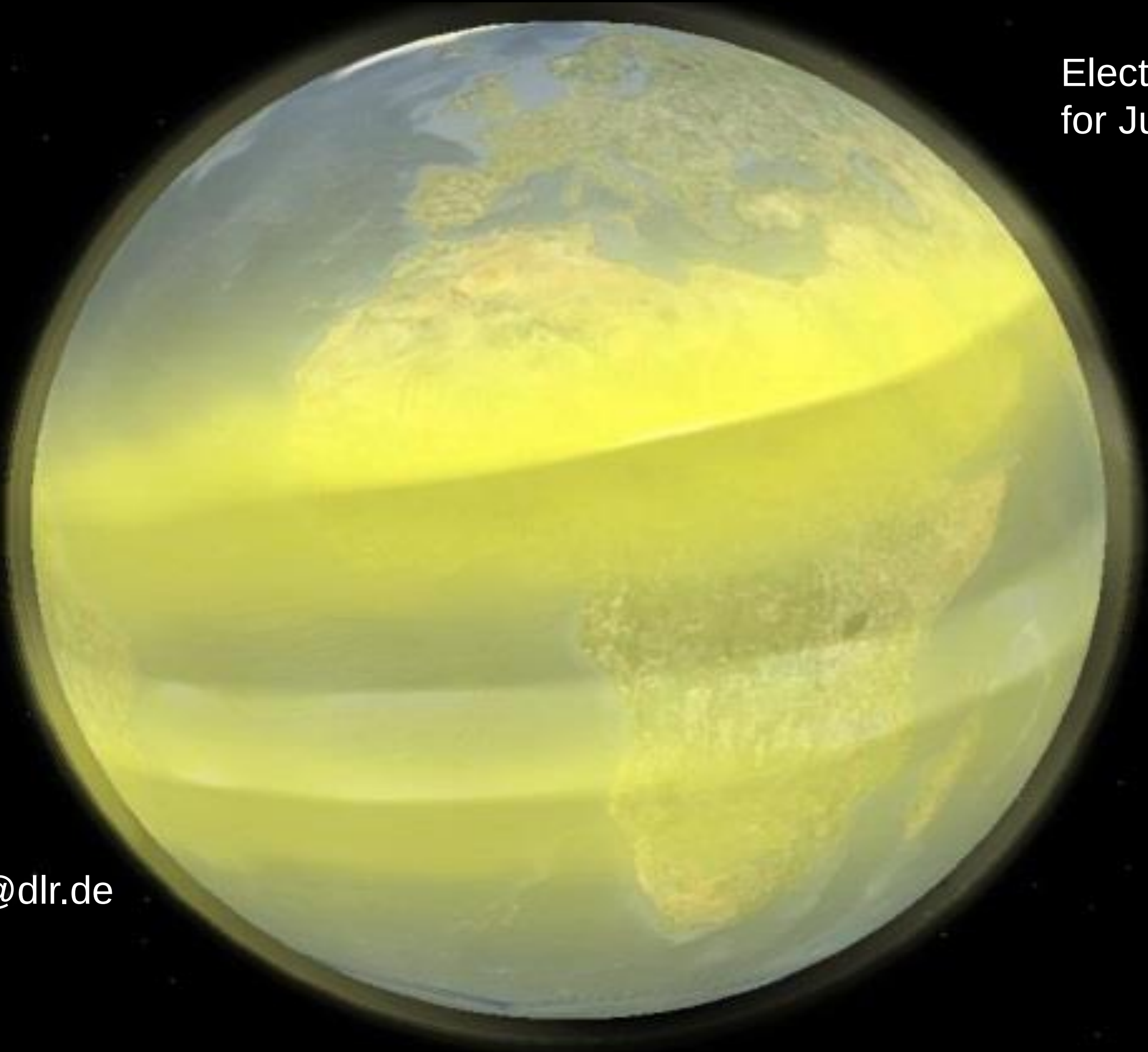
* Propagation velocity estimated between 15:08 and 17:23 UT

Summary and conclusions

- GIX indicates spatial TEC structures over a selected area in near real time with high temporal resolution   ($\Delta t \geq 1s$)
- SIDX indicates rapid change rates of TEC over a selected area with a time resolution Δt depending on the sampling rate of measurements
- Two different perturbation scales suggested
  - Academic based (use ionospheric parameters, solar wind relationships, comparative studies)
  - Application based (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 perturbations
  - Relationships between solar wind and indices are used to estimate dynamics of perturbation
- Close dialogue with users of space based radio systems (e.g. GNSS, remote sensing radars, radio astronomy) required to improve algorithms and scales.

Ionosphere from space

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



Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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Thank you !

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