

On the impact of ionospheric variability and disturbances on GNSS-based positioning applications

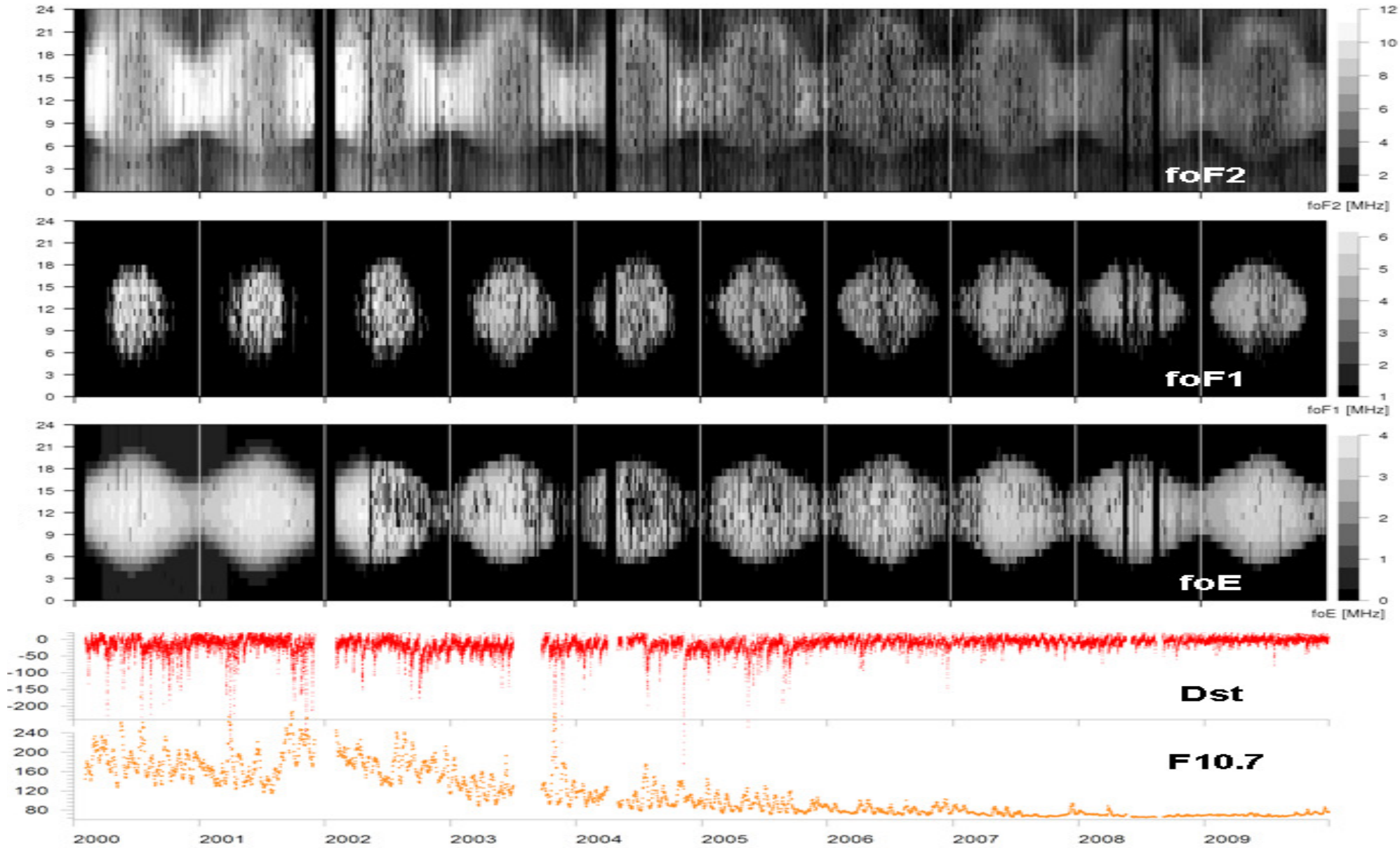
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The ionospheric plasma can significantly influence the propagation of radio waves and the ionospheric disturbances are capable of causing range errors, rapid phase and amplitude fluctuations (radio scintillations) of GNSS satellite signals that may lead to degradation of the system performance, its accuracy and reliability.

- Ionospheric variability and disturbances – observations
- Impact on GNSS-based positioning applications
- RMI services – Space Weather and Navigation Systems project
- Summary and Outlook

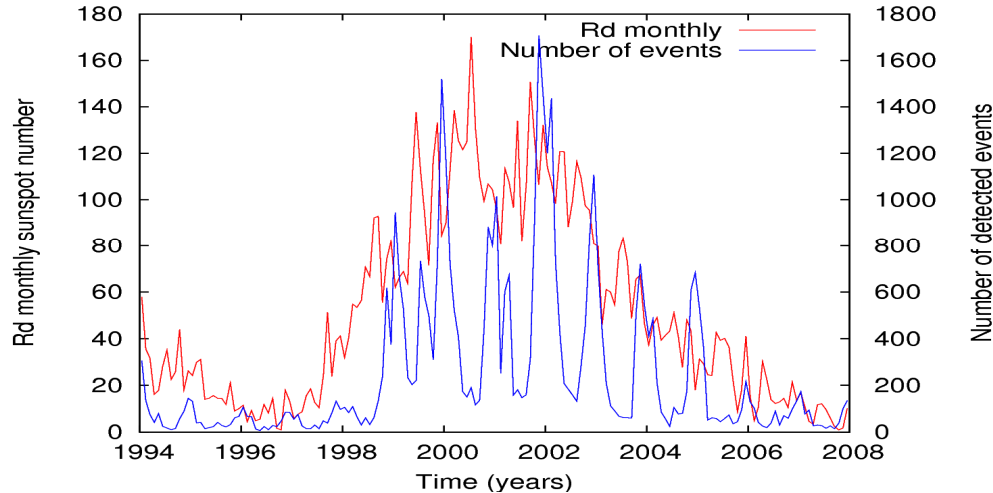
Ionospheric variability – critical frequencies



$$ROT = \frac{TEC(t + \Delta t) - TEC(t)}{\Delta t}$$

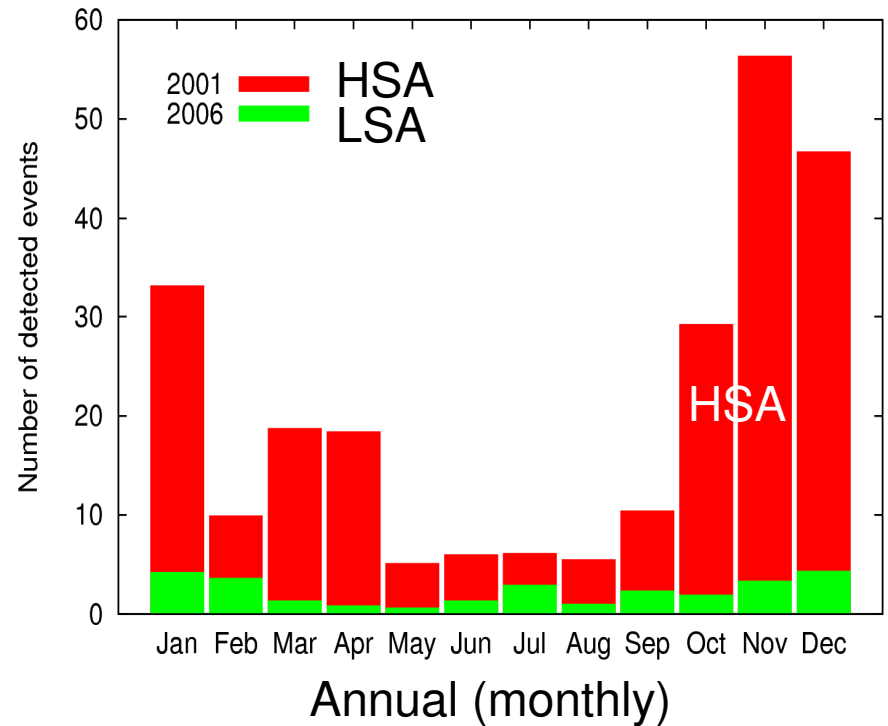
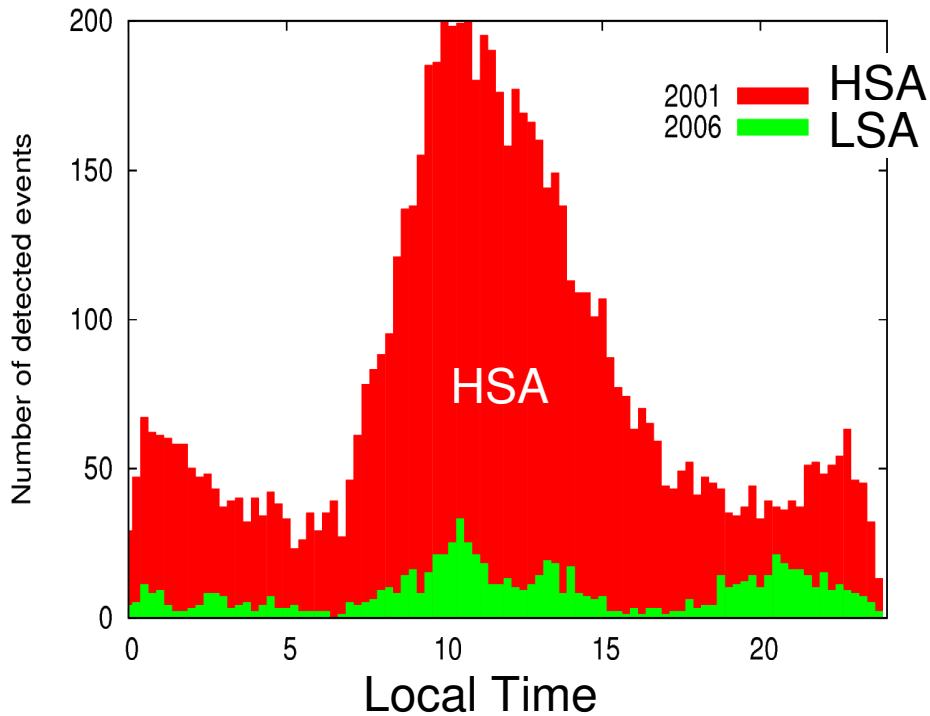
$$ROTI = \sigma(ROT)_{\Delta t}$$

Event registered if:
 $ROTI > 0.08 \text{ TECU/min}$

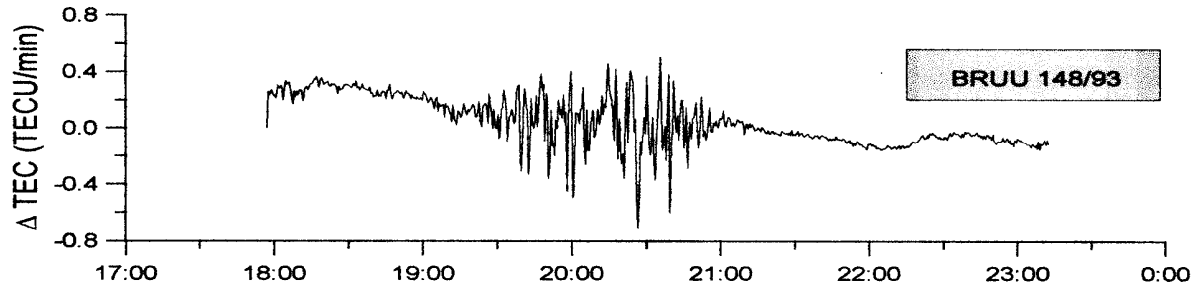


Small-scale structures
 (number of events)

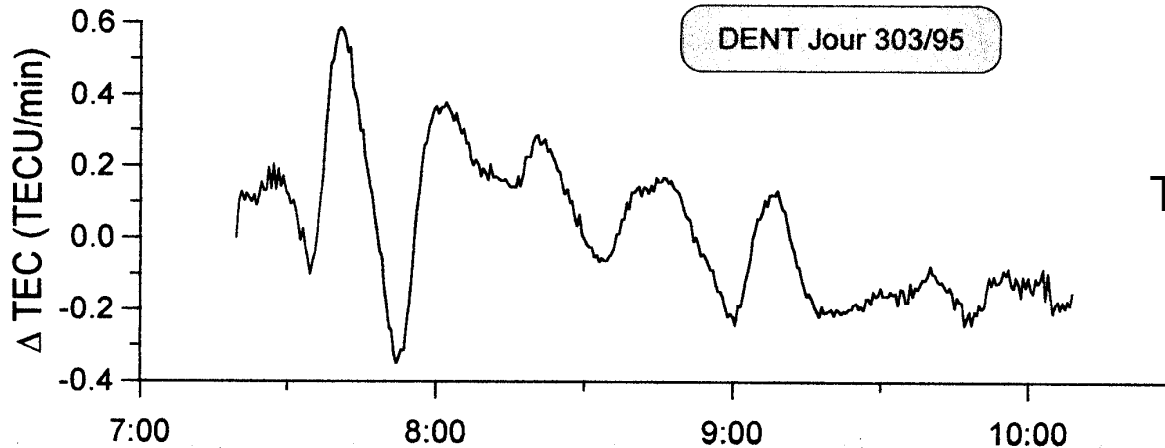
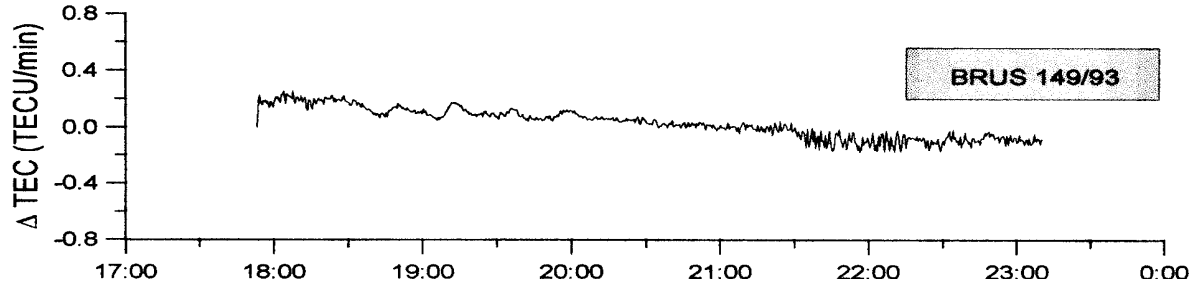
More frequent during
WINTER and **HSA**
 (high solar activity)



Ionospheric variability – TEC (structures)



Noise-like structures



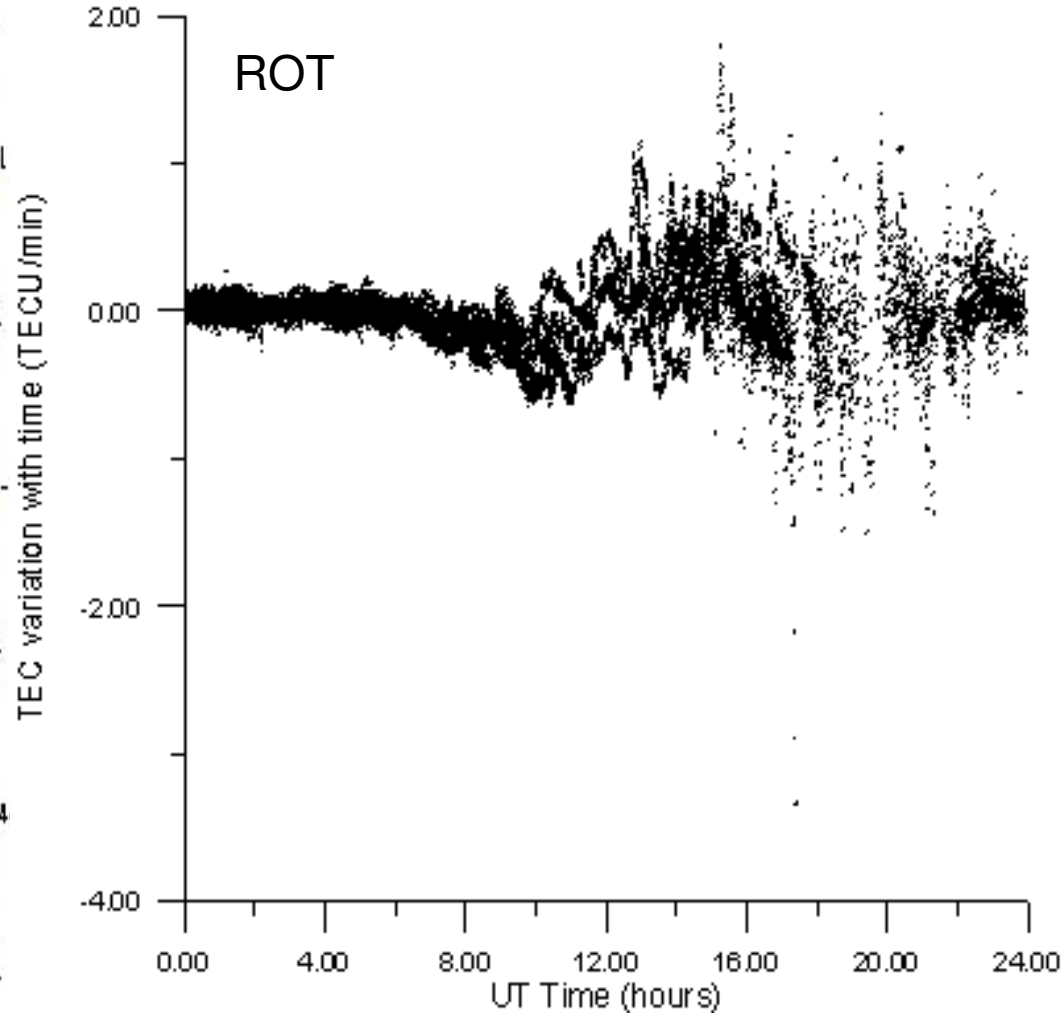
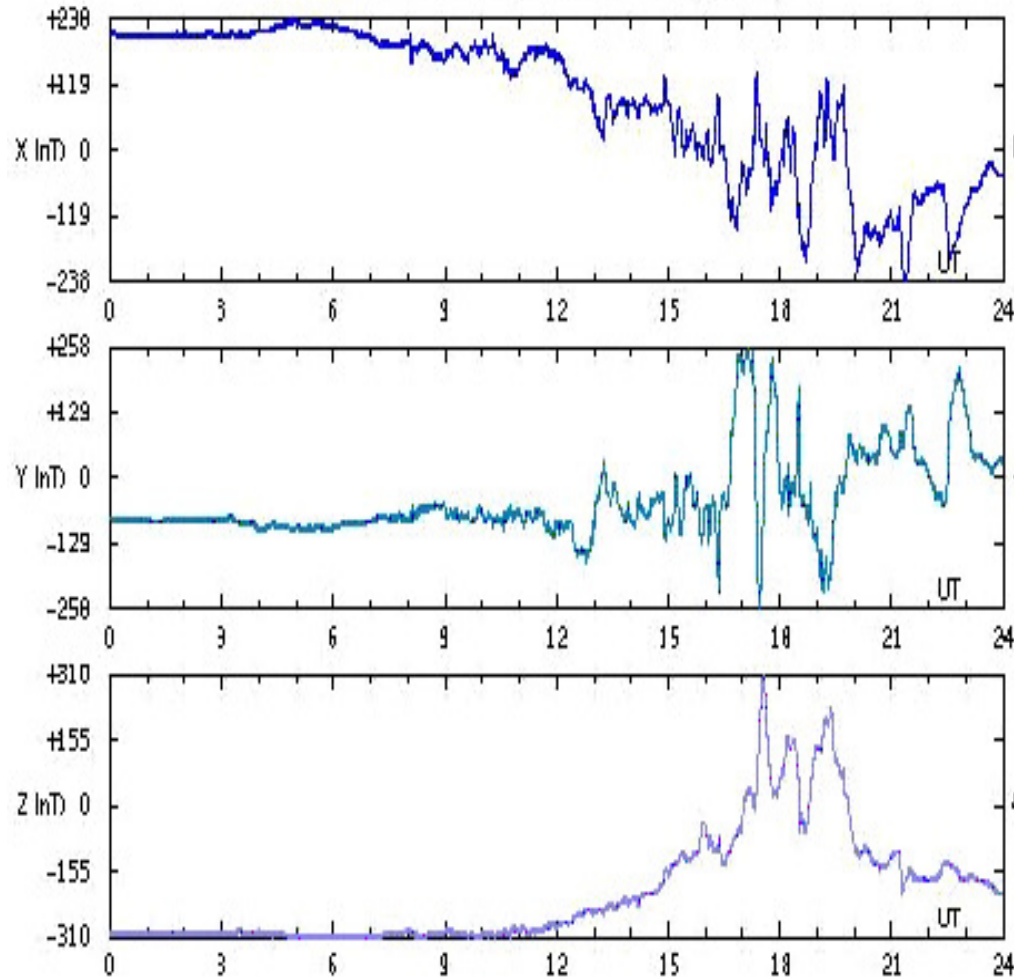
Traveling ionospheric disturbances

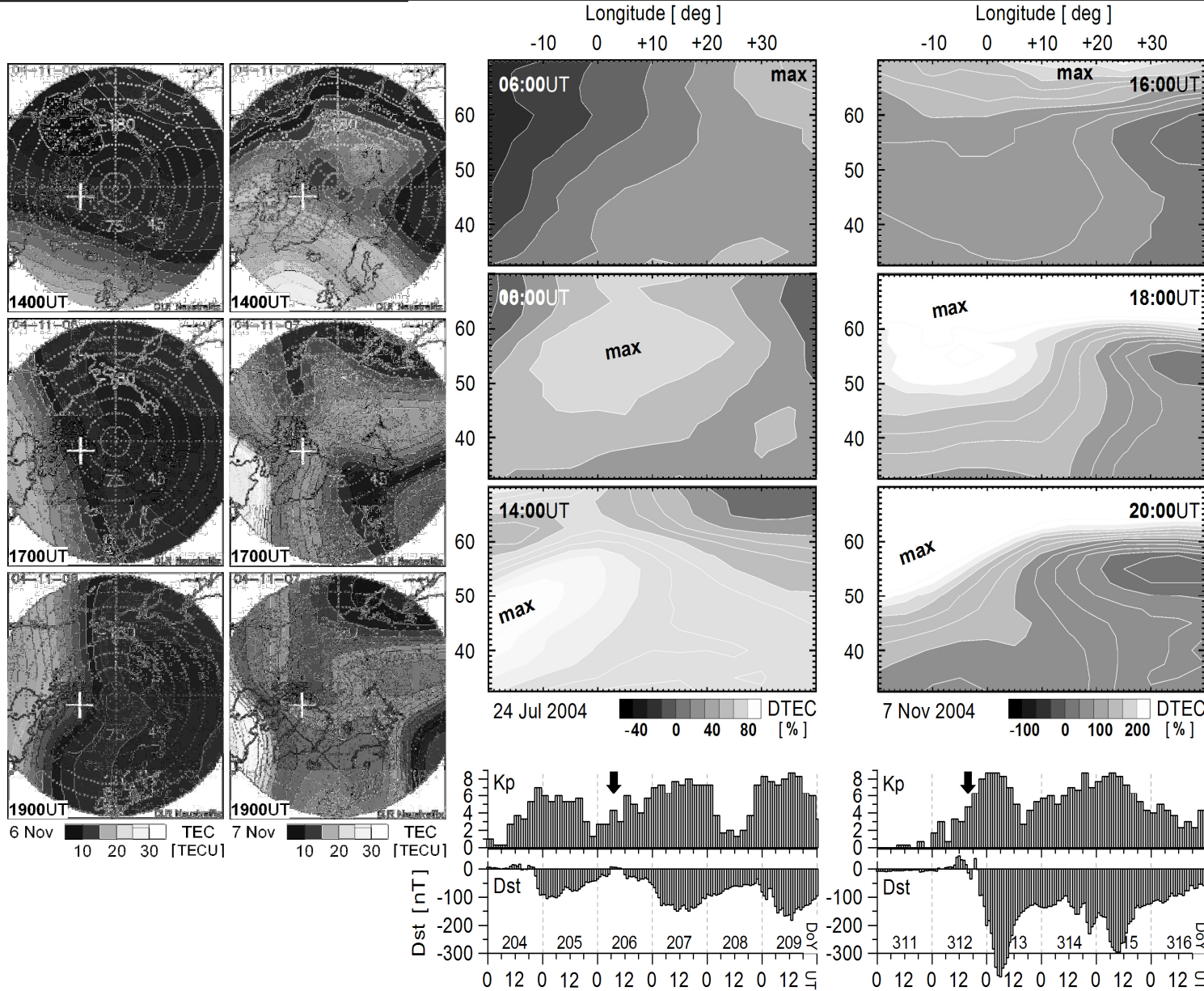
Ionospheric variability – TEC (storm-time)

INTERMAGNET One Minute Variation of Geomagnetic Field - NOV 20 2003

Definitive Data supplied by Royal Meteorological Institute of Belgium

DOU - Dourbes (Lat: 50.1 Long: 4.5)





TEC relative deviation (DTEC)
 $\Delta\text{TEC} = (\text{TEC} - \text{TEC}_{\text{med}}) / \text{TEC}_{\text{med}}$

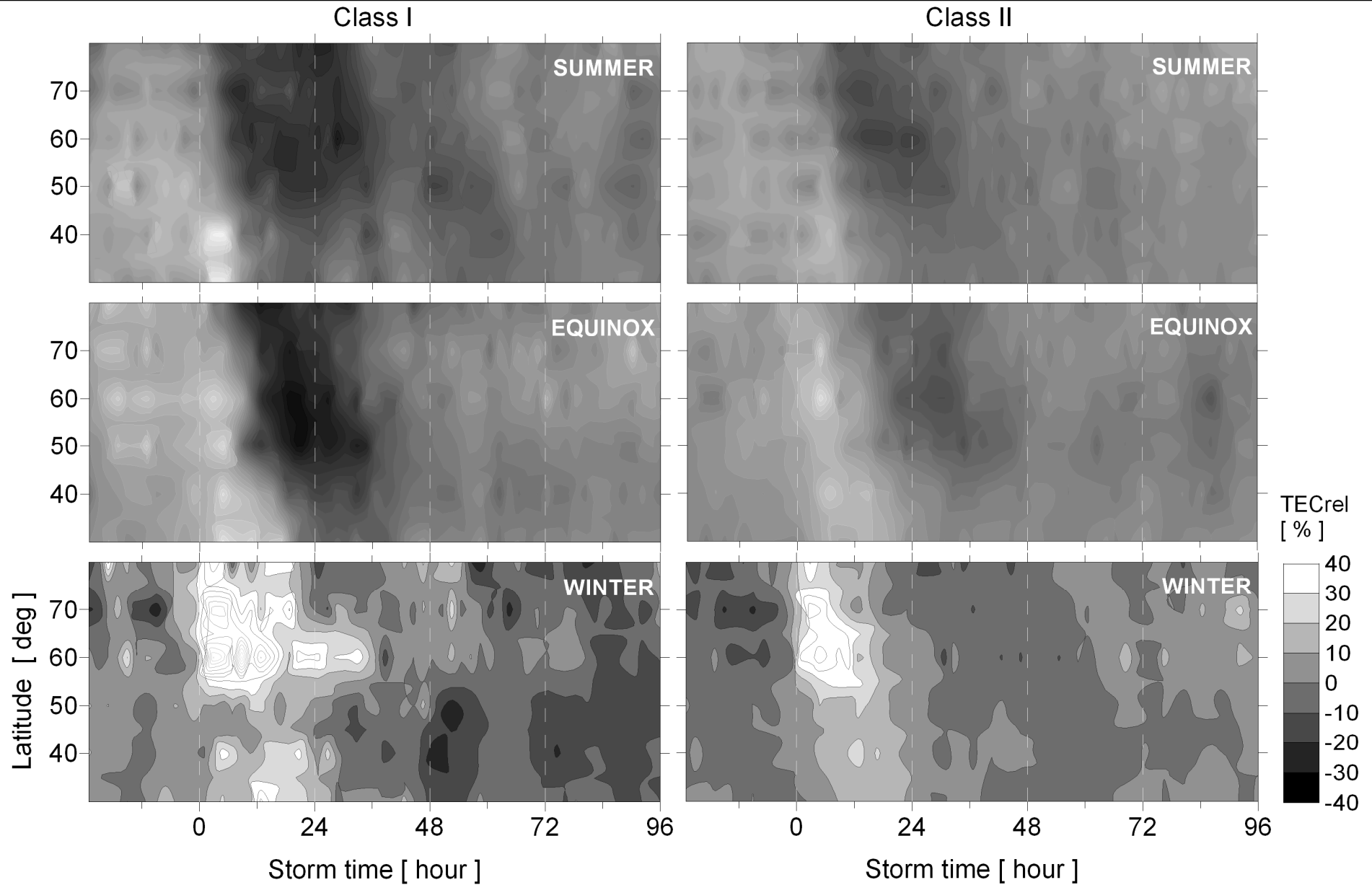
Summer (left panel):

Positive ΔTEC response (peak at 45°N). Plasma uplifting (+ reduced loss rate) due to and equatorward neutral winds following the high latitude heating and expansion.

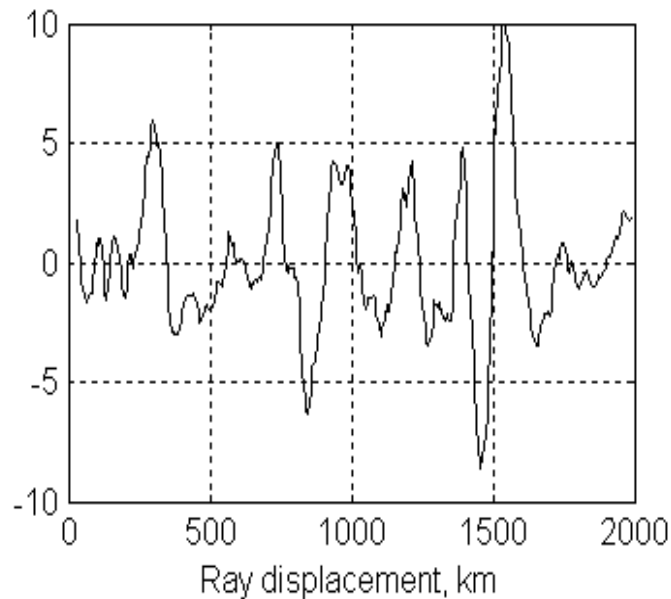
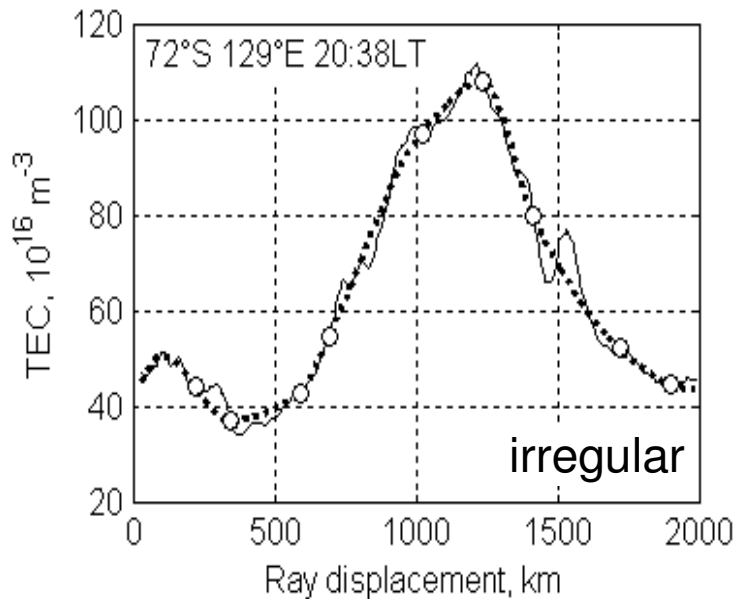
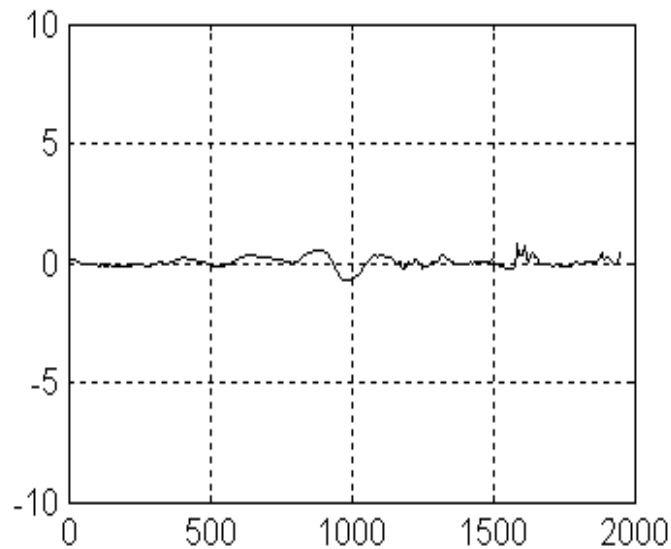
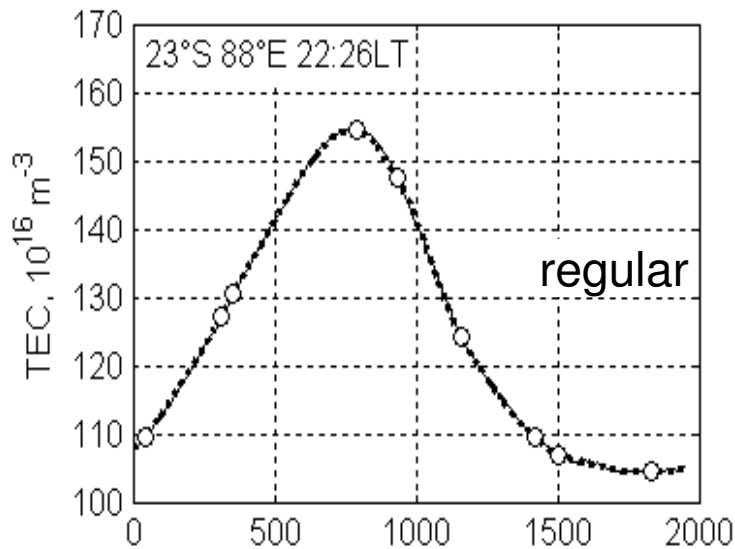
Winter (right panel):

Positive ΔTEC response. The peak however didn't propagate far below 50°N. Thermospheric winds blow preferentially from the summer to the winter hemisphere and so being in phase (summer) or anti-phase (winter) with the equatorward perturbation induced winds.

Ionospheric variability – TEC (storm-time)



Ionospheric irregularities



TEC(t) \Rightarrow TEC(s)
 Deviation of measured TEC(s) from TEC profile's (polynomial) approximation

$$\Delta TEC_a(s) = TEC_{Meas} - TEC_{Pol}$$

$$\Delta TEC_r(s) = \frac{\Delta TEC_a(s)}{TEC_{Meas}^{Max}}$$

$$\Delta TEC'(s) = d(\Delta TEC) / ds$$

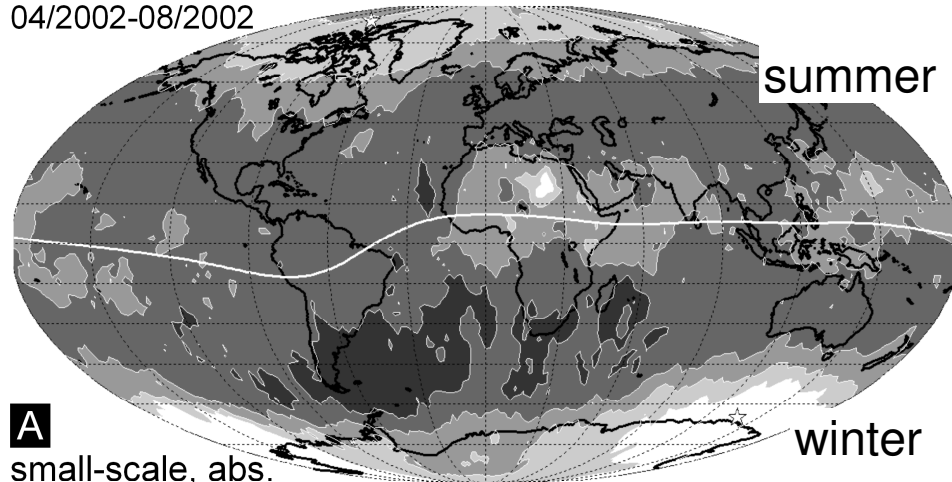
Disturbance Activity Level

$$DA = \sqrt{\frac{1}{D} \int_0^D \Delta TEC'(s)^2 ds}$$

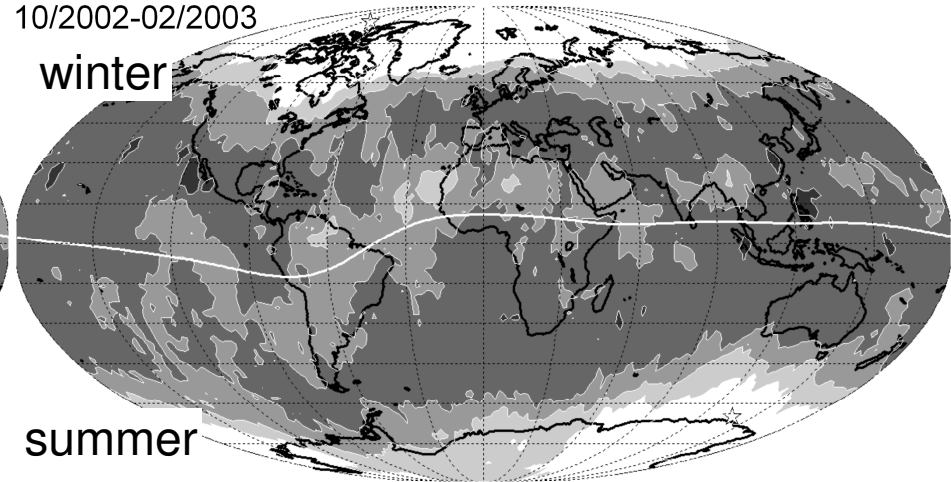
D – distance

Ionospheric irregularities (small-scale)

04/2002-08/2002



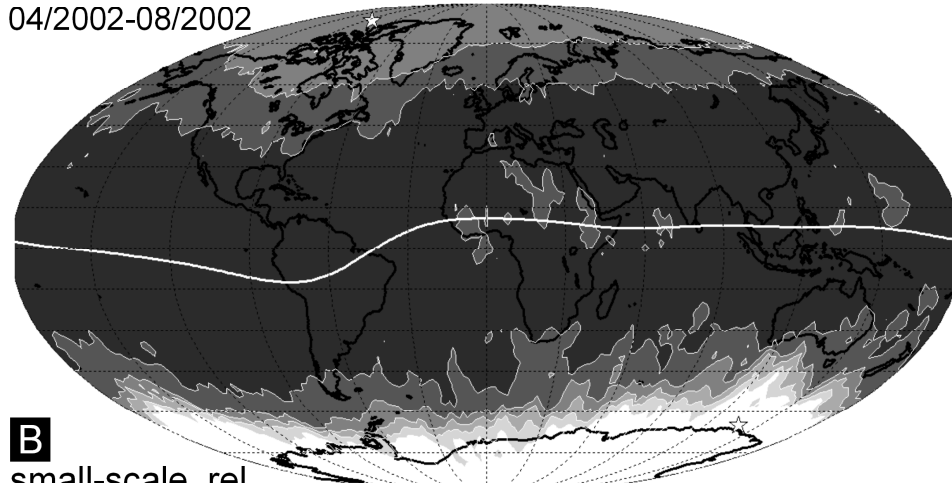
10/2002-02/2003



A
small-scale, abs.

0 2 4 6 8 [TECU . km]

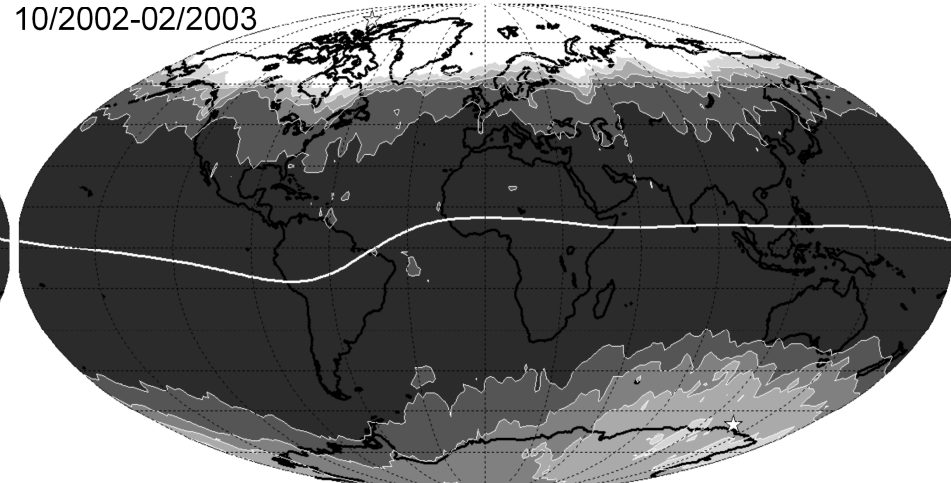
04/2002-08/2002



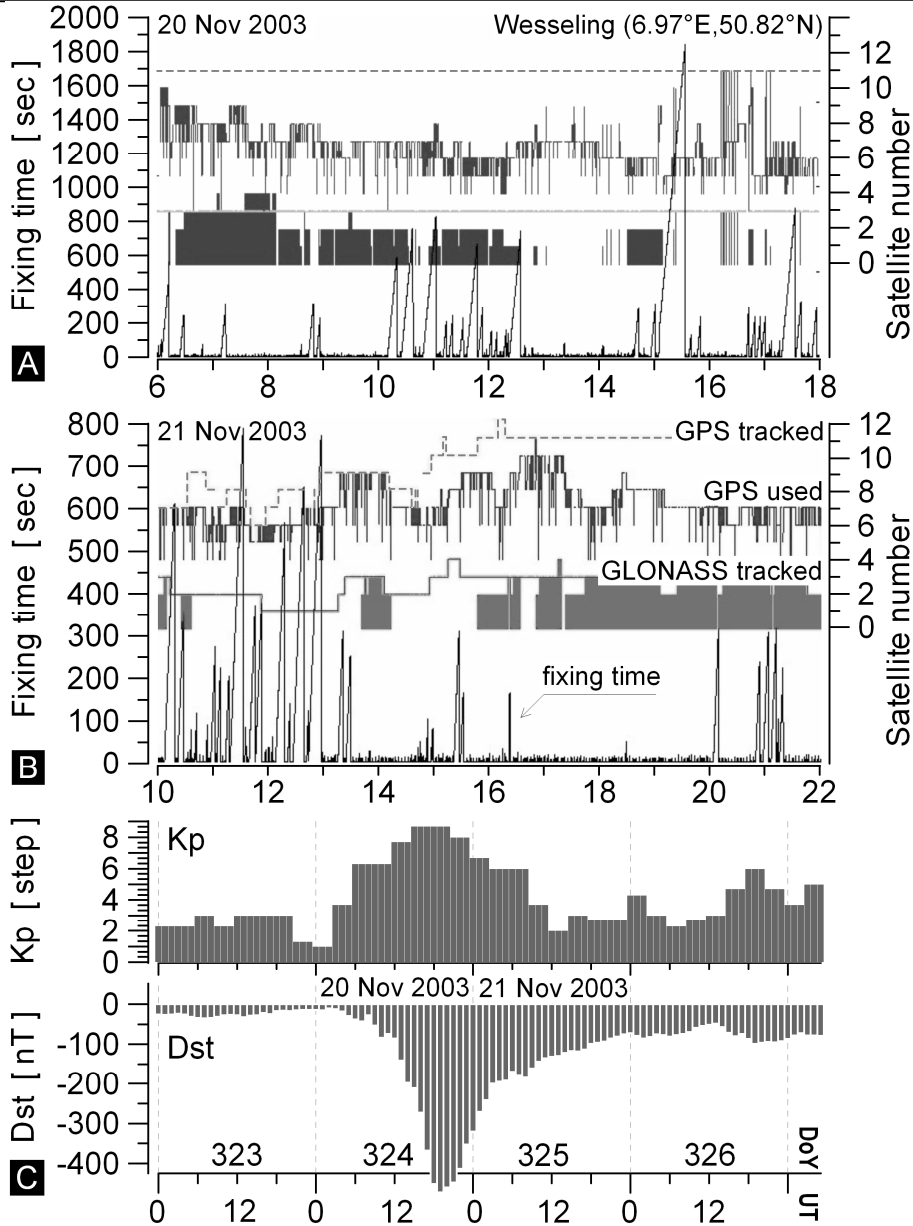
B
small-scale, rel.

0 0.04 0.08 [km]

10/2002-02/2003



- Pronounced activity at higher and equatorial latitudes
- Higher intensity during winter
- Higher occurrence frequency during day



• Increased time for fixing the ambiguities

Prolonged and/or frequent increases of the ambiguity fixing time may have adverse impact on GNSS positioning and safety-critical applications.

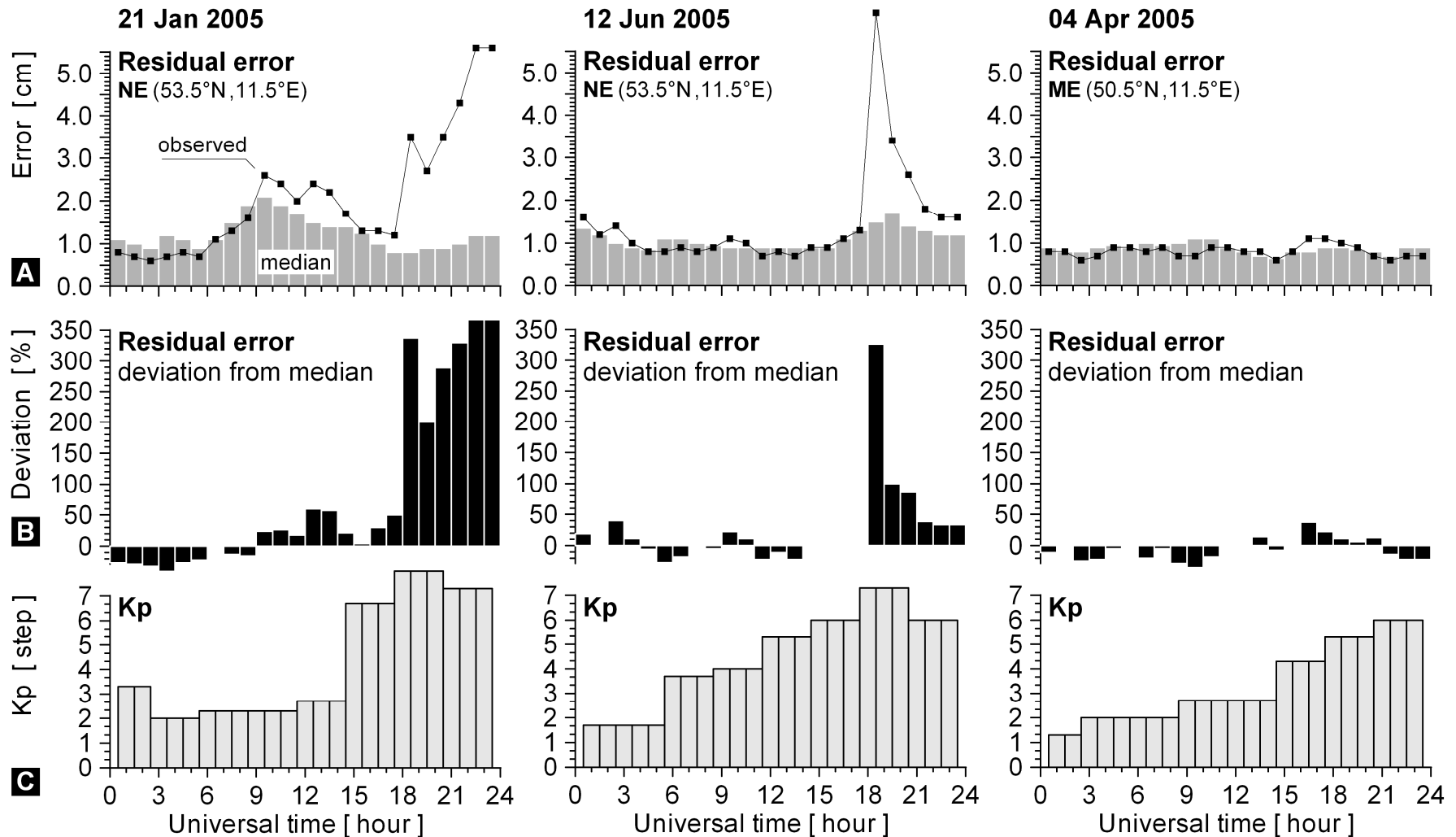
AFT Categorisation (1-3 accpt, 4-6 probl)

0 - 10 sec	1
10 - 60 sec	2
60 - 120 sec	3
120 - 300 sec	4
300 - 600 sec	5
600 + sec	6

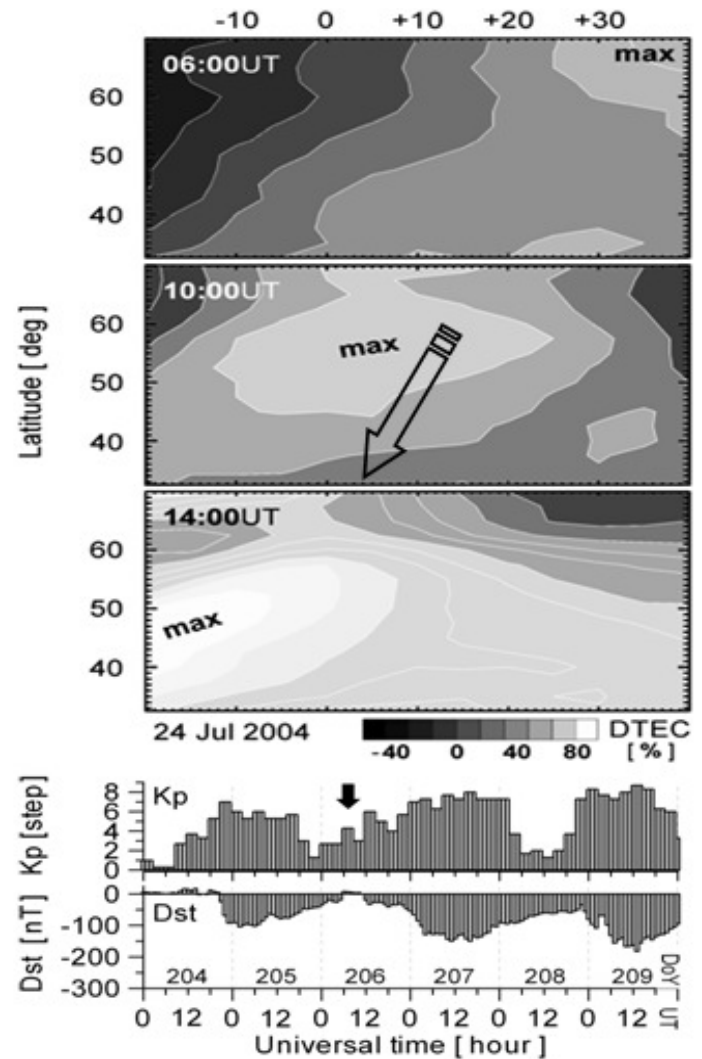
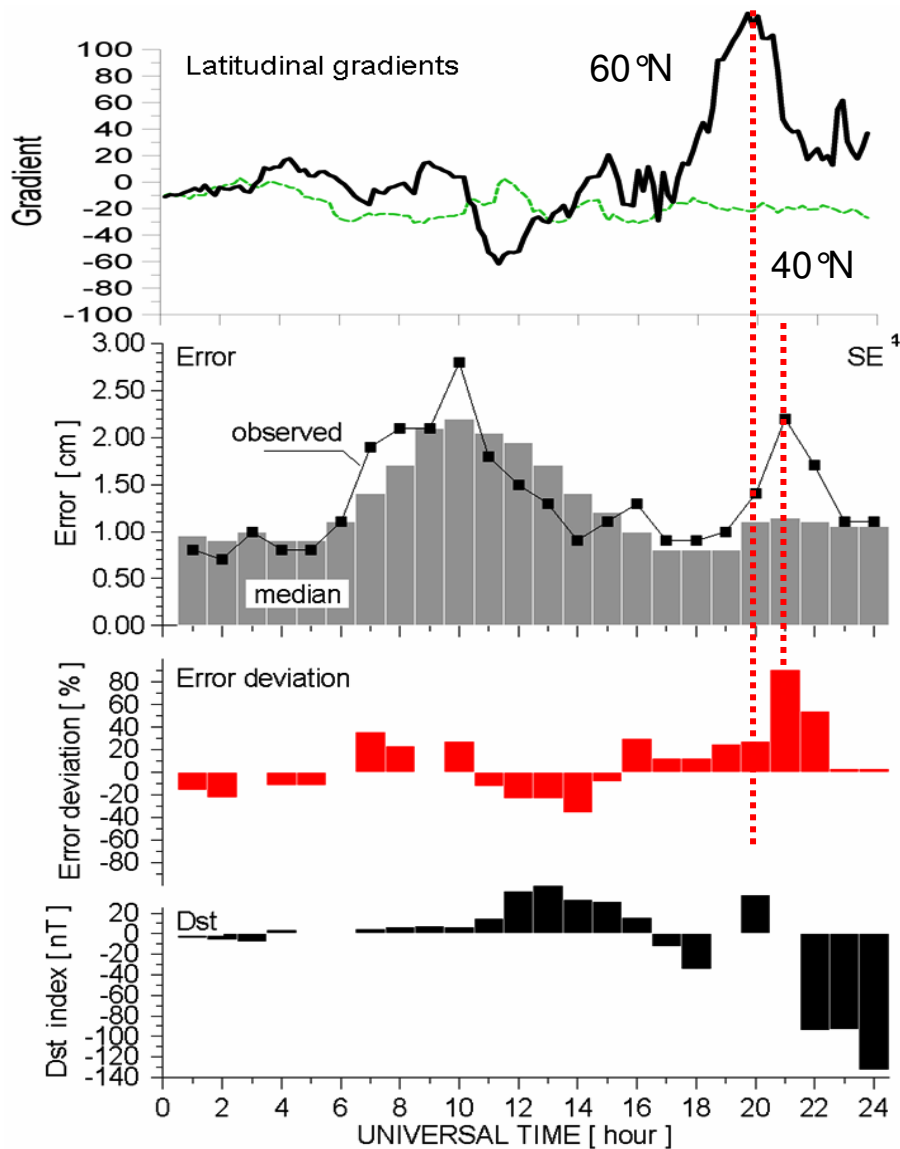
• Decreased number of tracked, processed, and used GNSS satellites

For each particular ground receiving station, it is necessary to track as many GNSS satellites as possible. Some of these 'tracked' satellites cannot be used due to restrictions imposed on the satellite elevation angle (elevation cut-off criterion), signal-to-noise ratio (SNR criterion), etc. The remaining satellites are used in the processing software for fixing the ambiguities. Further restrictions are imposed on the solution, such as limitation on error magnitude and stability of solution.

The number of 'processed' satellites should not be less than five to ensure reliable services.

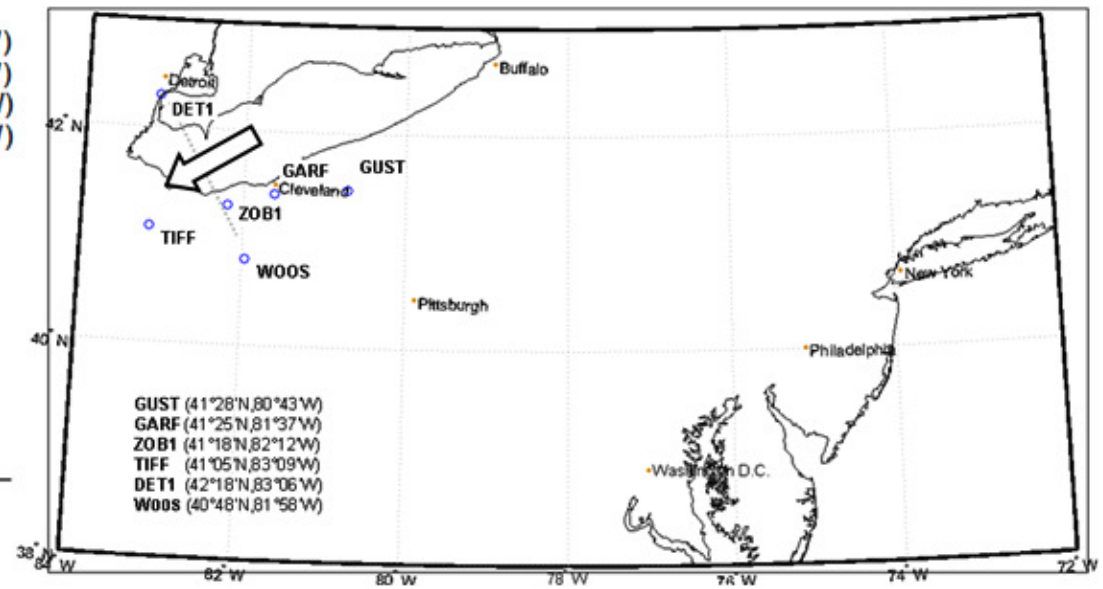
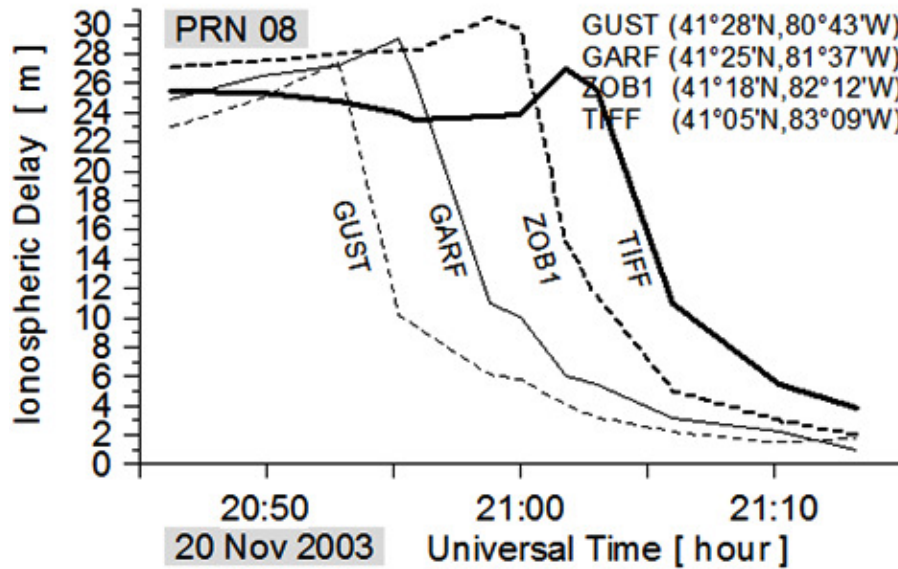
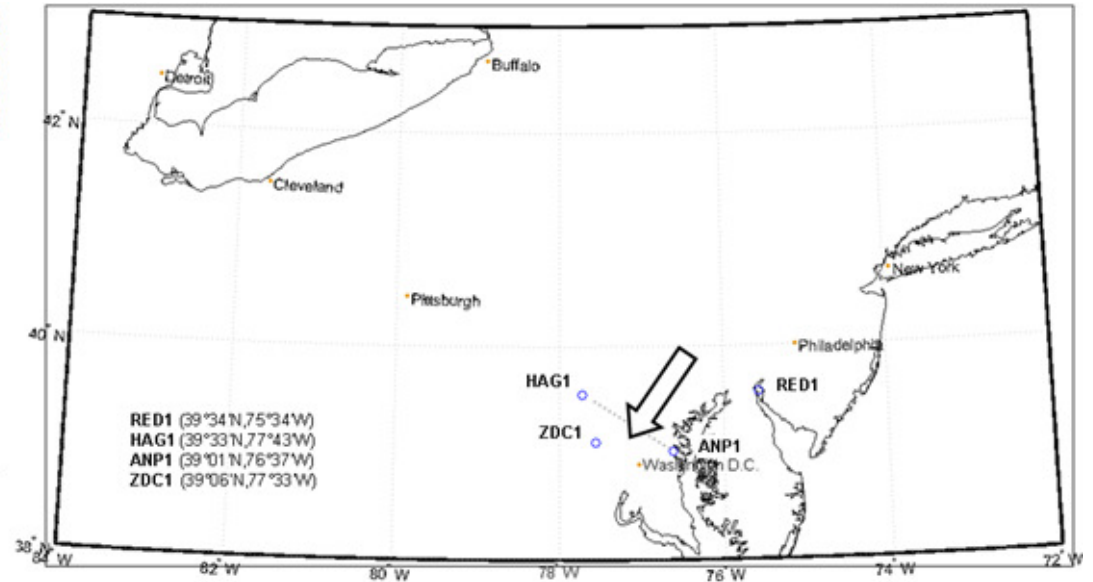
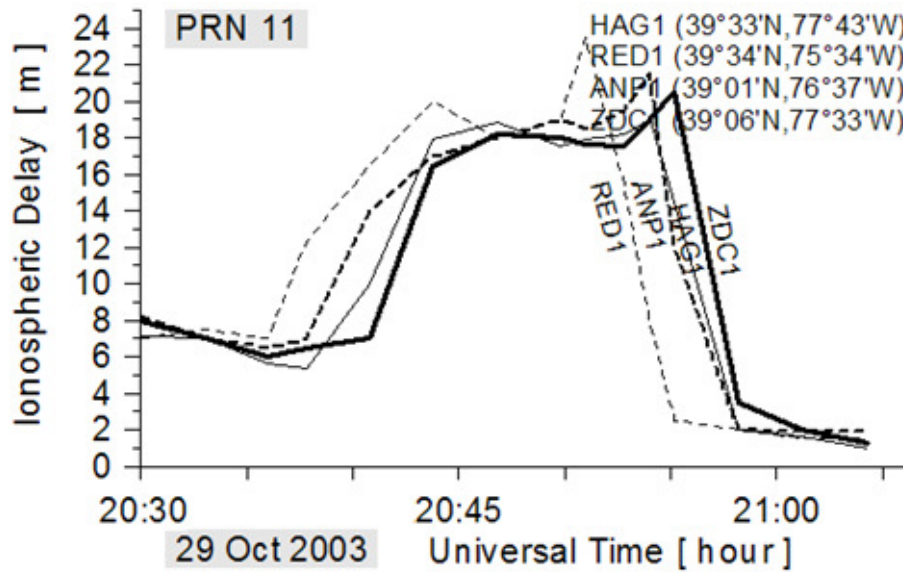


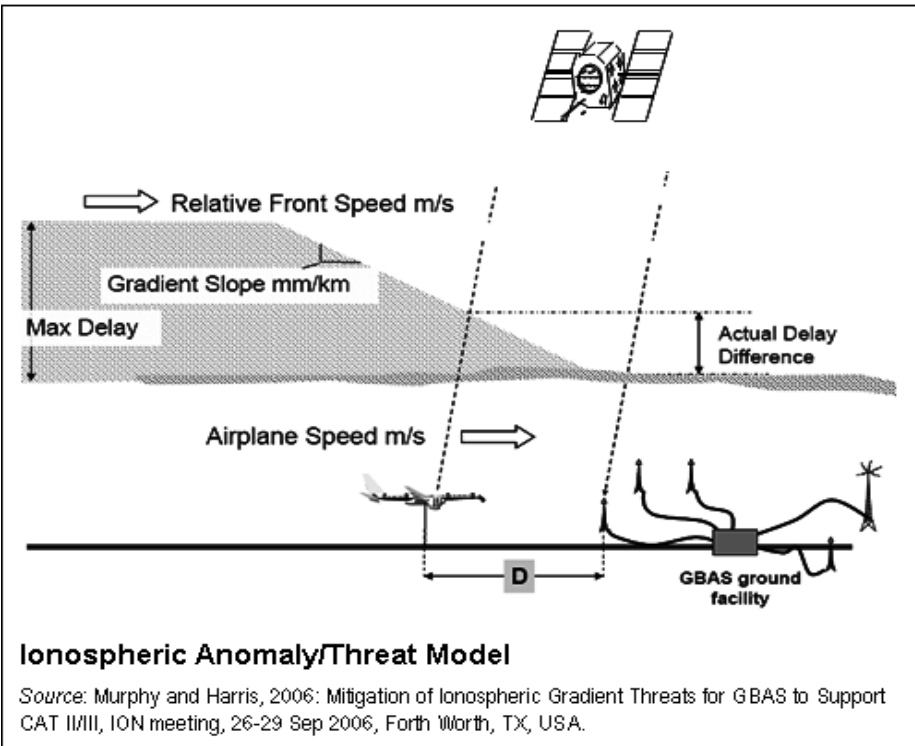
Ionospheric residual error – impact of geomagnetic activity/storms



Ionospheric residual error – impact of latitudinal / temporal gradients

Impact of ionospheric disturbances on aviation





For a given GPS satellite i , the code measurement made by the user (e.g. aircraft) affected by an ionospheric error (a.k.a. slant ionospheric delay):

$$I_u^i = 40.3 \frac{TEC_u^i}{f^2}$$

Code measurement made by the reference station on the same satellite i also affected by an ionospheric error:

$$I_r^i = 40.3 \frac{TEC_r^i}{f^2}$$

The reference station provides the value of I_r^i as ionospheric correction to the user.

Quality of differential ionospheric correction depends on the value of

$$I_u^i - I_r^i$$

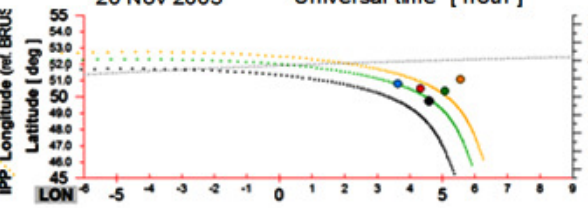
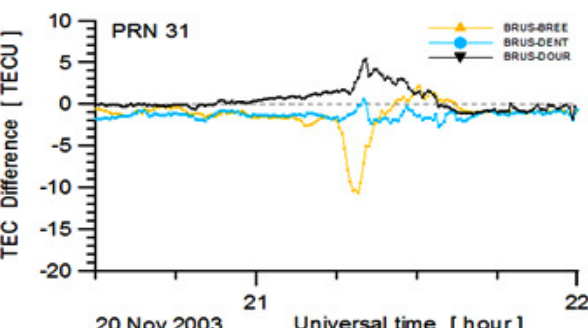
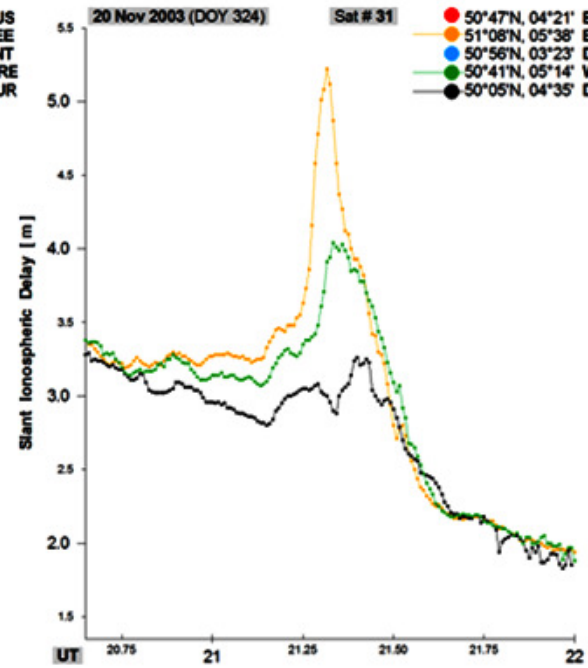
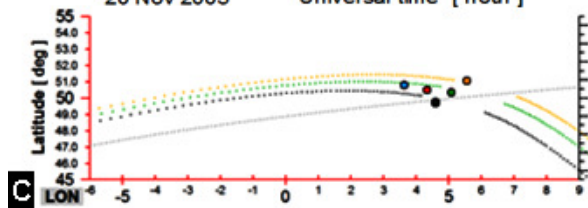
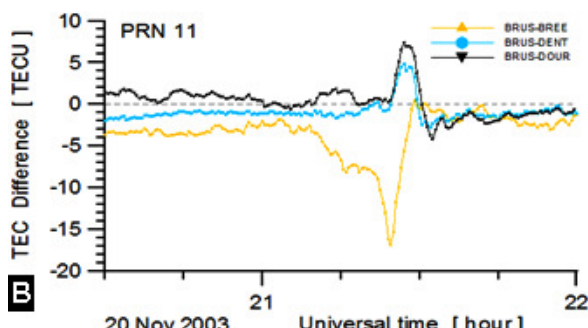
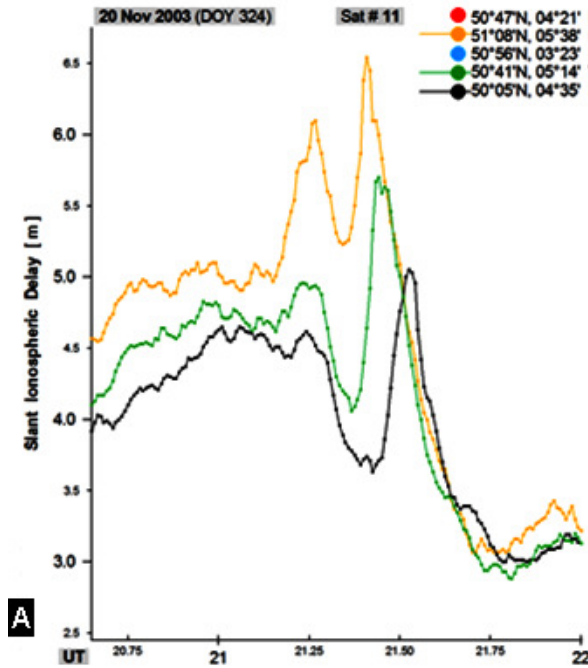
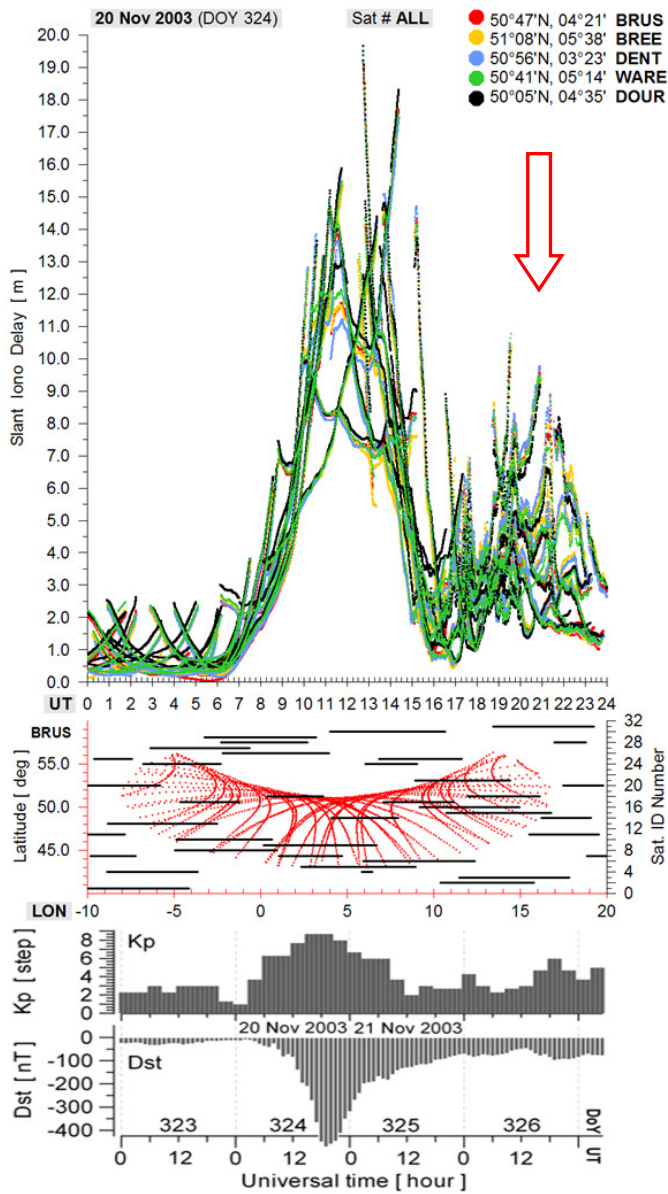
(i.e. the difference between the slant delays measured at the user and at the reference station).

This difference depends on

$$TEC_u^i - TEC_r^i$$

The ionospheric spatial anomaly can be presented as a semi-infinite “cloud” with a wave front pattern.

The ionospheric gradient is modelled as the linear change in vertical ionosphere delay between the “high” (anomalous) and “low” (nominal) delay zones.



The ionosphere/space weather effects on GNSS signal propagation remain some of the main error sources for several positioning techniques

- GNSS signals are electromagnetic signals and as such are nonlinearly **dispersed and refracted** when transmitted through a highly charged environment like the ionosphere
- Dispersion and refraction of the GPS signal is referred to as an ionospheric range effect because signal **dispersion and refraction cause an error** in the GPS range value
- Ionospheric **range effects are frequency dependent**
- The error effects of ionosphere refraction on the GPS range values are **dependent on solar activity, local time, and satellite geometry**. Ionospheric delay can vary from 40-60 m during the day and 6-12 m at night.
- Resolution of ionospheric refraction can be accomplished by use of a dual-frequency receiver (a receiver that can simultaneously record both L1 and L2 frequency measurements). The L1 and L2 signals can be differenced, and the ionospheric delay uncertainty can be reduced to less than 5 m.

The Space Weather and Navigation Systems (SWANS) research and development project (<http://swans.meteo.be>) is an initiative of the Royal Meteorological Institute (RMI) under the auspices of the Belgian Government via the Solar-Terrestrial Centre of Excellence (STCE).

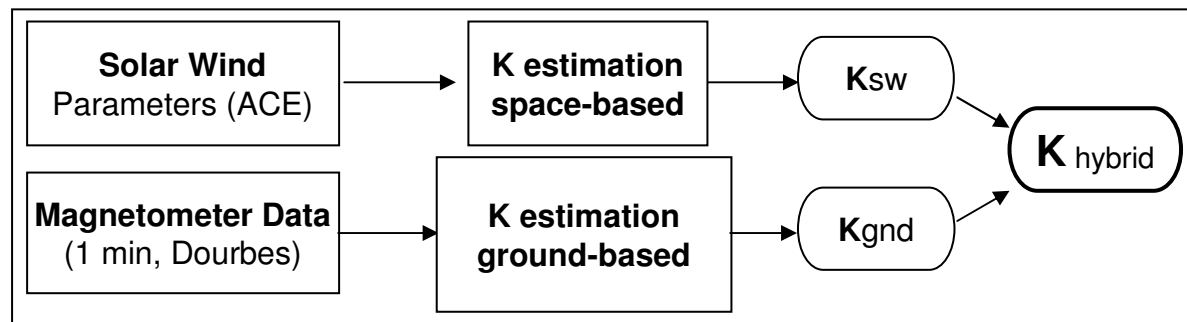
- Research on space weather and its effects on GNSS applications
- Permanent monitoring of the local/regional geomagnetic and ionospheric activity
- Development/operation of relevant nowcast, forecast, and alert services
- Consult professional GNSS/GALILEO users in mitigating space weather effects

Objective:

- To develop service/s that can promptly evaluate the current level of the local geomagnetic activity and to estimate in advance the activity index K.

Developments:

- *Nowcast.* The K nowcast system is based on a fully automated computer procedure for real-time digital magnetogram data acquisition, dataset screening, establishing the regular variation of the geomagnetic field, calculating the K index, and issuing an alert if storm-level activity is indicated.
- *Forecast.* A new hybrid model has been developed utilising space-based (solar wind) observations and local ground-based (magnetometer) measurements to predict (a proxy of) the K index.

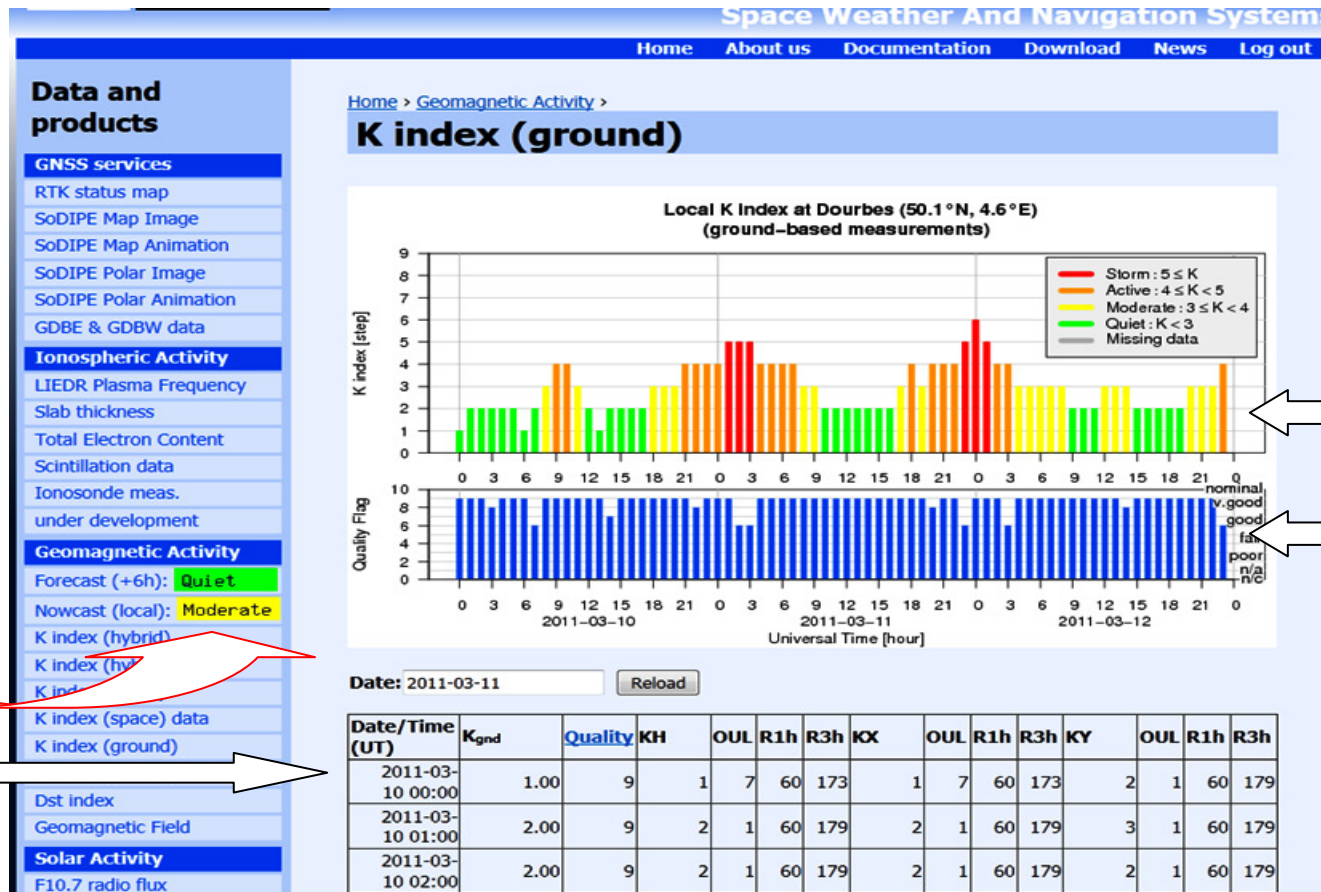


Service Type:

- Nowcast: update – every 60 min, latency less than 3 min after the hour mark
- Forecast: update – every 60 min, forecast time horizon – up to 6 hours ahead

Service Output:

- K index value - data files (ASCII), plots
- Quality Flag (QF) – data acquisition and processing quality assessment
- Alerts – web (verbose & colour code), email



Alert (web based)

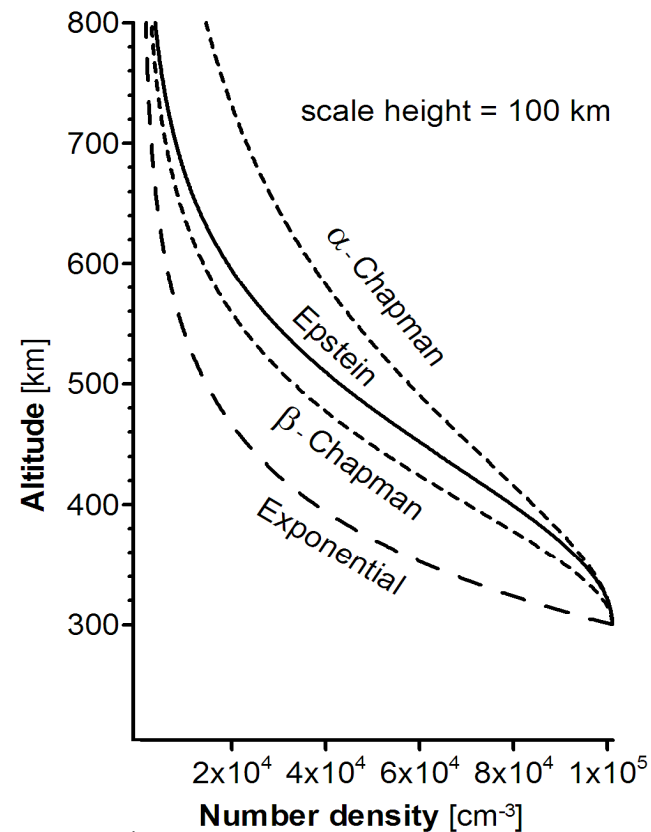
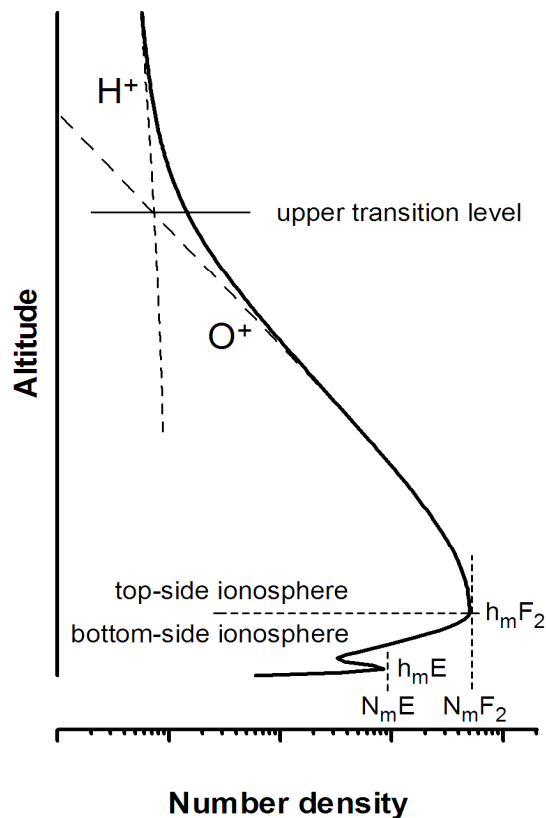
Data Selection

K index nowcast

Quality Flag

Objective:

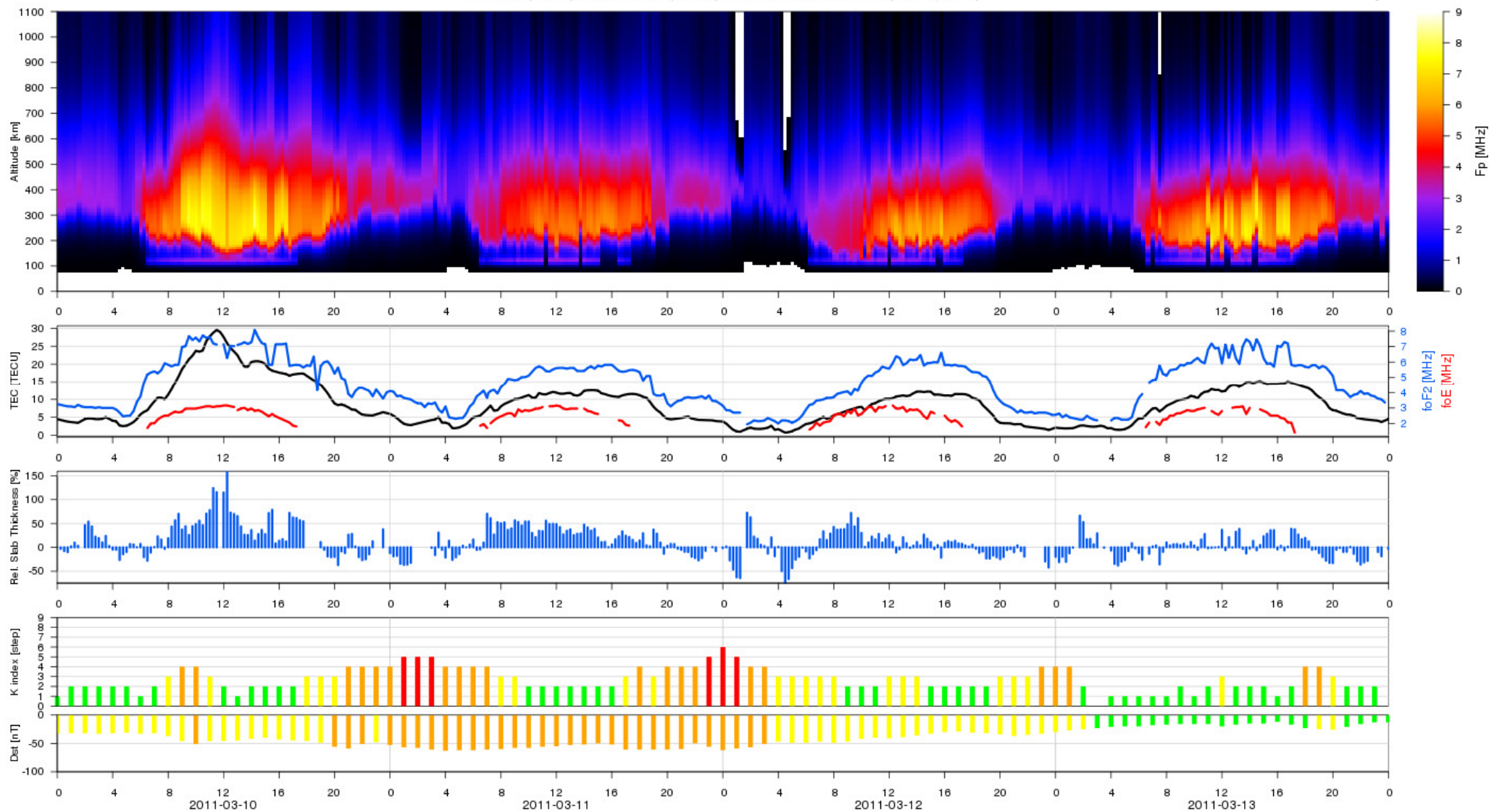
Development of an operational service for monitoring the local ionospheric electron density distribution on a real-time basis using GNSS and vertical incidence sounding measurements.



$$f_p [\text{MHz}] \approx c_p N_e^{0.5} [\text{el} / \text{m}^3]$$

$$c_p = 0.898 \times 10^{-5}$$

Electron density profile reconstruction in real time from GPS (DOUR) and ionosonde (DB049) measurements at Dourbes (50.1°N, 4.6°E)

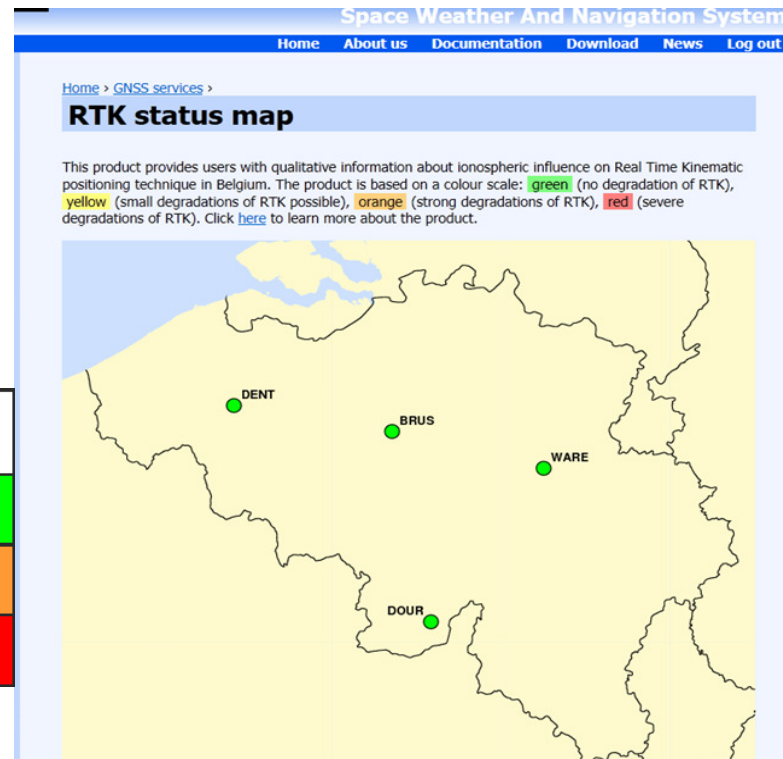


- Provides a **quick look at the small-scale ionospheric effects** on the RTK precision for several GPS stations in Belgium
- Assesses the effect of small-scale ionospheric irregularities by **monitoring the high-frequency rate of TEC** (ROT, TECU/min) at a given station
- ROT calculated using ‘geometric-free’ combination of GPS dual frequency measurements (no ambiguity resolution)

$$ROT = \frac{TEC(t + \Delta t) - TEC(t)}{\Delta t}$$

$$ROTI = \sigma(ROT)_{\Delta t}$$

	RoTEC max at BRUS [TECU/min]
Quiet	0.309
Disturbed	0.837
Extreme	8.933



http://swans.meteo.be/GNSS/RTK_map

- A (colour) code assigned to each station, code ranging from “quiet” (green) to “extreme” (red) and referring to the local ionospheric conditions.

- Alerts dispatched via e-mail to subscribed users when disturbed conditions are observed.

Relative positioning = determination of a baseline between 2 receivers
with accuracy of a few centimetres

Basic observable = double differences of phase measurements (DD)

Advantages :

cancellation of all error sources common to the two stations

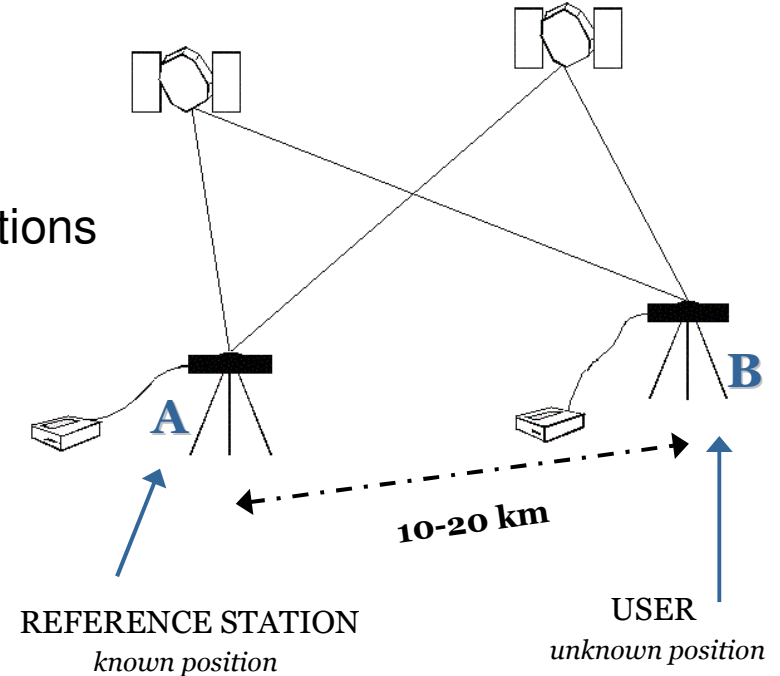
→ no clocks/orbit errors

→ atmospheric errors are (usually) negligible

BUT

residual ionosphere can be a threat

for high-accuracy applications



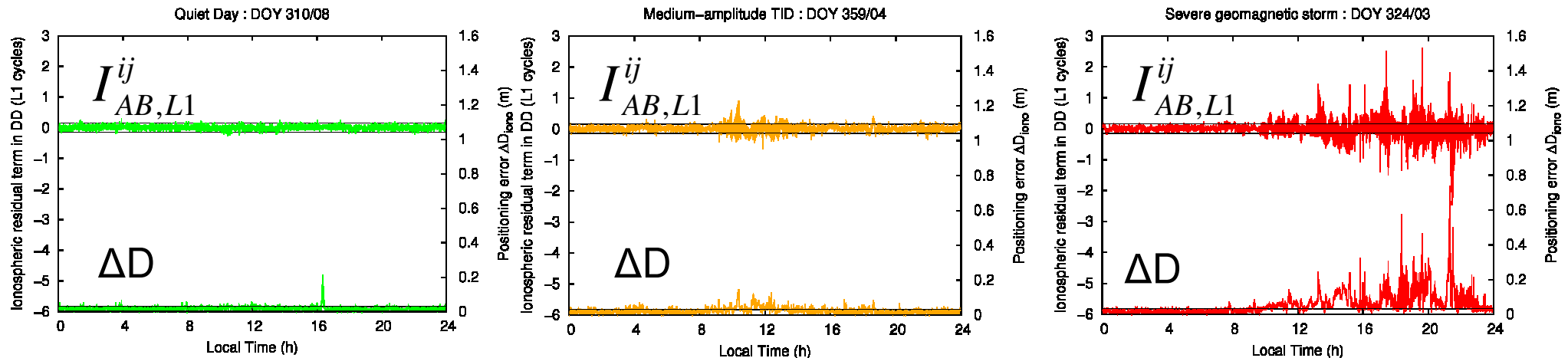
Objective

Development of software (SoDIPE-RTK) to monitor the ionospheric effects on high-precision real-time positioning (RTK targeted in particular)

Methodology

- Geometric-Free combination of double-differenced (DD) phase measurements used
- Compute the ambiguity term considering the whole DD observation period
- Isolate the ionospheric residual term on each carrier
- Compute IPE, the positioning error (on L1) due to the ionosphere only (least-squares adjustment applied, in topocentric coordinates)
- IPE mean and standard deviation computed (each baseline, 15 min time resolution)
- A (colour) code assigned to each baseline, range from “nominal” (green) to “extreme” (red) error level

Influence of TIDs and geomagnetic activity (11 km baseline)



During TID's or geomagnetic storms, the positioning error due to the ionosphere (ΔD) is significantly larger than the nominal value (**3 cm**).

Maximum values can reach:

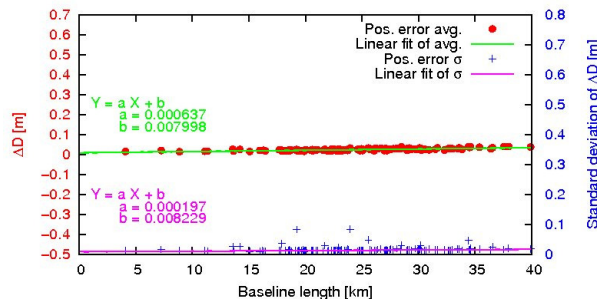
- medium amplitude TID: **~ 15 cm**
- geomagnetic storm: **~ 65 cm**

The positioning accuracy depends on:
ionospheric activity, baseline length, and baseline orientation.

Influence of baseline length

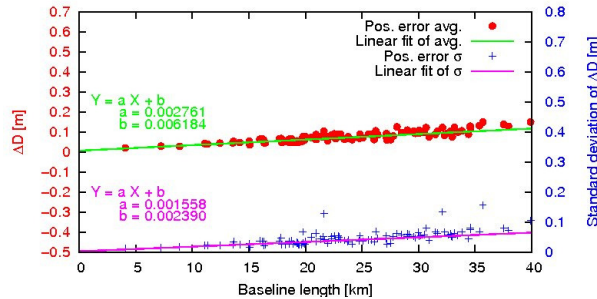
Computation of daily ΔD { mean (red dots) } for all AGN (Active Geodetic Network) baselines
 { std. dev. (blue crosses) }

Quiet



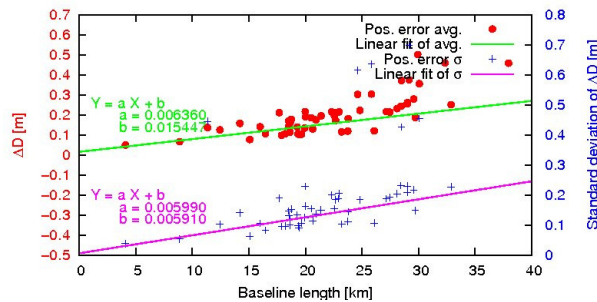
Mean = 0.008 + 0.6 ppm [m]
 SD = 0.008 + 0.2 ppm [m]

Disturbed



Mean = 0.006 + 3 ppm [m]
 SD = 0.002 + 2 ppm [m]

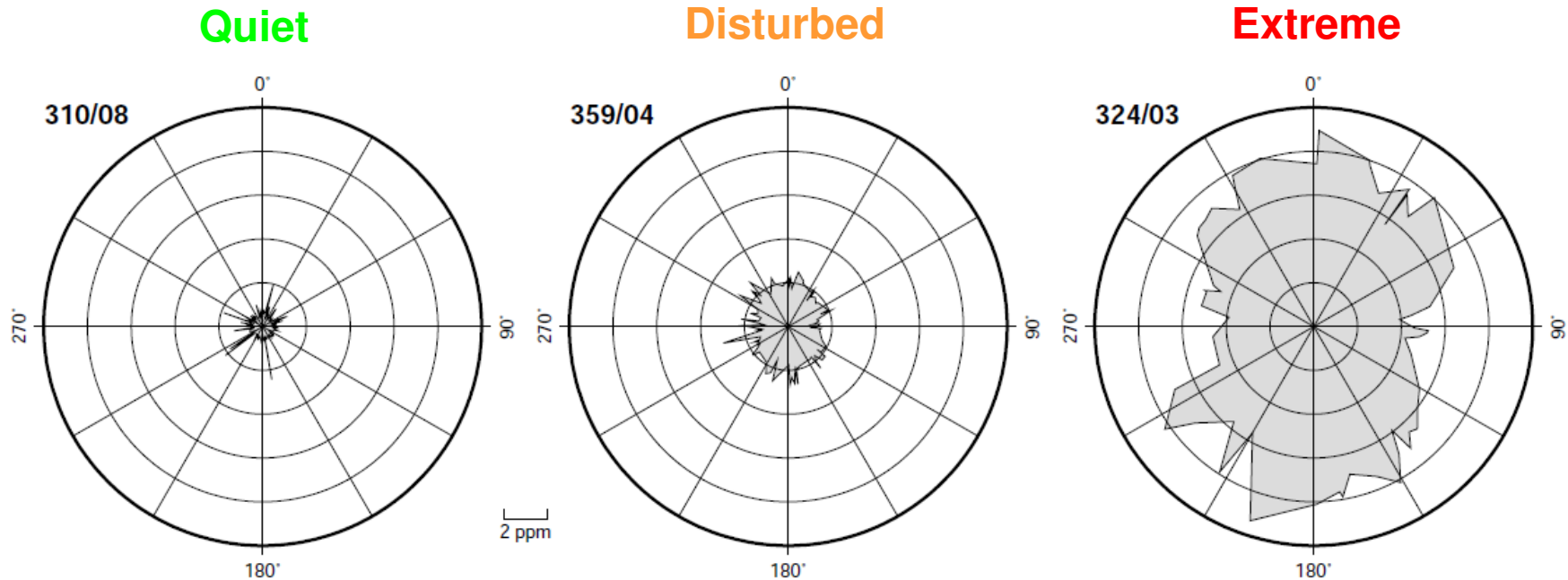
Extreme



Mean = 0.015 + 6 ppm [m]
 SD = 0.006 + 6 ppm [m]

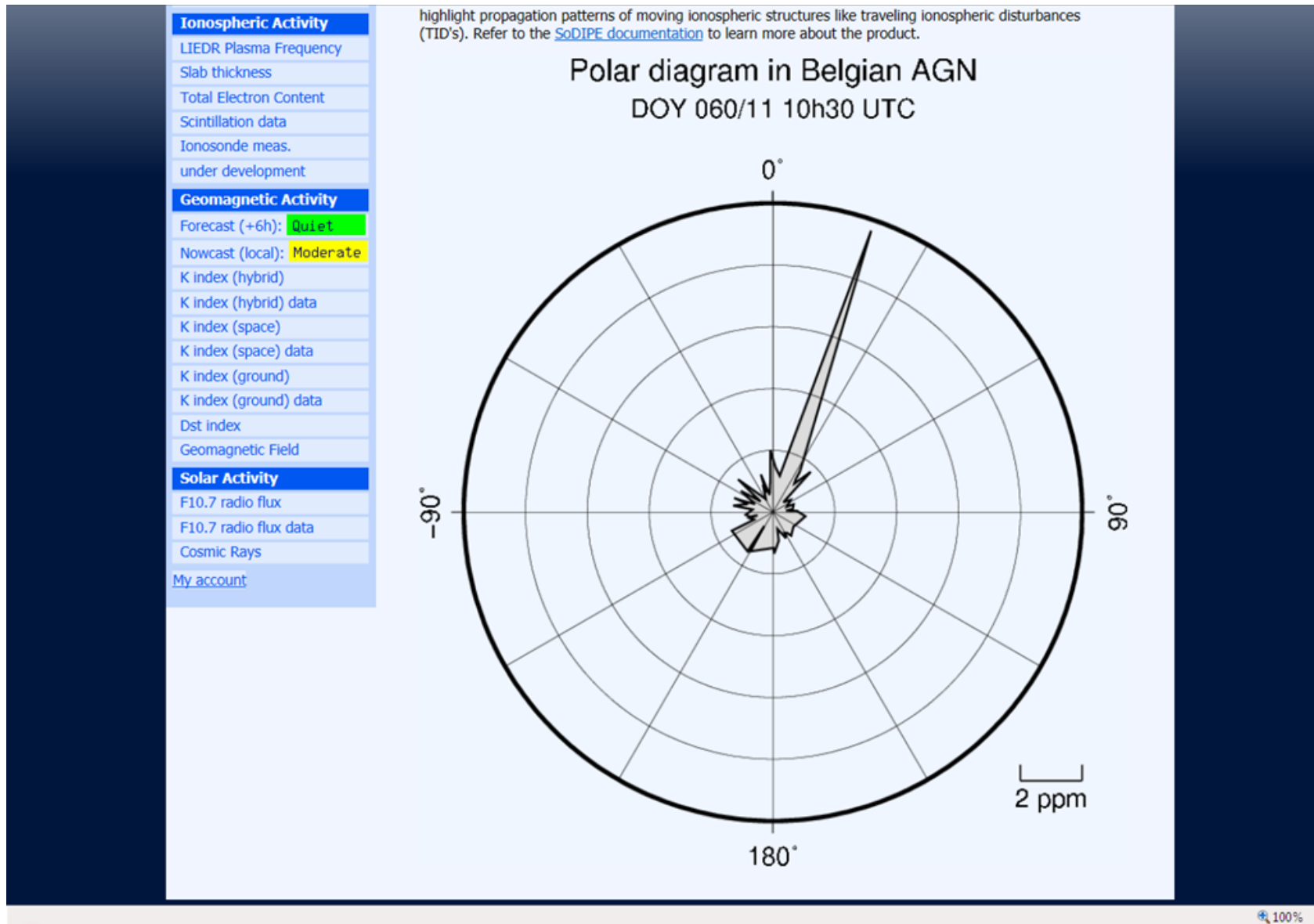
Influence of baseline orientation

1. Remove the **offset** (intercept of « quiet » regression line, *i.e.* 8 mm)
2. Computing of ΔD **weighted** by baseline length (ΔD_w)
3. Compute **daily mean** and **std. dev. of ΔD_w** for all baselines

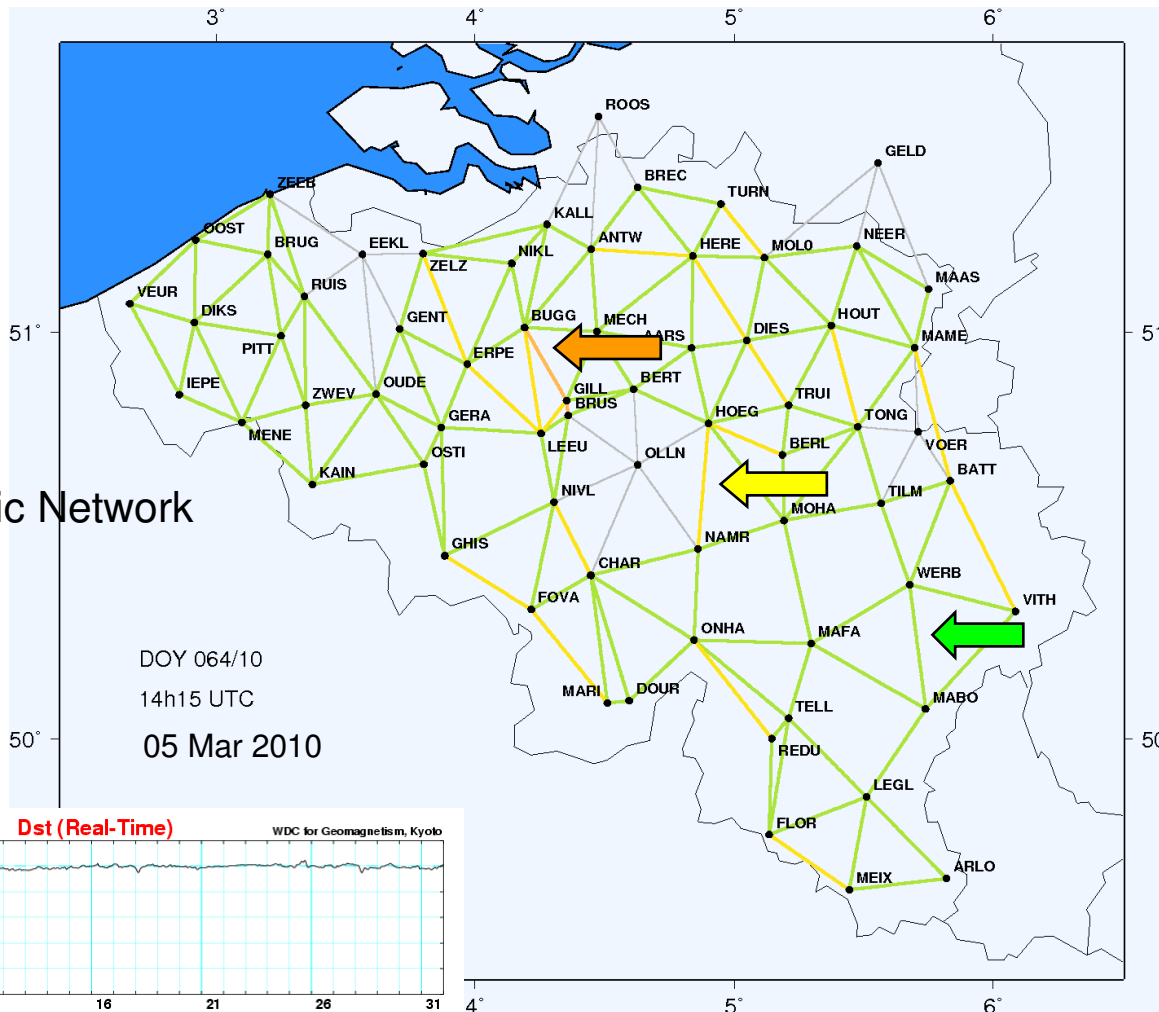


➔ Allows identification of moving ionospheric disturbances

Sharpest TEC gradients observed for baselines oriented parallel to the disturbance propagation



- Positioning error is “translated” onto a map where the colors (from green to red) give the magnitude of the ionospheric error depending on the region



Yellow, Orange, Red
 → Iono disturbance
 (small / strong / severe accuracy degradation)



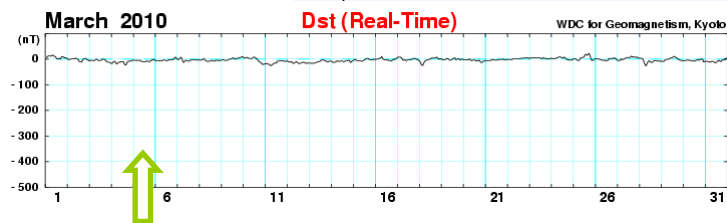
Green
 → No iono disturbance
 (no degradation)

Belgian AGN
 Active Geodetic Network

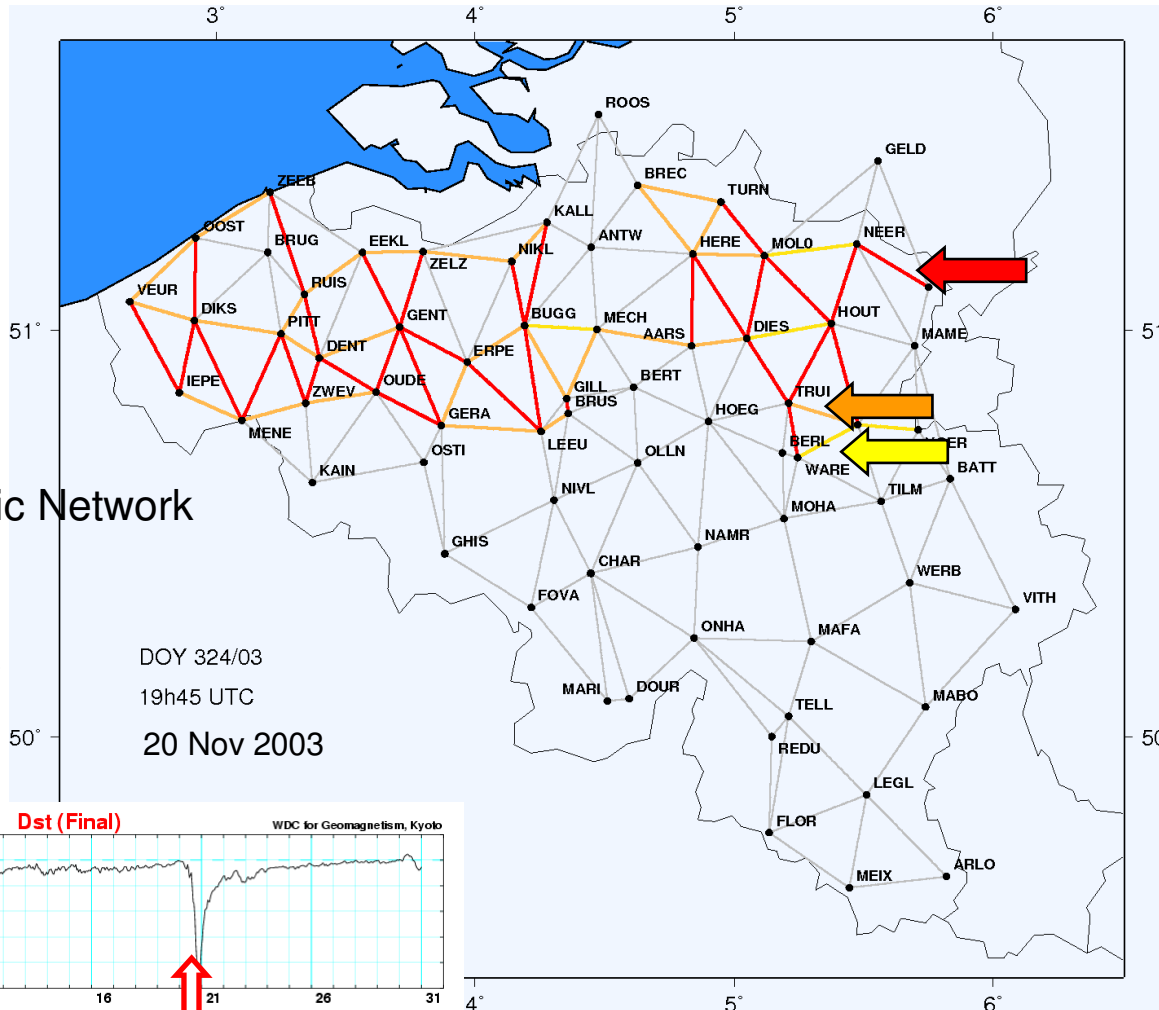
66 stations
 160 base lines

DOY 064/10
 14h15 UTC
 05 Mar 2010

05 Mar 2010



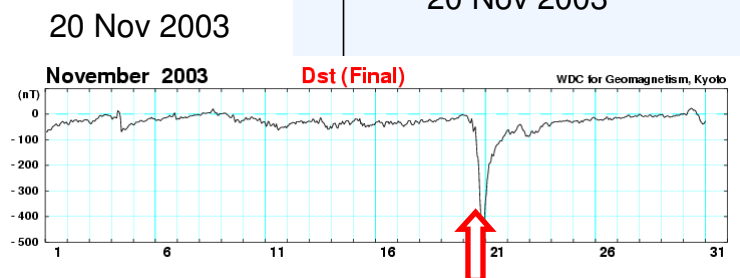
- Positioning error is “translated” onto a map where the colors (from green to red) give the magnitude of the ionospheric error depending on the region



Belgian AGN Active Geodetic Network

66 stations
160 base lines

DOY 324/03
19h45 UTC
20 Nov 2003



Yellow, Orange, Red
→ Iono disturbance
(small / strong / severe accuracy degradation)



Green
→ No iono disturbance
(no degradation)

The screenshot shows the SWANS website interface. At the top, there is a navigation bar with links for Home, About us, Documentation, Download, News, and Log. A 'User Registration' label with an arrow points to the 'Log' link. On the left side, there is a 'Data and products' menu with categories like GNSS services, Ionospheric Activity, Geomagnetic Activity, and Solar Activity. An arrow labeled 'Service Selection' points to the 'GNSS services' category, and another arrow labeled 'Date/Time Selection' points to the 'SoDIPE Map Image' link. Below the menu, there are 'Alerts' for Geomagnetic Activity: 'Forecast (+6h): Quiet' (green) and 'Nowcast (local): Moderate' (yellow). The main content area displays the 'SoDIPE Map Image' for a specific date and time (2011-03-01T13:00:00Z). A map of Belgium shows a network of GNSS stations with lines connecting them, color-coded by ionospheric influence (green, yellow, orange, red). A 'Date' selector shows '2011', '60', and '13:00' with 'Previous 15'' and 'Next 15'' buttons. A 'Reload' button is also present. Below the map, there is a description of the product and a link to the documentation.

- **Ionosphere/space weather effects on GNSS signal propagation remain some of the main error sources** for several GNSS-based positioning techniques and applications
- Modern **GNSS-based applications demand high accuracy and precision** :
 - simultaneous real-time observation of several ionospheric characteristics is essential
 - operational monitoring of the background solar and geomagnetic activity also necessary
 - use of advanced instrumentation is crucial
- GNSS service providers **do understand the importance of ionosphere/space weather impact** on their service applications and **are interested in operational ionosphere/space monitoring services** that can assist them in mitigating the impact BUT on certain conditions:
 - reliability (accuracy, precision, punctuality, and availability)
 - relevance (appropriate quantities/characteristics, not scientific information)
 - flexibility (error bounds, alerts, communication media)
 - confidentiality

Future work:

- Develop reliable (local) **ionospheric forecast**
- Develop empirical models to **forecast the occurrence of ionospheric disturbances** which pose identified threats to GNSS-based positioning (TIDs, noise-like structures, ...)