Ionospheric research and development activities
at the Royal Meteorological Institute of Belgium

Local ionospheric activity - nowcast and forecast services

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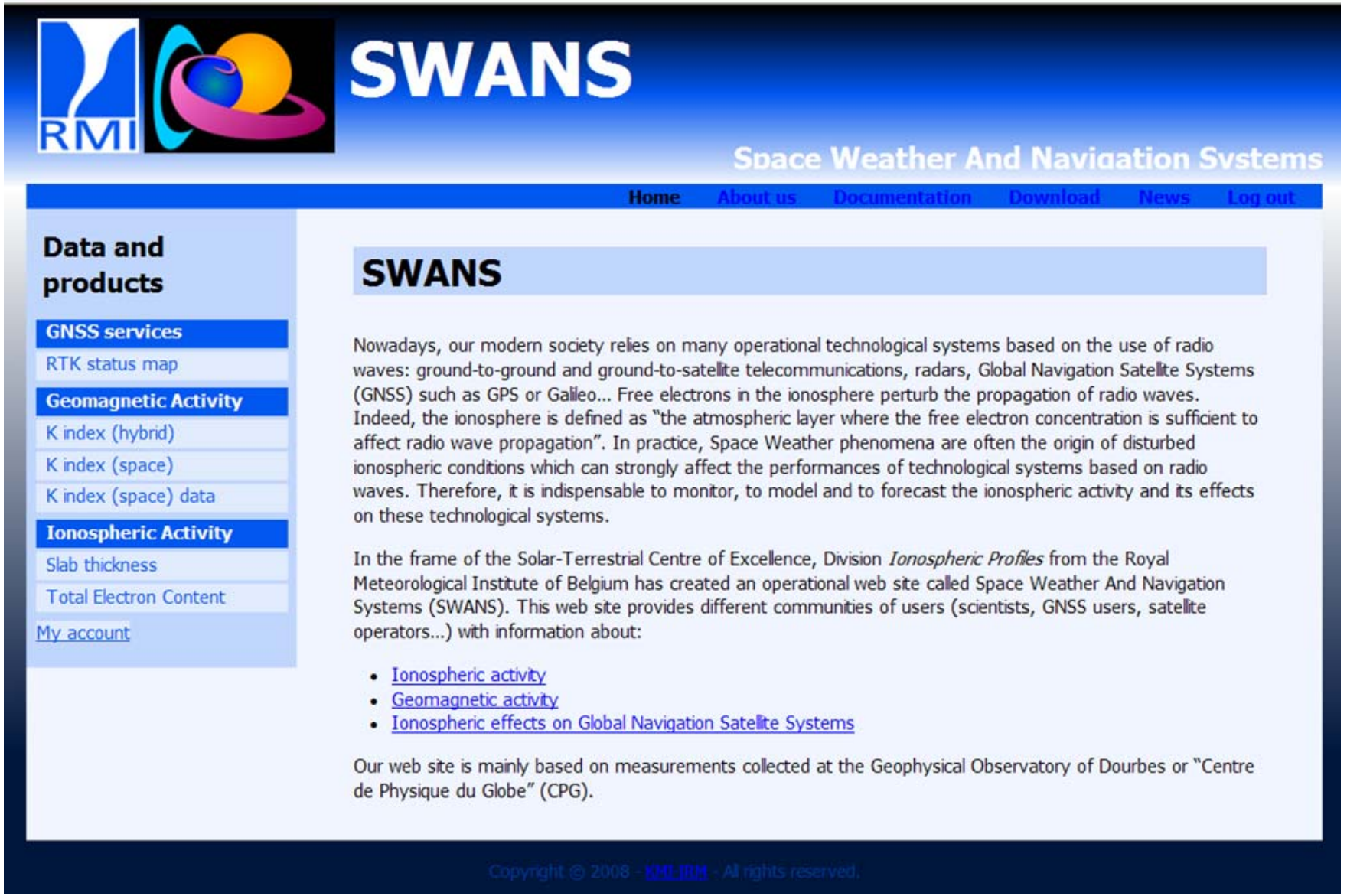
Outline

- Introduction (RMI / STCE / SWANS)
- Geomagnetic activity
- Ionospheric slab thickness
- Ionospheric/electron density
- Ionospheric activity (small-scale structures)
- Summary and Outlook


SWANS
Space Weather And Navigation Systems
Home
About us
Documentation
Download
News
Log out
Data and products
GNSS services
RTK status map
Geomagnetic Activity
K index (hybrid)
K index (space)
K index (space) data
Ionospheric Activity
Slab thickness
Total Electron Content
My account
SWANS
Nowadays, our modern society relies on many operational technological systems based on the use of radio waves: ground-to-ground and ground-to-satellite telecommunications, radars, Global Navigation Satellite Systems (GNSS) such as GPS or Galileo... Free electrons in the ionosphere perturb the propagation of radio waves. Indeed, the ionosphere is defined as "the atmospheric layer where the free electron concentration is sufficient to affect radio wave propagation". In practice, Space Weather phenomena are often the origin of disturbed ionospheric conditions which can strongly affect the performances of technological systems based on radio waves. Therefore, it is indispensable to monitor, to model and to forecast the ionospheric activity and its effects on these technological systems.
In the frame of the Solar-Terrestrial Centre of Excellence, Division Ionospheric Profiles from the Royal Meteorological Institute of Belgium has created an operational web site called Space Weather And Navigation Systems (SWANS). This web site provides different communities of users (scientists, GNSS users, satellite operators...) with information about:
Ionospheric activity
Geomagnetic activity
Ionospheric effects on Global Navigation Satellite Systems
Our web site is mainly based on measurements collected at the Geophysical Observatory of Dourbes or "Centre de Physique du Globe" (CPG).
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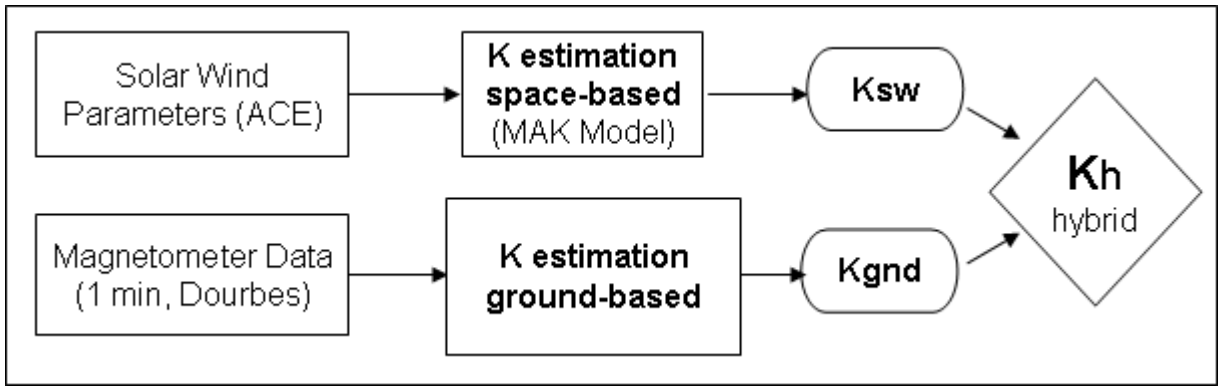
A new algorithm for modelling and predicting the geomagnetic activity index

The space-based estimate (Ksw) uses Advanced Composition Explorer (ACE) satellite data and an analogue model (MAK) relating the planetary geomagnetic index to solar wind parameters.

The ground-based estimate (Kgnd) uses magnetometer measurement data from the station in Dourbes to estimate the local geomagnetic index in real time.



Bzm – IMF Bz modified function
P – solar wind dynamic pressure
V – solar wind velocity

(space-based) **Nowcast** ➔ $Ksw = a_o + a_1 B_{zm} + a_2 P + a_3 V + a_4 B_{zm}^2 + a_5 P^2$

(hybrid) **Nowcast** ➔ $Kh(0) = Ksw(0) + K_{mean} + [Kgnd(0) - Ksw(0) - K_{mean}] * \exp(-1/6)$

(hybrid) **Forecast** ➔ $Kh(+\tau) = Kh_{mean} + [Kh(0) - Kh_{mean}] * \exp(-\tau/13)$

Note: The hybrid approach inherits the advantages of the space based concept with the robustness of the ground-based estimation of K

Source: Kutiev et al. (2009): Hybrid model for nowcasting and forecasting the K index J. Atm. Terr. Physics, 71, 589-596.

Geomagnetic Activity - Nowcast and Forecast

SWANS

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Home About us Documentation Download News Log out

Data and products

- **GNSS services**
  - RTK status map
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  - K index (hybrid)
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- **Ionospheric Activity**
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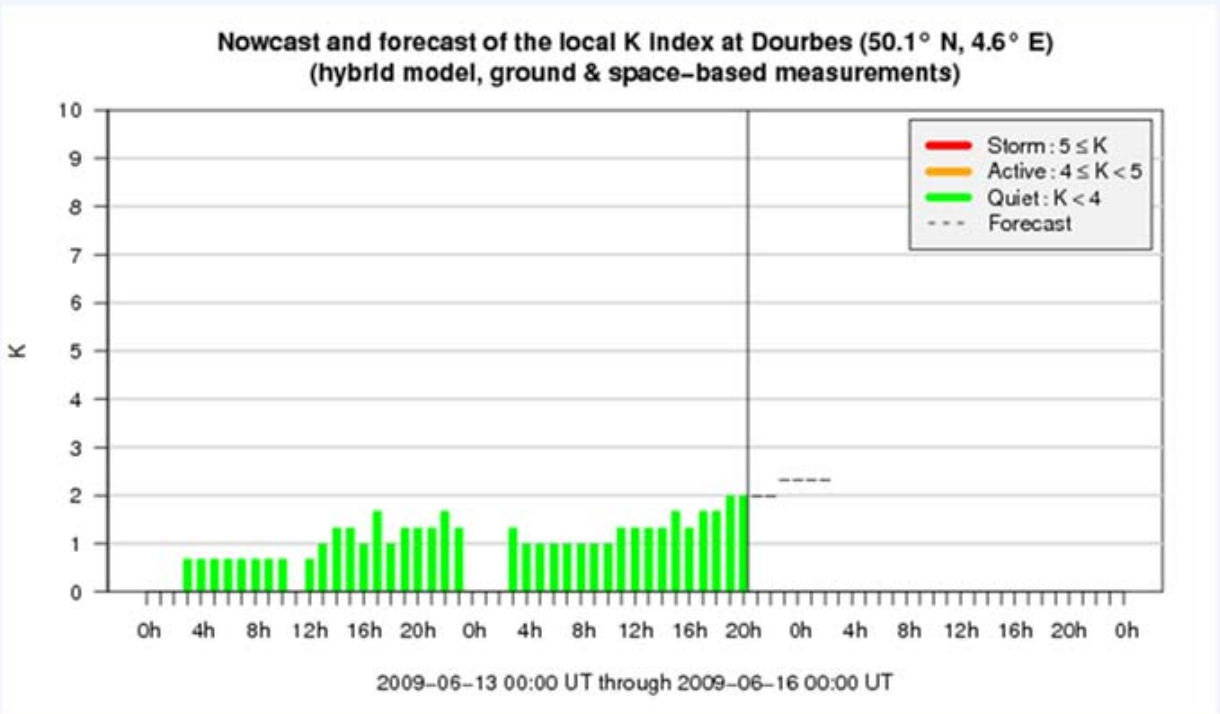
My account

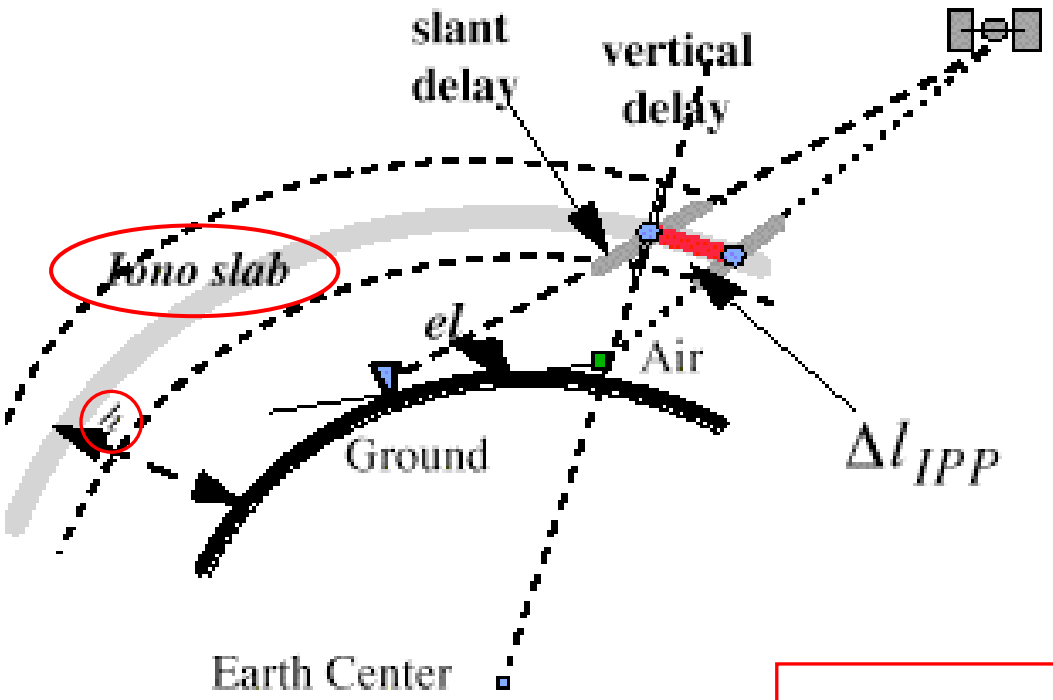
Home › Geomagnetic Activity ›

K index (hybrid)

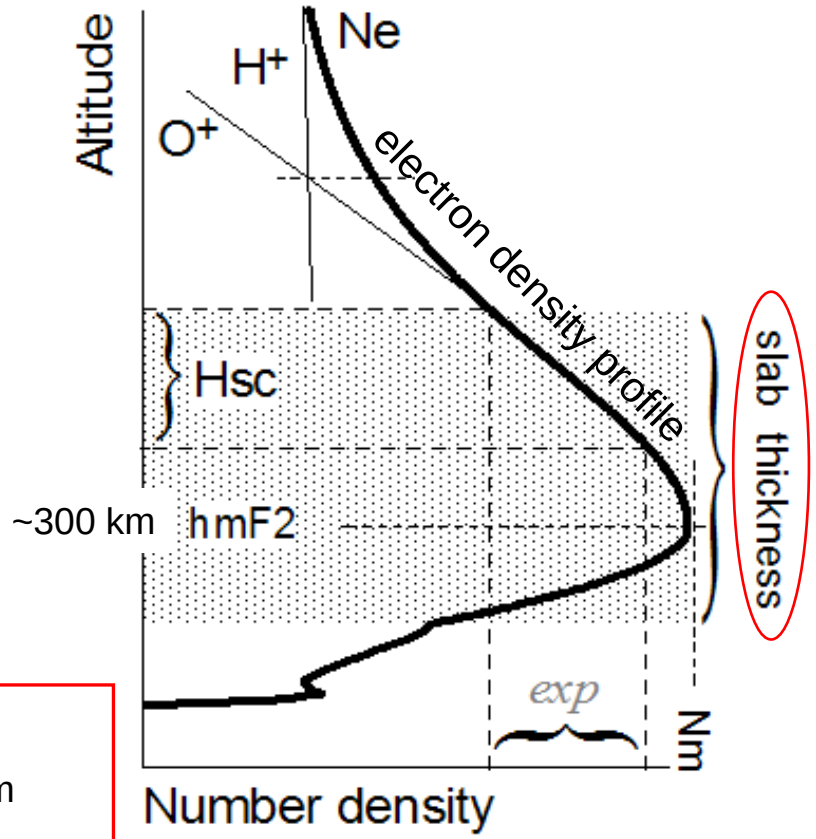


http://gpsweather.meteo.be/geomagnetism/dourbesk

Iono shell model, iono slab, iono slab thickness



Ionosphere Shell Model



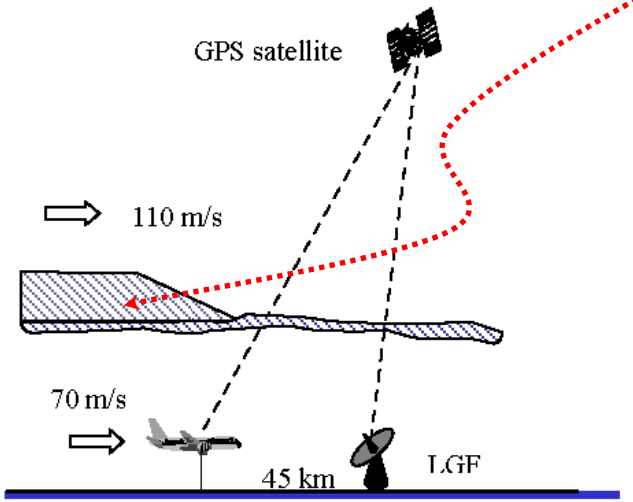
τ =TEC / Nm

The ionospheric slab thickness (τ) is defined as the ratio of the total electron content (TEC) to the maximum electron density (Nm). Alternatively, τ is the depth of an idealized ionosphere which has the same electron content as the actual ionosphere but uniform electron density equal to the maximum electron density of the actual ionosphere.

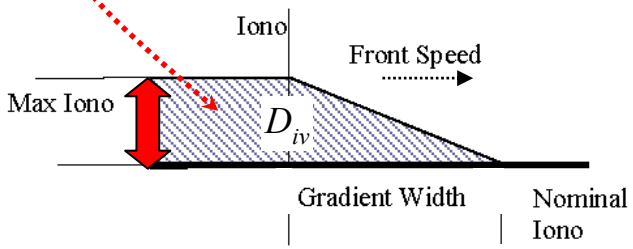
Source: Christie et al. (1999): The effects of local ionospheric decorrelation on LAAS. Proc. ION NTM, San Diego CA, January 1999.

Iono gradient anomaly model and iono slab thickness

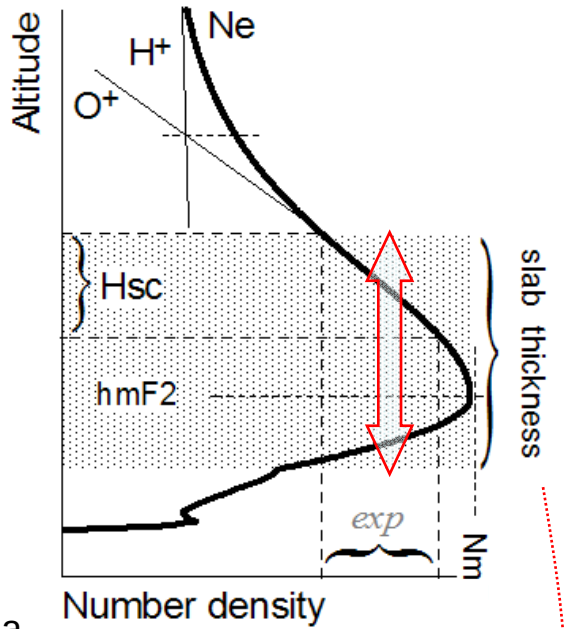
anomalous iono delay



A "Near-Worst-Case" LAAS User Scenario



Simplified (Baseline) Model of Ionosphere Anomaly



The iono spatial anomaly can be presented as a semi-infinite "cloud" with a wave front pattern. The iono gradient is modelled as the linear change in vertical ionosphere delay between the "high" (anomalous) and "low" (nominal) delay zones.

penetration / critical frequency of the ionospheric F2 layer, i.e. the minimal frequency allowing vertical propagation through the entire ionosphere $f_o F_2$

GNSS carrier frequency f_c

$$D_{iv} \propto \left(\frac{f_o F_2}{f_c} \right)^2 \tau$$

D_{iv} iono delay (vertical)

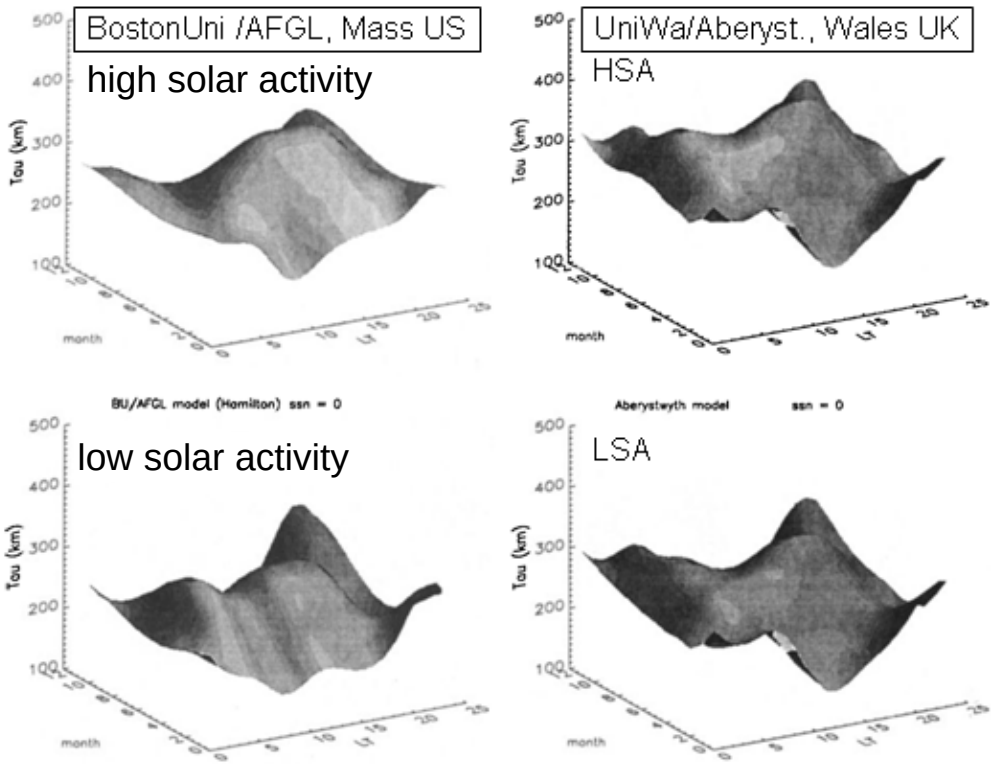
relation to

τ iono slab thickness

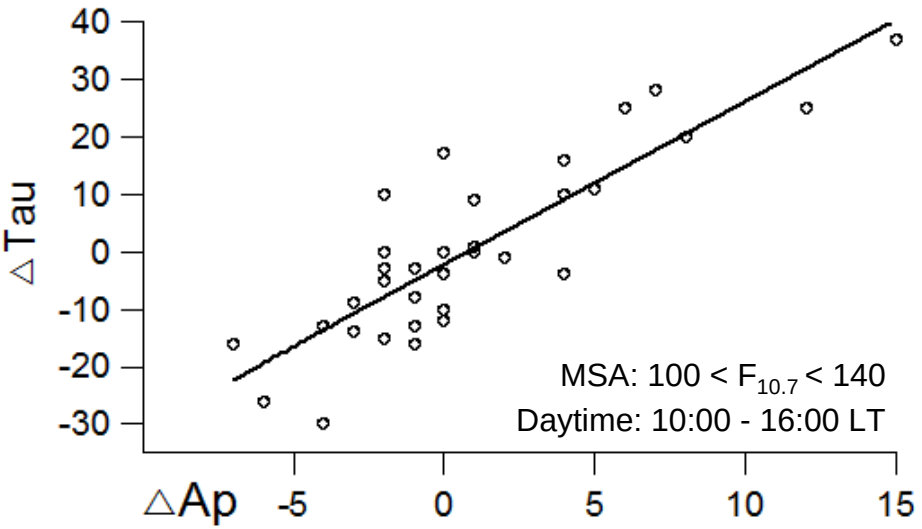
Source: Luo et al. (2003): LAAS ionosphere spatial gradient threat model. Proc. ION GPS, Portland OR, September 2003.

Iono slab thickness - regular and irregular behaviour

regular (geomagnetically quiet-time)



irregular (active geomagnetic conditions)



A positive correlation detected between the monthly mean slab thickness (Tau) and the monthly mean planetary geomagnetic index (Ap) at middle latitudes and moderate solar activity (MSA) (Kersley, J.Atm.Terr.Phys., v.38, p.1357-1360, 1976)

- Diurnal variations - higher night-time values during low solar activity (LSA), opposite during high solar activity (HSA)
- Spatial variations - no clear-cut trends for latitudinal, undetermined for longitudinal
- Seasonal variations - greater in summer than in winter
- Solar activity dependence - at mid/high latitudes - in general, increases with solar activity during all seasons
- Geomagnetic activity dependence - at mid/high latitudes – in general, increases with geomagnetic activity
- Pre-dawn enhancement (PDE), an established feature - larger at lower latitudes
- Post-sunset enhancement (PSE), pronounced at mid/high latitudes, esp. during HSA winter and equinoxes

Source: Fox et al. (1991): Ionospheric equivalent slab thickness and its modeling applications. Radio Science, 26(2), 429-438.

Iono slab thickness - regular and irregular behaviour

irregular / anomalous (storm-time)

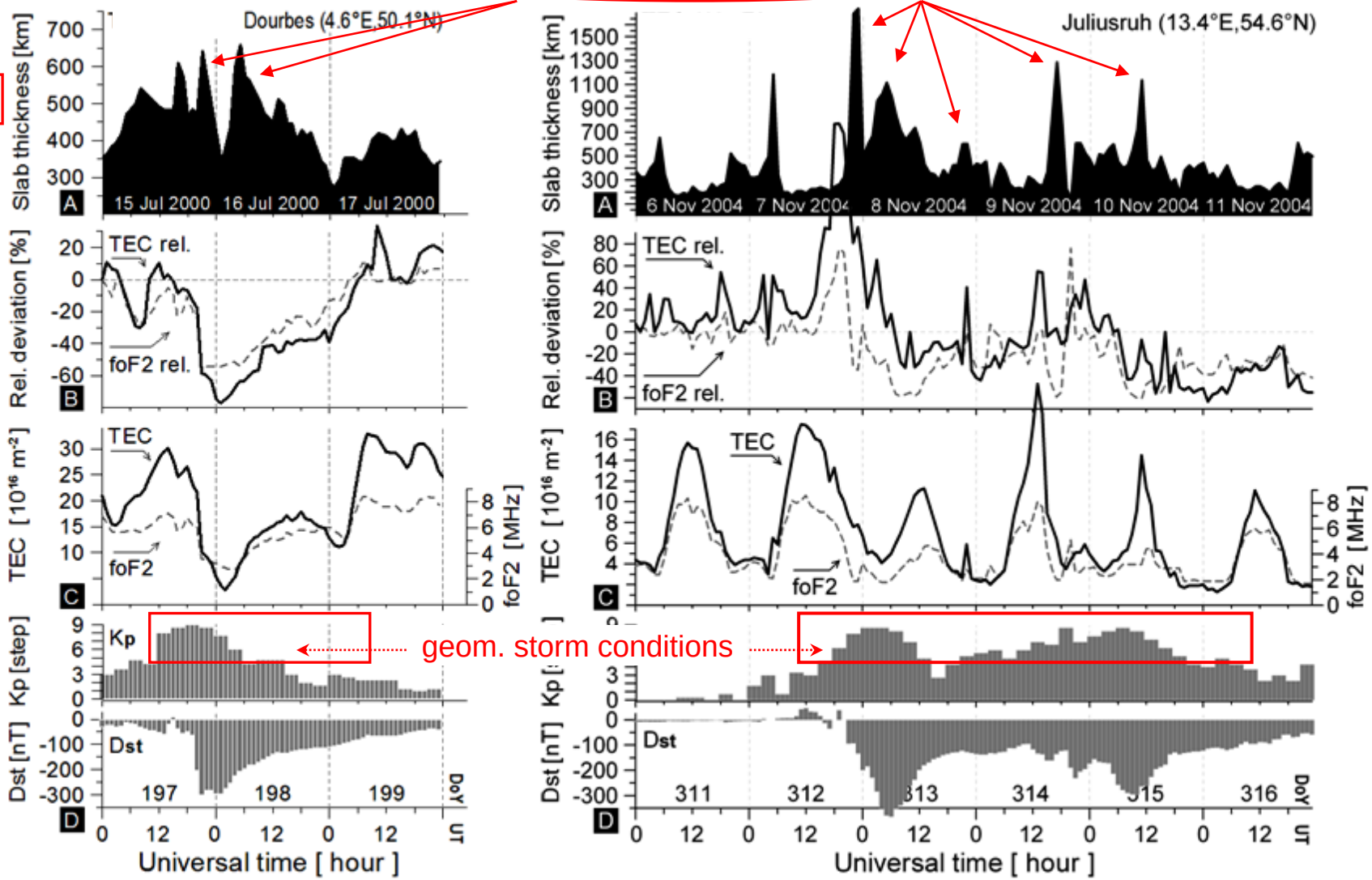
Iono slab thickness

τ =TEC / Nm

Iono TEC and foF2 relative deviations from monthly medians [%]

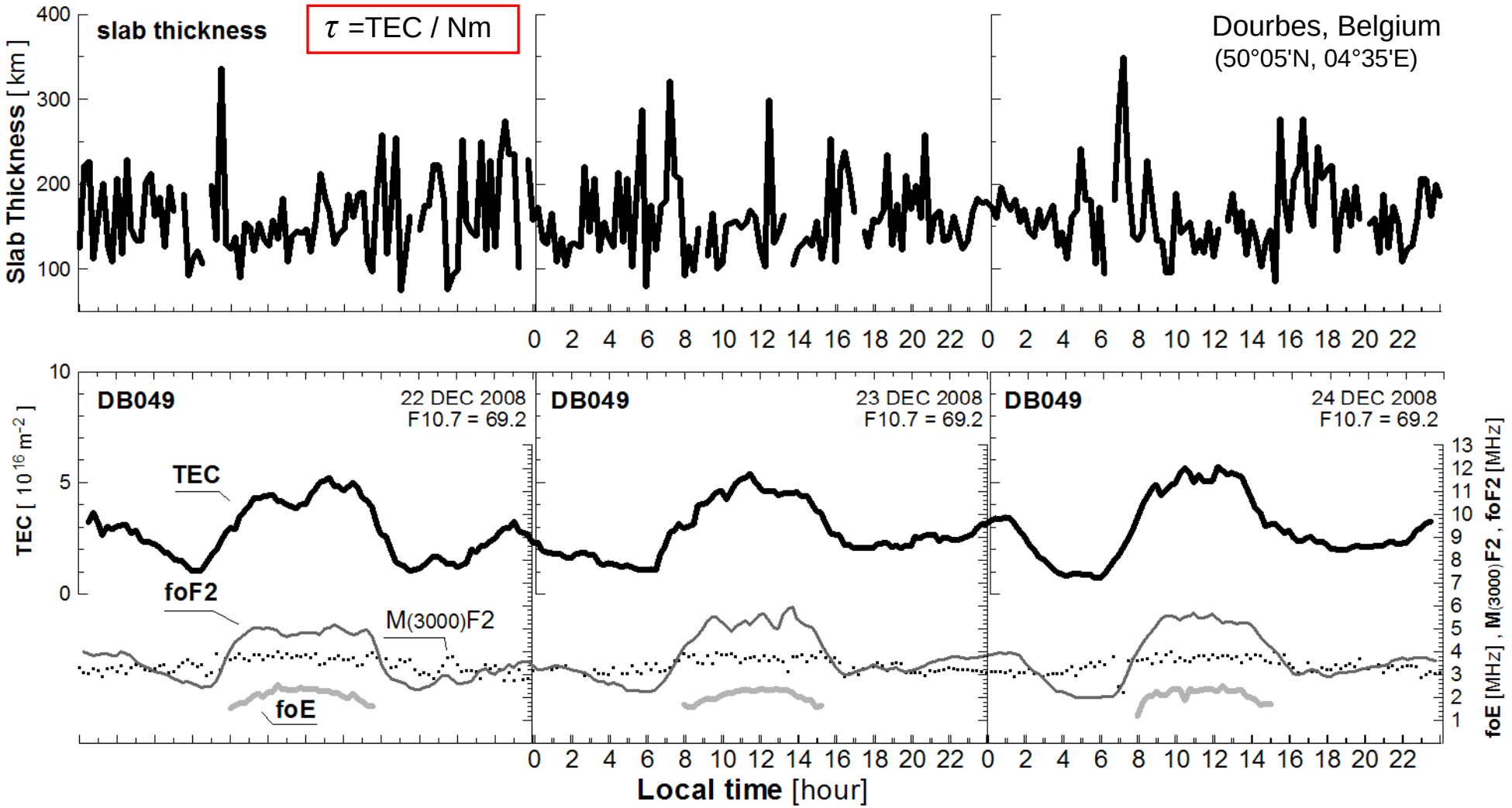
Iono Total Electron Content (TEC) and critical frequency (foF2)

Geomagnetic activity indices, Kp and Dst



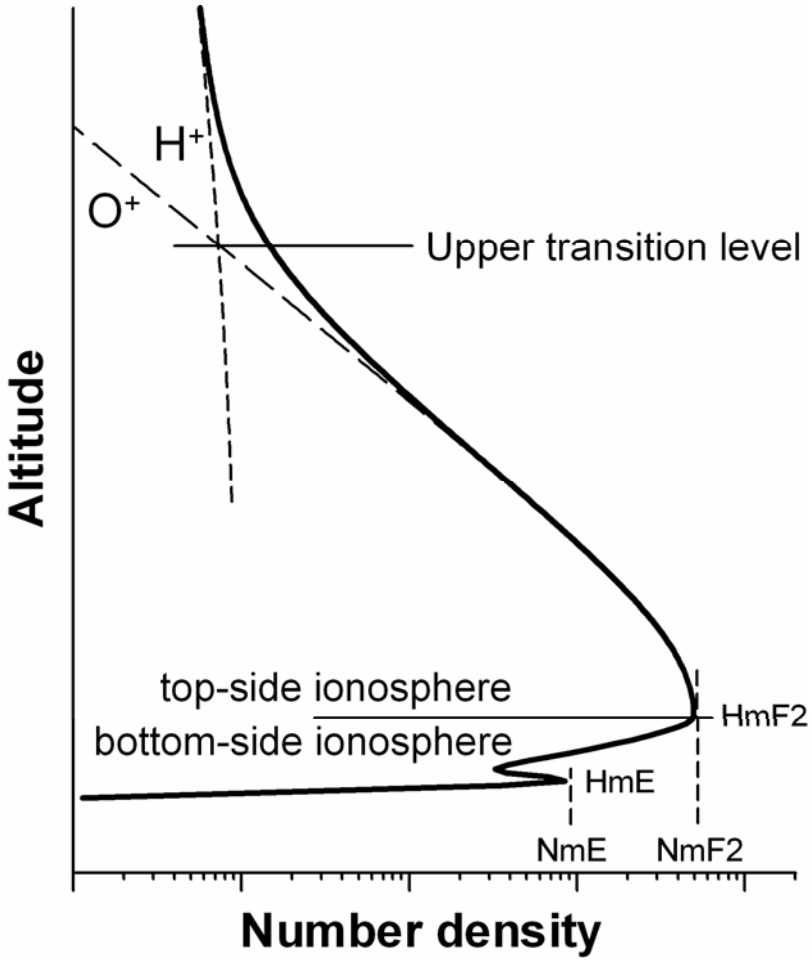
Source: Stankov et al. (2005): Generation and propagation of ionospheric disturbances studied by ground and space based GPS techniques. Proc. International Ionospheric Effects Symposium (IES), May 3-5, 2005, Alexandria, VA, USA, Paper No. A064/9B2, 807–814.

Slab thickness monitoring service



Real-time monitoring results for Dourbes (50°05'N, 04°35'E), Belgium. European regional mapping also possible.

LIEDR – Local Ionospheric Electron Density Reconstruction



Purpose

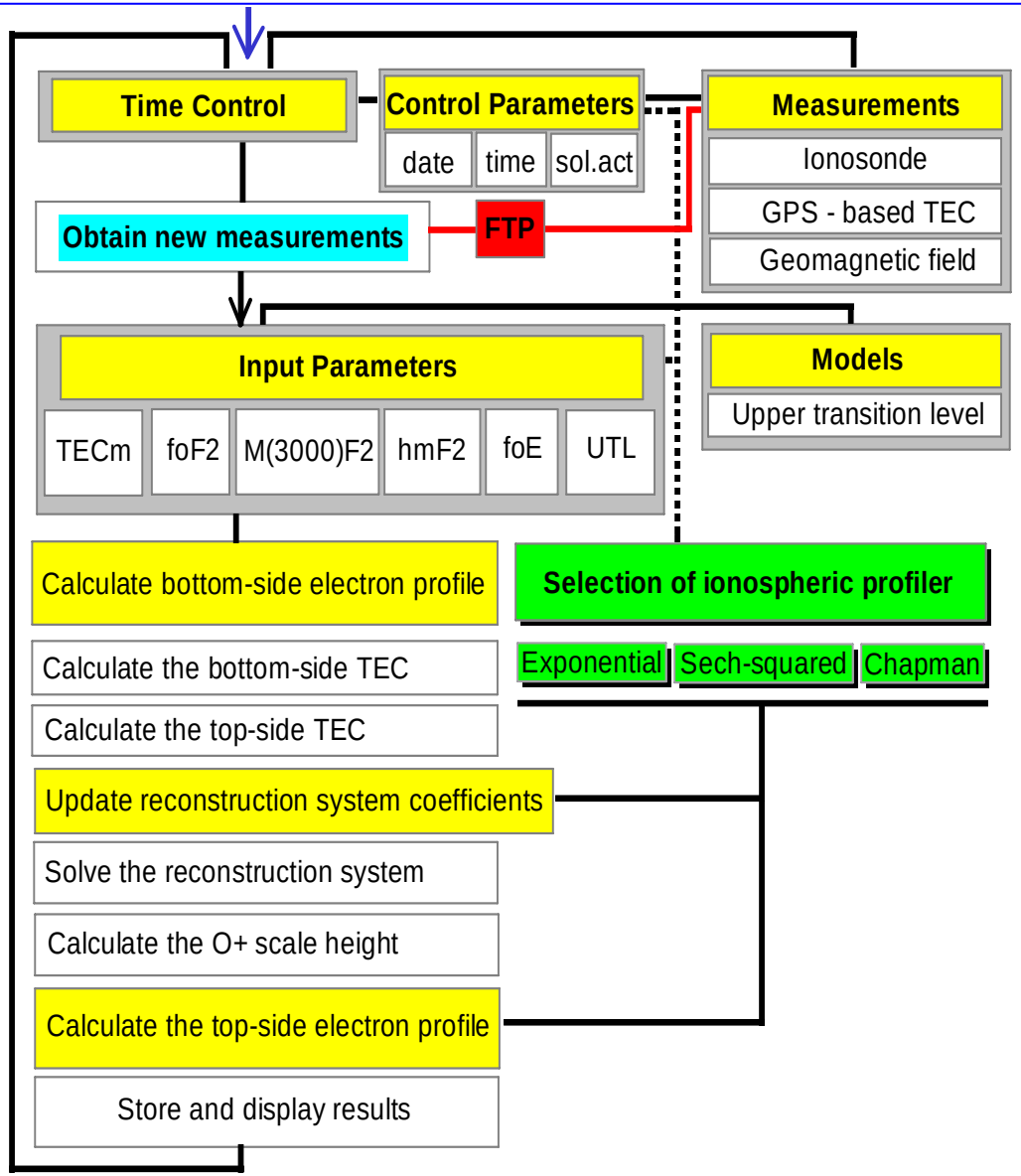
- Operational procedure for **reconstruction of the ionospheric vertical electron density distribution** at the site of a digital ionosonde, on a **real-time** basis

- **Concurrent observations** (GPS TEC, ionosonde, direct satellite) used for reliably deducing **the most adequate electron density profile** for a given location and time, on a real-time basis

- **Post-processing capabilities** – to be used for research and further development of the operational system

Source: Stankov et al. (2003): A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. Journal of Geophysical Research, 108(A5), 1164, doi:10.1029/2002JA009570.

LIEDR – Local Ionospheric Electron Density Reconstruction



- A **stand-by procedure**: execution triggered by either a time control system or the arrival of new measurements. Relies heavily on regular influx of ionosonde, geomagnetic and GPS TEC discrete measurement data.

- **Synchronized processing**: representative results obtained for a given location at a given time. Flexibility, in terms of time resolution, offered by the digital ionosonde and the collocated GPS receiver. Current **nominal measurement rate** - 15 minutes. Processing **latency** not more than a couple of minutes.

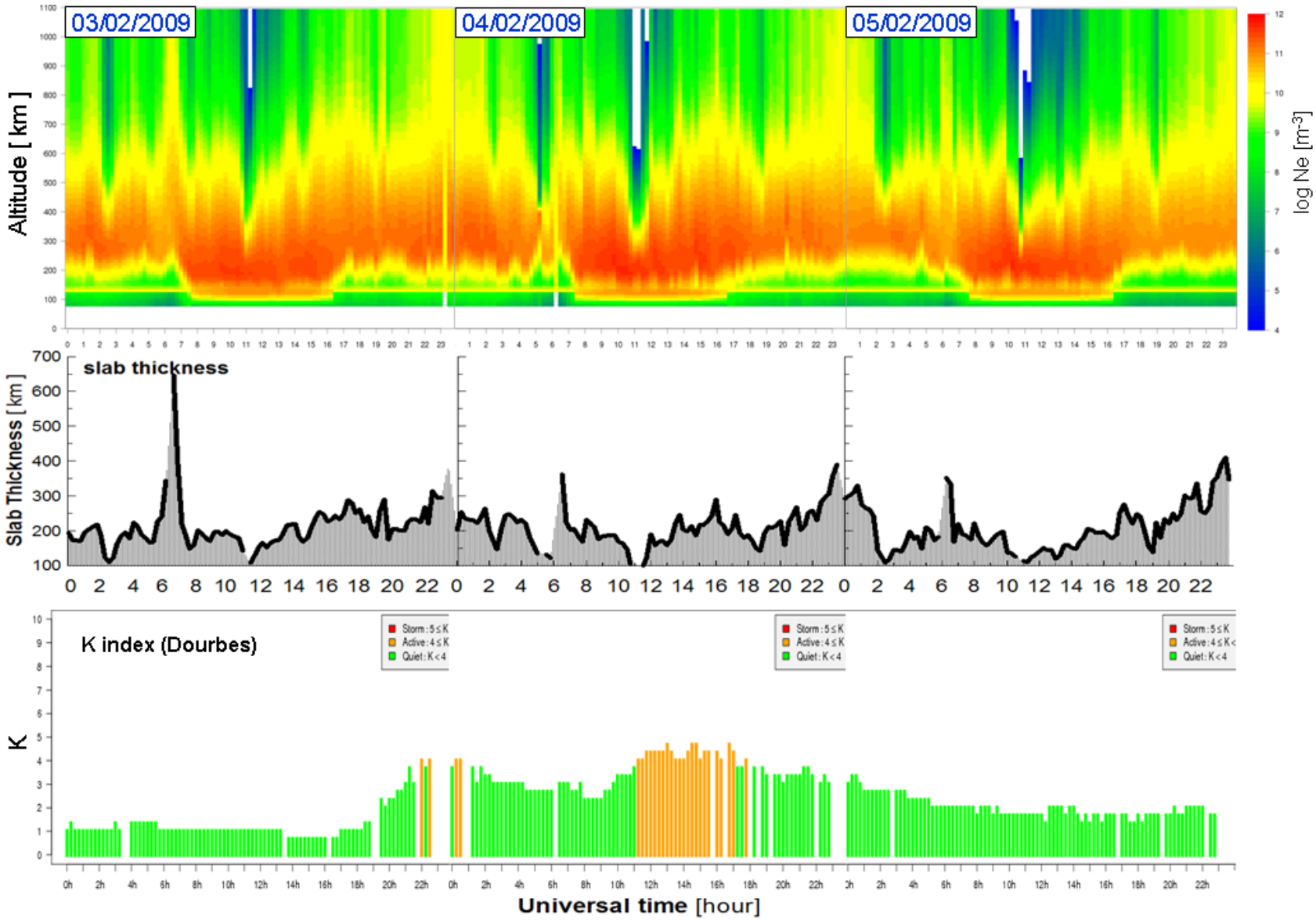
- **Procedure stages**: transmission of measurement data and retrieval of input parameters, construction of the bottom- and top- side electron profile, backup and display of results. Data **transmission using File Transfer Protocol**, except the UTL values (empirical model incorporated into the reconstruction software).

- **Selection options** for the theoretical **profiler**: top-side (oxygen and hydrogen) ion densities reconstructed with **Epstein, Chapman, Exponential** ionospheric profilers.

- **Final stage**: all results promptly displayed and archived (for post-processing).

Source: Stankov et al. (2003): A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. Journal of Geophysical Research, 108(A5), 1164, doi:10.1029/2002JA009570.

LIEDR – Local Ionospheric Electron Density Reconstruction



Ionospheric activity (small-scale structures)

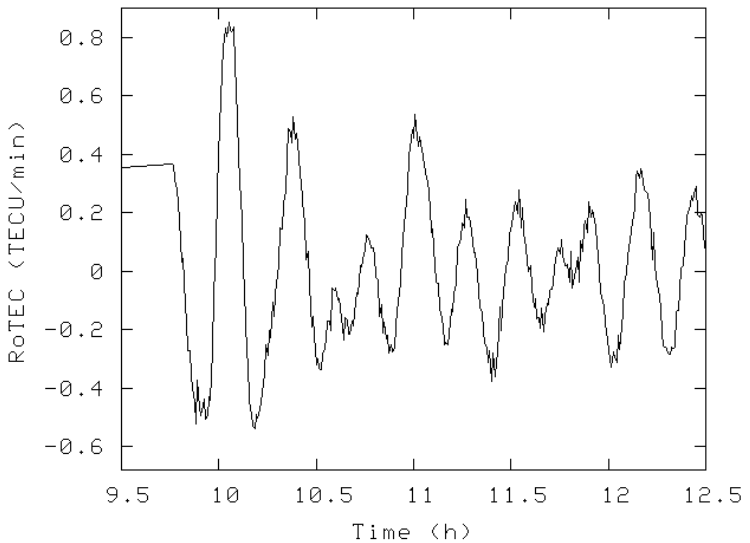
- Detection of small-scale structures possible by monitoring Rate of TEC
- RoTEC monitored using 'geometric-free' combination of GPS dual frequency measurements (no ambiguity resolution)

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

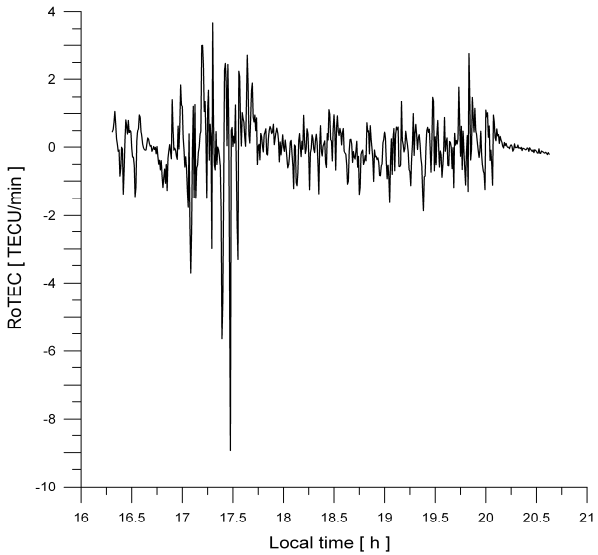
$$ROTI = \sigma(ROT)_{\Delta t}$$

- Two types of structures detected :

Travelling Ionospheric Disturbances (TID's)



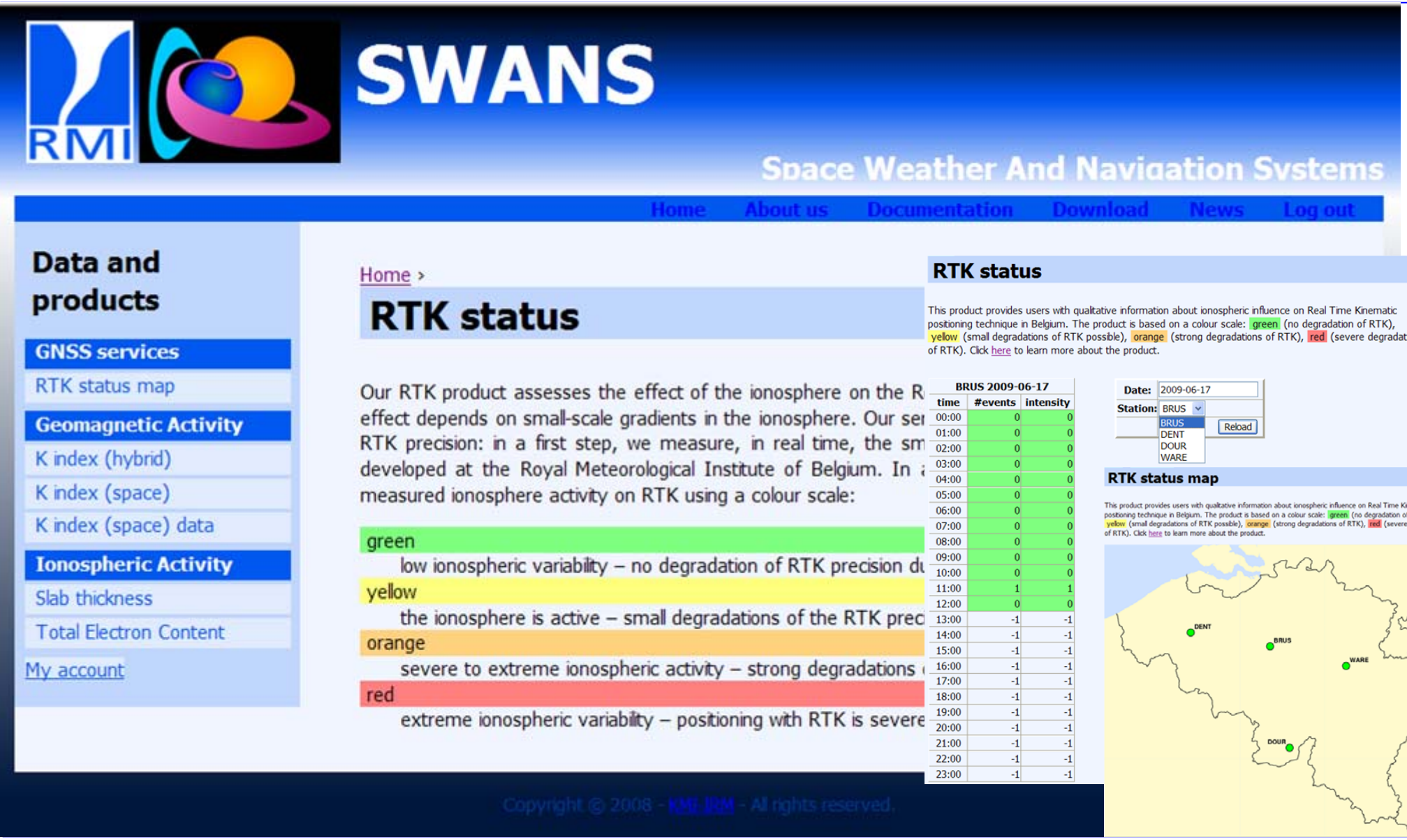
Noise-like structures



- Based on the number and amplitude of detected ionospheric irregular structures, assessment of ionospheric effects on differential GNSS is made (using a colour scale)

Source: Warnant et al. (2007): Monitoring variability in TEC which degrades the accuracy of Real Time Kinematic GPS application, Advances in Space Research, 39(5), 875-880.

Ionospheric activity (small-scale structures)



http://gpsweather.meteo.be/ionosphere/RTK_map

Summary and Outlook

- Modern GNSS-based applications demand high precision -- **observing a single ionospheric characteristic not sufficient** - simultaneous real-time observations of several characteristics (including 'derivative' measures like the ionospheric slab thickness) plus the solar/geomagnetic background is **essential**.

- **Electron density reconstruction technique** - suitable for investigating **local storm-time ionosphere development**. Possibilities for extension to regional ionosphere monitoring. Necessity for **solar and geomagnetic nowcast/forecast**.

- **Ionospheric slab thickness** -- a key ionospheric shape/condition parameter with largely unexplored real-time monitoring applications. Provides opportunities for detection and quantitative assessment (indexing) of (anomalous) ionospheric conditions in real time.

- **Operational applications** range -- from ionospheric/space weather monitoring, research & modelling (further understanding the ionospheric morphology, validating existing ionospheric models) -- to improving comm/nav systems performance (incl. HF propagation and ray tracing, adverse ionospheric effects warnings/mitigation).

- **GBAS / iono threat model** -- since the iono slab thickness is related to iono threat model parameters (slope and width), its monitoring with high spatial and temporal resolution can contribute to further development and use of the iono threat model.

Annex: Recent Publications

• Stankov, S.M., R. Warnant, K. Stegen, 2009. Trans-ionospheric GPS signal delay gradients observed over mid-latitude Europe during the geomagnetic storms of October-November 2003. Advances in Space Research, Vol.43, No.9, pp.1314-1324.

• Kutiev, I., P. Muhtarov, B. Andonov, R. Warnant, 2009. Hybrid model for nowcasting and forecasting the K index. Journal of Atmospheric and Solar-Terrestrial Physics, Vol.71, pp.589-596.

• Stankov, S.M., R. Warnant, 2008. Ionospheric slab thickness – analysis and monitoring applications. Proc. Ionospheric Effects Symposium (IES), May 13-15, 2008, Alexandria, VA, USA, pp.159-164.

• Warnant, R., M. Bavier, H. Brenot, S. Lejeune, J. Spits, S.M. Stankov, G. Wautelet, 2008. GALILEO local component for the detection of atmospheric threats. Proc. Ionospheric Effects Symposium (IES), May 13-15, 2008, Alexandria, VA, USA, pp.149-149.