Global TEC service for ionospheric delay correction and different approaches for higher order effects mitigation

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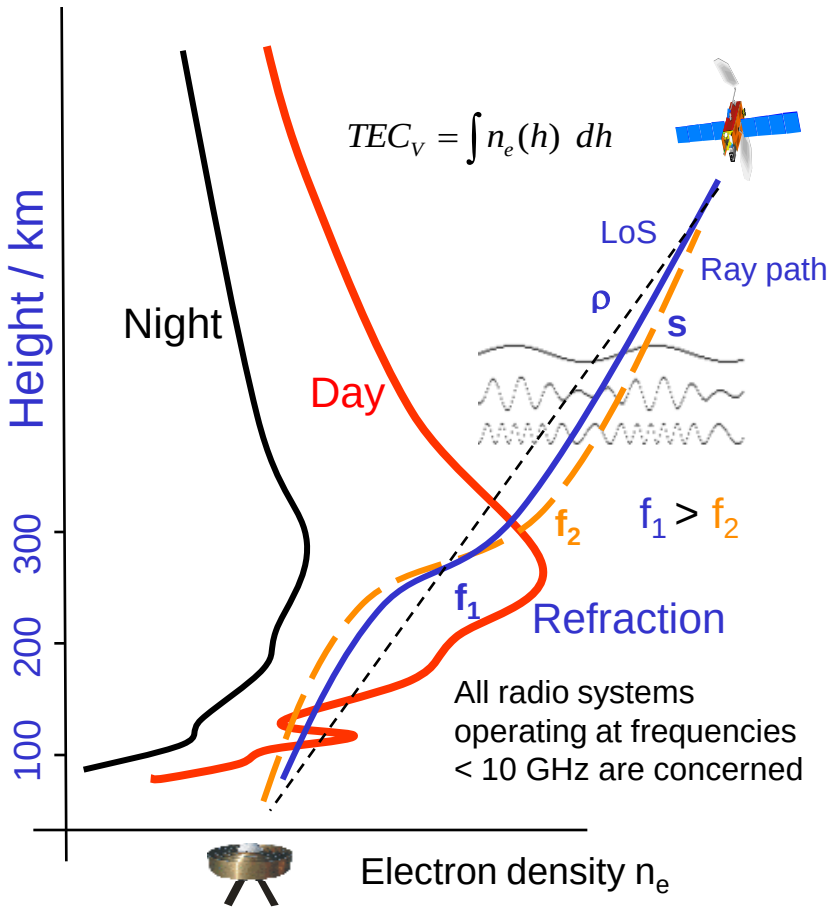
Outline

- Introduction
- TEC data base
- Generation of global TEC maps
  - Modelling
  - Mapping
- TEC forecast
- Disturbance Ionosphere Index (DIX)
- Higher order correction approaches
- SWACI service
- Conclusions

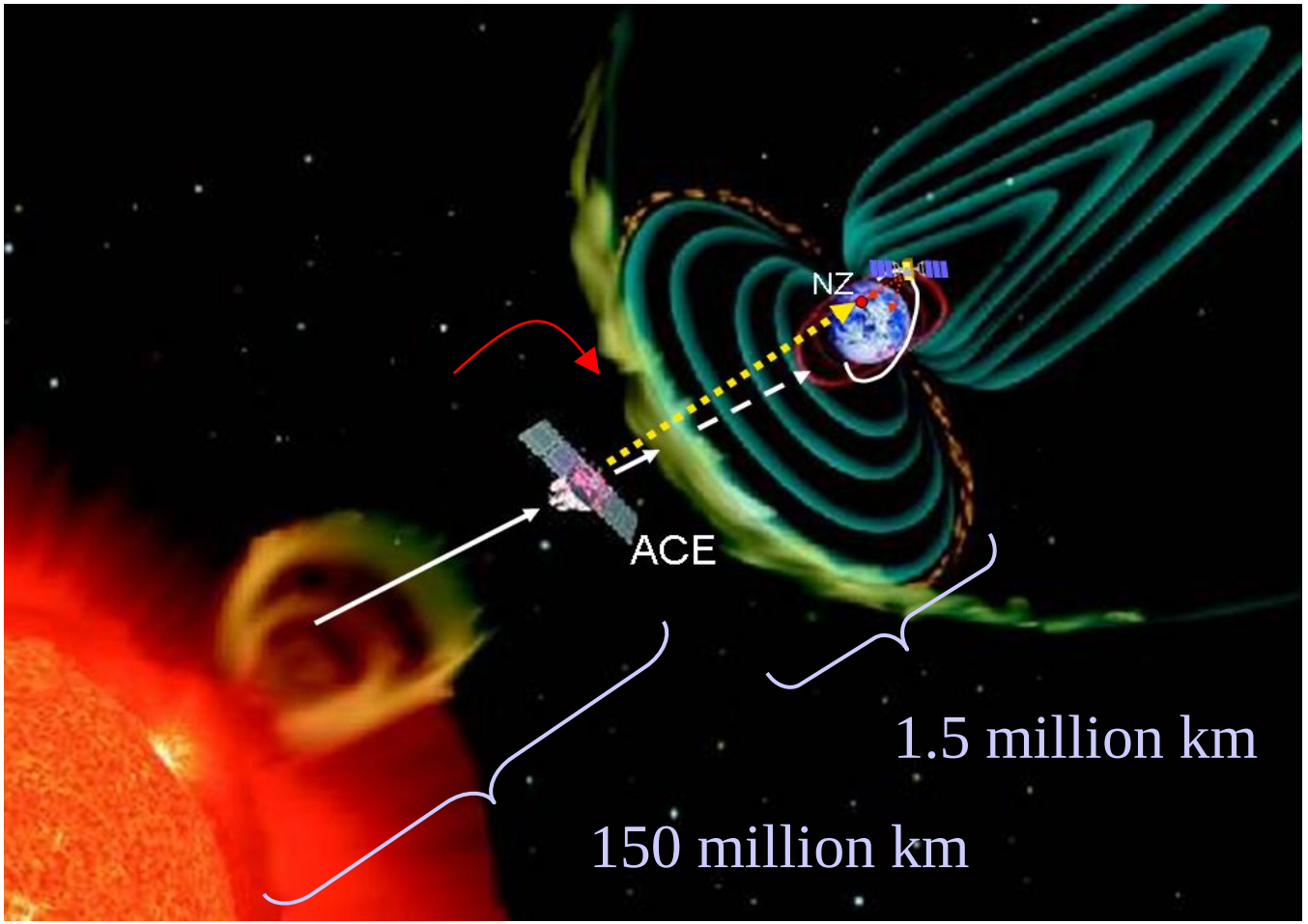
Introduction: Why ionospheric information is needed

- Ionospheric plasma causes refraction, diffraction, scattering, absorption of radio signals
- Ionosphere is biggest error source in single frequency applications
- Correction or mitigation of ionospheric propagation errors is needed
- Monitoring and reconstruction of the ionosphere in near real time
- Forecasting of ionospheric state
- Forecast requires solar wind information

Ionosphere – vertical structure



Solar wind monitoring by ACE Satellite

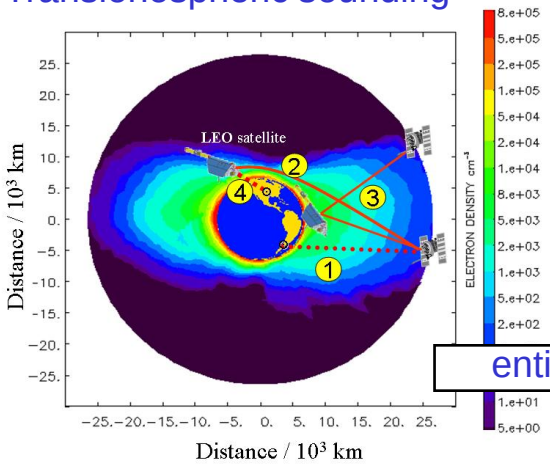


ACE: Advanced Composition Explorer

- DLR Neustrelitz contributes to the Solar Wind Real Time (SWRT) Network of NOAA to ensure continuous information on the solar wind

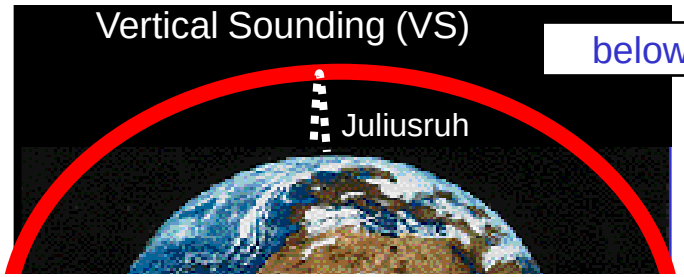
Ionosphere sounding techniques used in SWACI

Transionospheric sounding

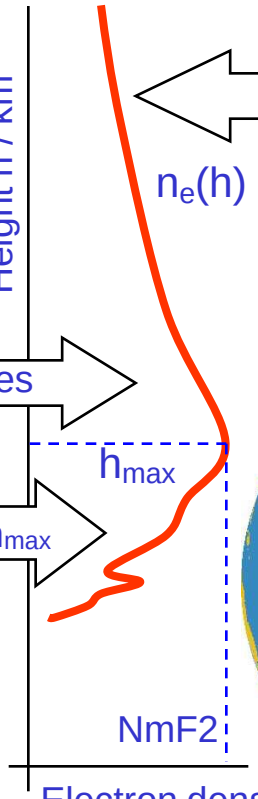


entire profiles

Vertical Sounding (VS)



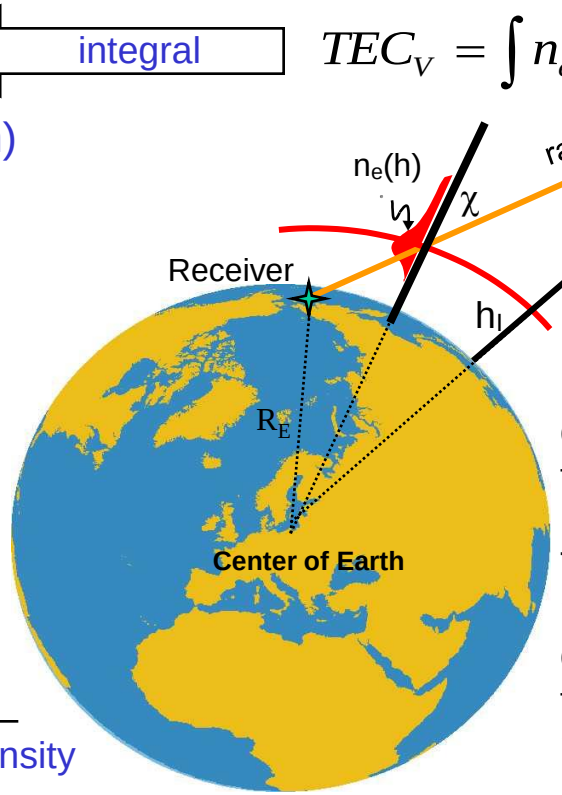
below h_{max}



Total Electron Content

integral

$$TEC_V = \int n_e(h)dh$$



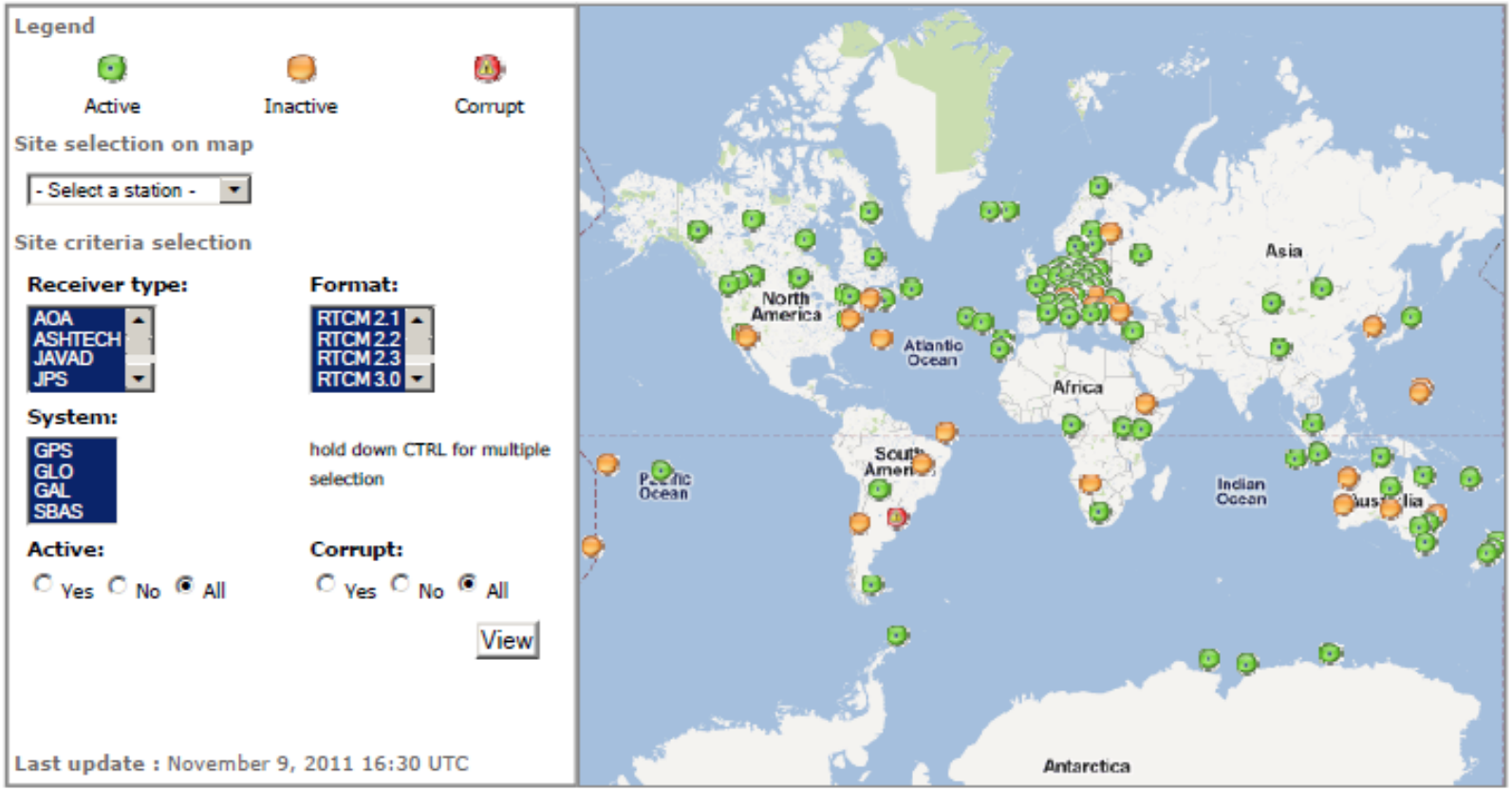
First order range error is proportional to TEC

TEC has a direct meaning for correcting single frequency GNSS navigation

1 GNSS ground
2 Radio occultation
3 Topside TEC
4 Beacon satellite

- Ionospheric information provided by SWACI is mainly obtained by ground and space based GNSS measurements
- Coordination with other measurement techniques
  - Vertical sounding (Juliusruh, Tromsoe, Pruhonice)
  - Beacon satellite measurements

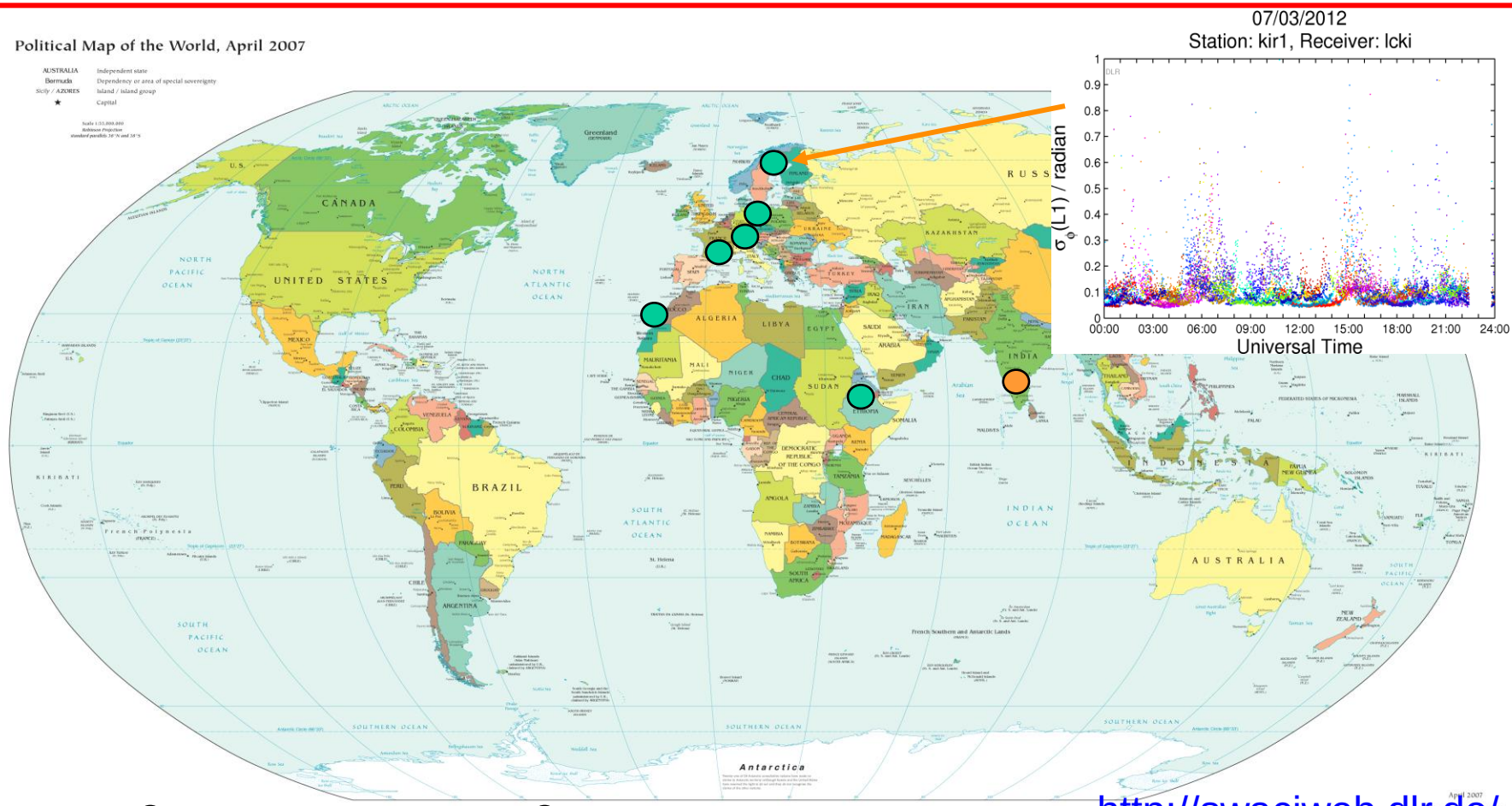
TEC data base: IGS Real Time Pilot Project



Further data sources: EUREF

AxioNet

DLR scintillation network

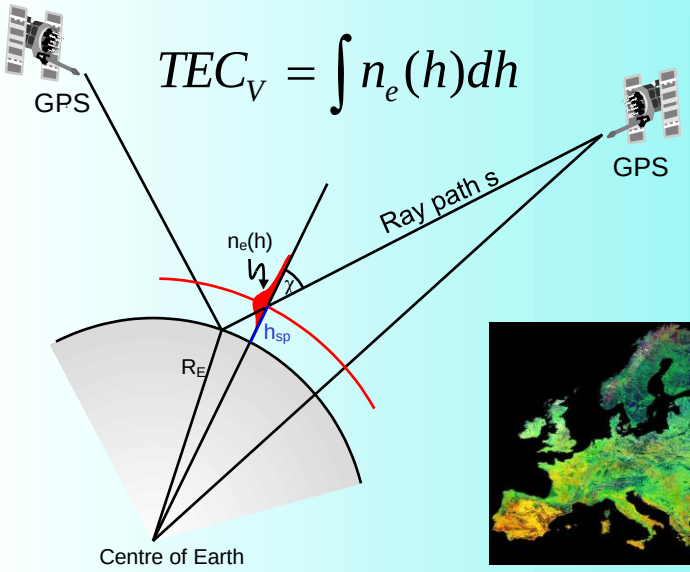


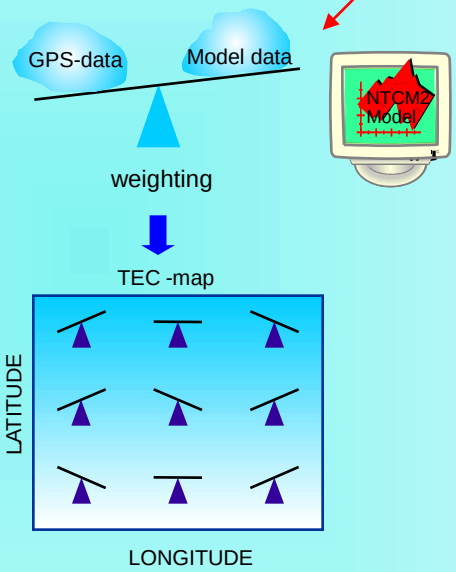
The DLR network contributes to the ESA project MONITOR via SWACI

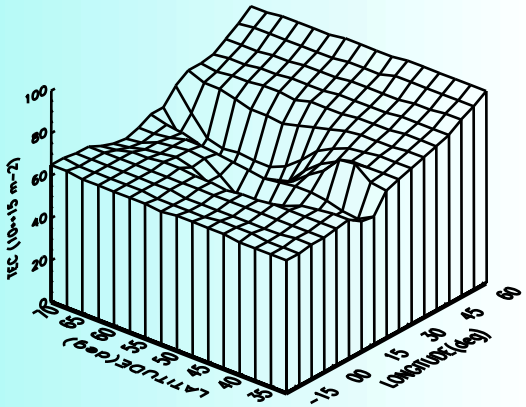
Generation of TEC-maps

Europe	post proc. (1 day)	http://www.kn.nz.dlr.de/daily/tec-eu
Global	**operational (5 min)**	**http://swaciweb.dlr.de**
North Pole	post proc. (1 day)	http://www.kn.nz.dlr.de/daily/tec-np

NTCM-EU, NTCM-NP, NTCM-SP, NTCM-GL





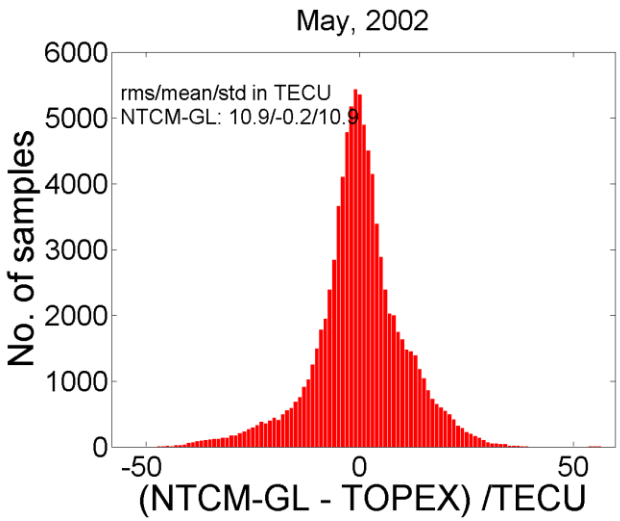


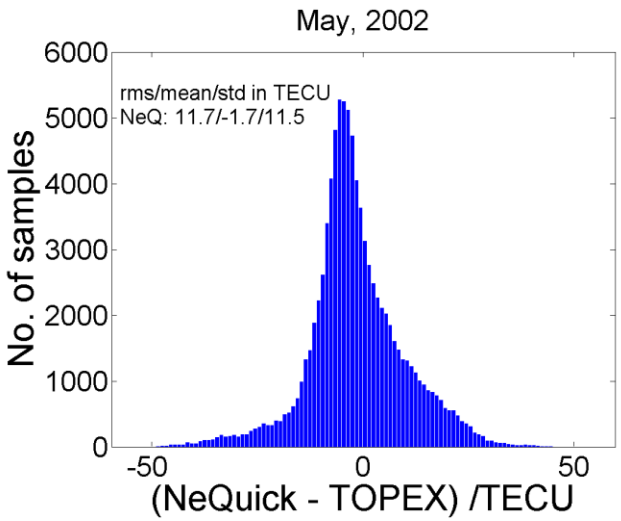
Measurement, Calibration	Conversion to vertical	Assimilation of measurements into the regional TEC model	TEC- Map

Jakowski, N., Modern Ionospheric Science, (Eds. H.Kohl, R. Rüster, K. Schlegel), Berlin, pp 371-390,1996
Jakowski, N., Proc. 2nd COST251 Workshop, (Ed. A. Vernon), 30-31 March, 1998, Side, pp 51-57, 1998

Neustrelitz TEC Model – GLobal (NTCM-GL)

$$\mathrm{TEC}^{vert}_{\mathrm{NTCM\text{-}GL}} = f(LT, doy, \varphi, \lambda, \varphi_m, F10)$$





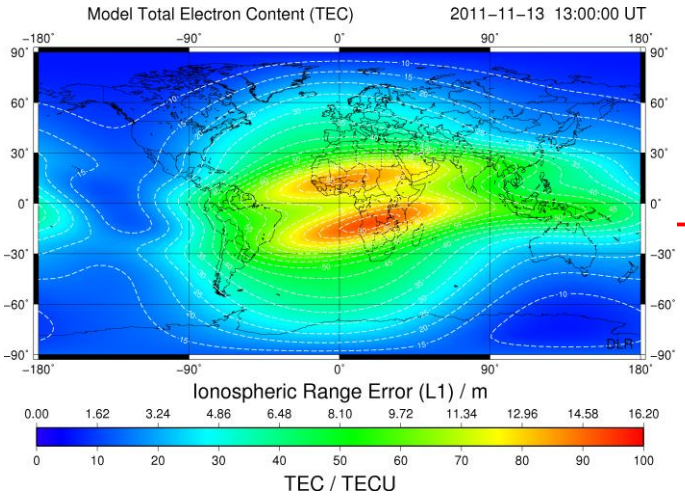
LT: Local Time
doy: day of year
φ geogr. lat
λ geogr. lon
φ_m geom. lat
F10: 10,7cm radio flux
TOPEX: Altimeter-meas. TOPEX/Poseidon

- TEC maps from Center for Orbit Determination in Europe, Univ. Bern, CODE (1998-2007)
- NTCM-GL robust, needs only 12 coefficients, solar activity control by F10.7 cm radio flux
- Similar TEC performance as NeQuick.

Jakowski N, Hoque MM, Mayer C (2011) A new global TEC model for estimating transionospheric radio wave propagation errors, Journal of Geodesy, 85 (12), Seiten 965-974. Springer. DOI: 10.1007/s00190-011-0455-1. ISSN 0949-7714

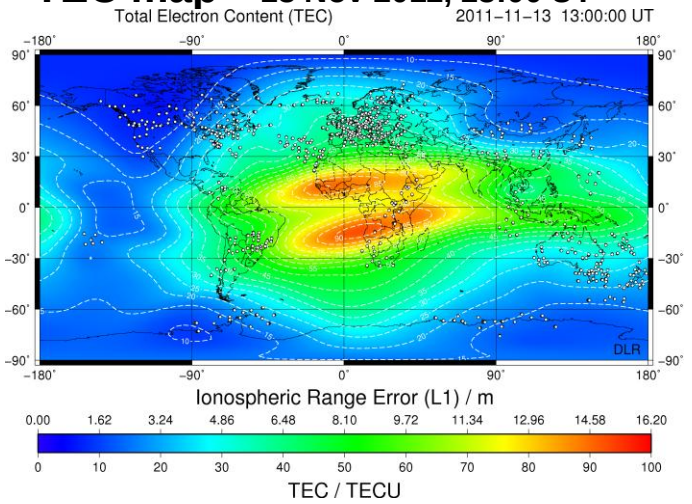
Global TEC map reconstruction

TEC model **13 Nov 2011, 13:00 UT**

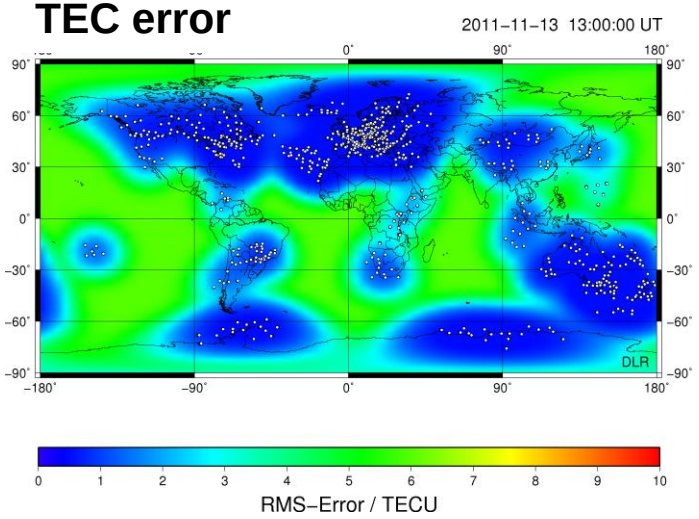


+ Data

TEC map **13 Nov 2011, 13:00 UT**



TEC error

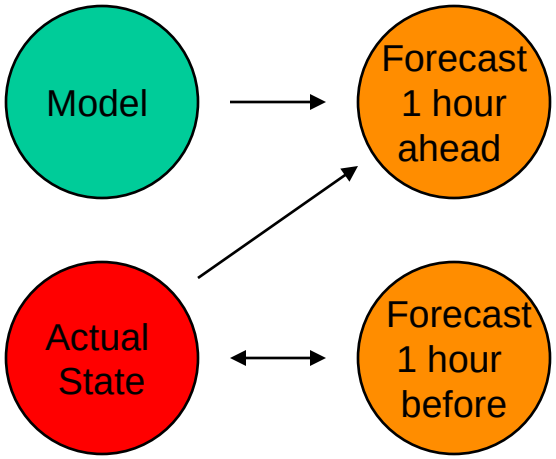


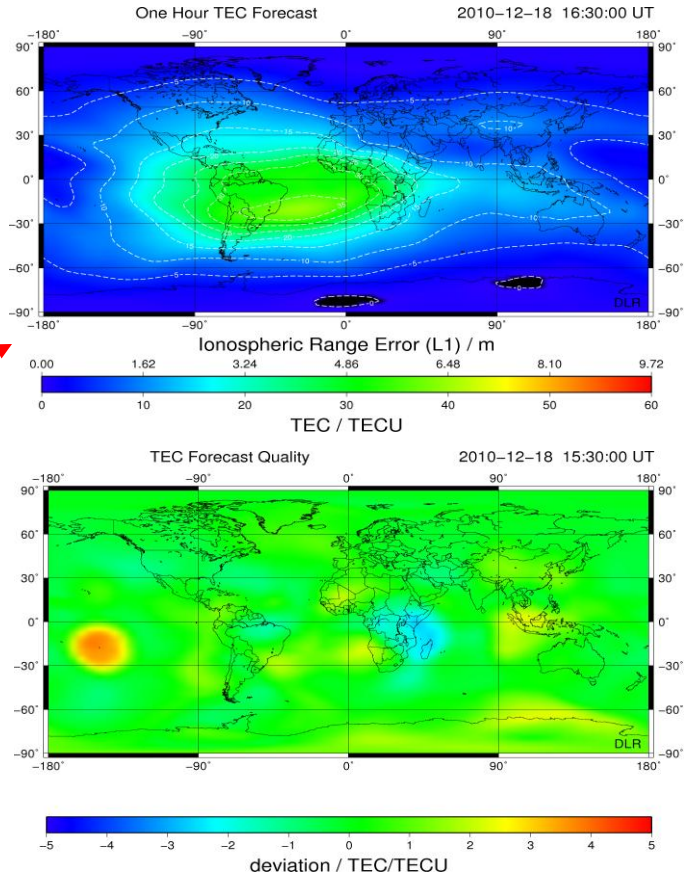
- The near real time reconstruction of global TEC maps is mainly based on IGS data provided within the IGS Real-Time Pilot Project 2007-2010.
- The maps are updated every 5 minutes and therefore fulfil requirements of single frequency users.
- Model assisted mapping is able covering large data gaps

Jakowski N., C. Mayer, M. M. Hoque, and V. Wilken (2011b), Total electron content models and their use in ionosphere monitoring, *Radio Sci.*, *46*, RS0D18

Prediction of the Total Electron Content (TEC)

- Prediction is derived from the current TEC level and related trends taking into account climatological behaviour (Model Medians)
- Immediate control of the predictoion quality by comparing the forecast given one hour before with actual data

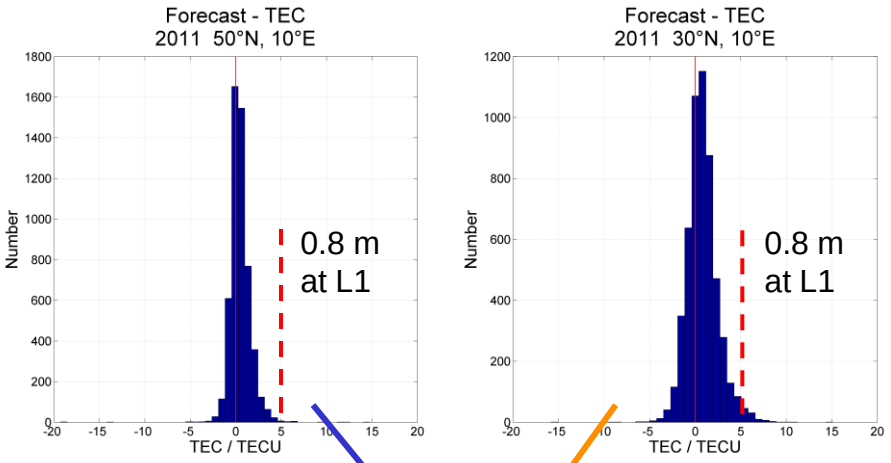


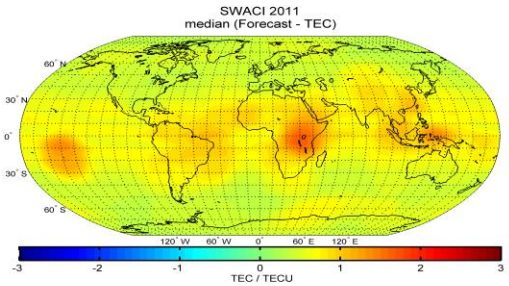


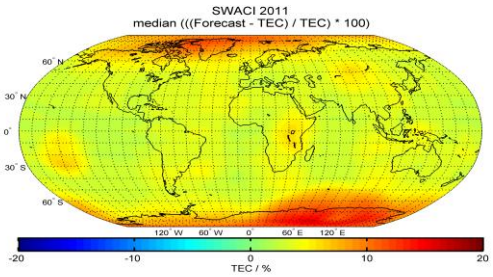
Prediction 1 hour ahead (upper panel) and subsequent control (lower panel)

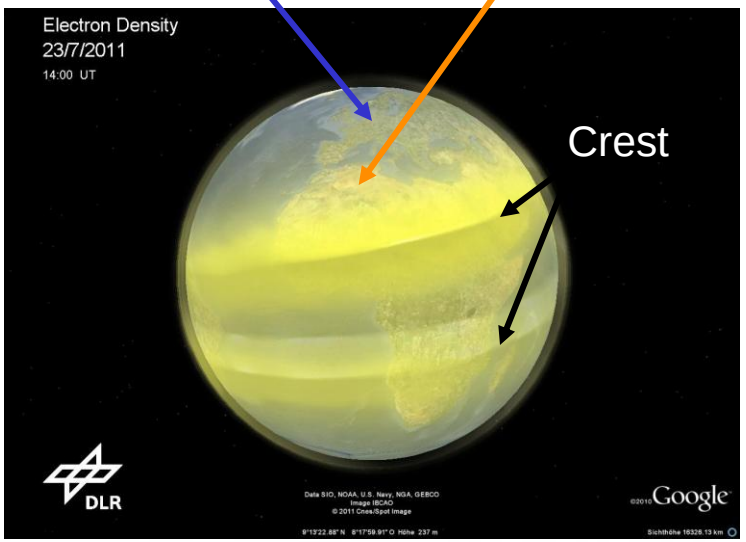
Accuracy of the TEC prediction

- Accuracy of forecast depends on the geographic-geomagnetic relationships, season, local time and solar activity
- Absolute range errors are below 0.5 m, increase towards equatorward.
- Relative errors lie in the range of about 10% with maxima at the poles



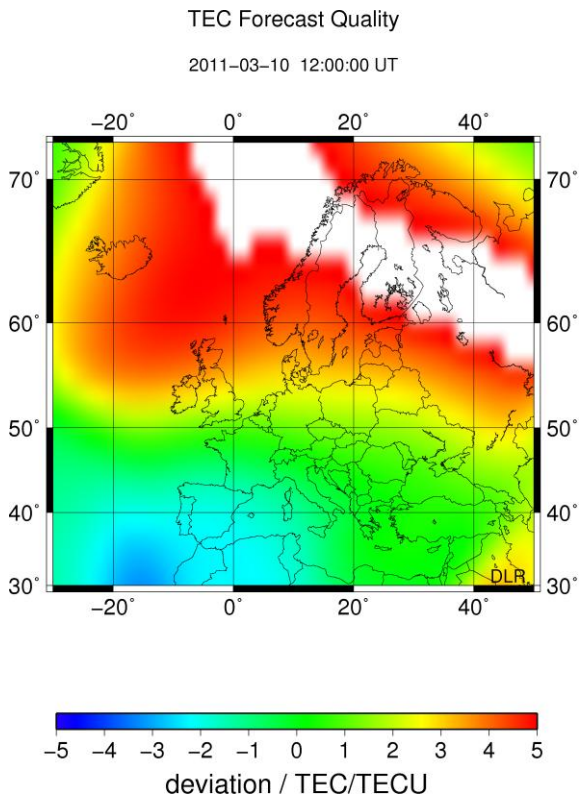






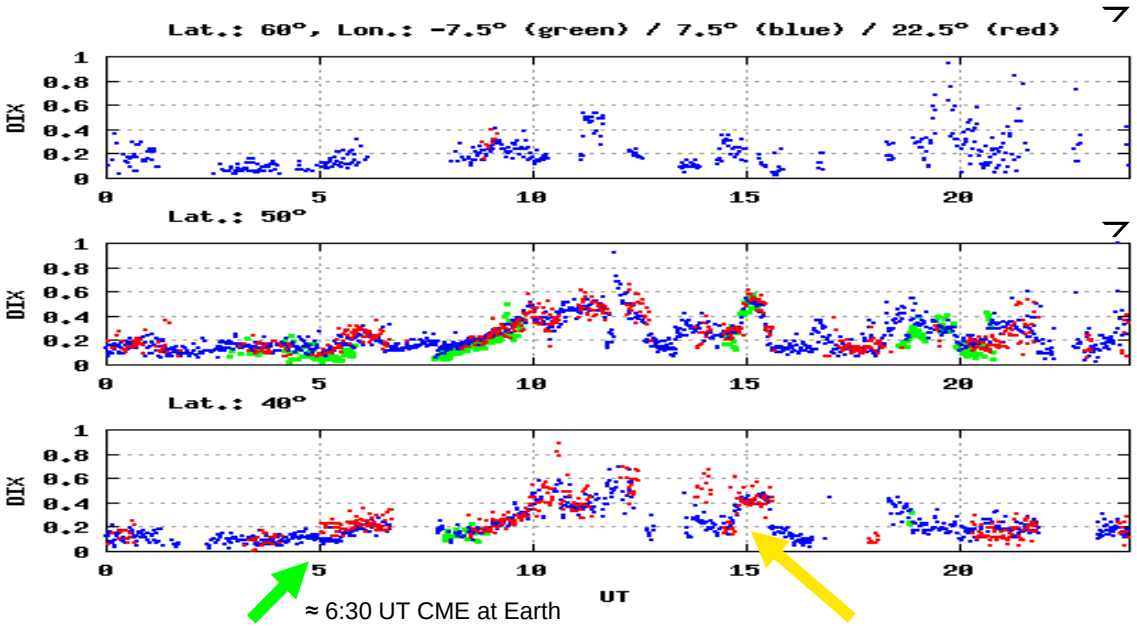
Storm detection

- Ionospheric perturbations degrade the performance of GNSS- applications e.g. of ground and space based augmentation systems.
- Knowledge of actual perturbation degree of the ionosphere is required in particular for Safety of Life (SoL) - applications.
- Conception of a Disturbance Ionosphere Index (DIX) has been developed.
- DIX is robust, calibration free, reflects physical conditions, not impacted by measuring techniques
- Knowing space weather drivers and their solar –terrestrial relationships, DIX can be predicted.
- This is a challenging task for upcoming years under high solar activity conditions



Forecast quality of TEC forecast 1 hour ahead on 10 March 2011
If color scale is exceeded, white color appears

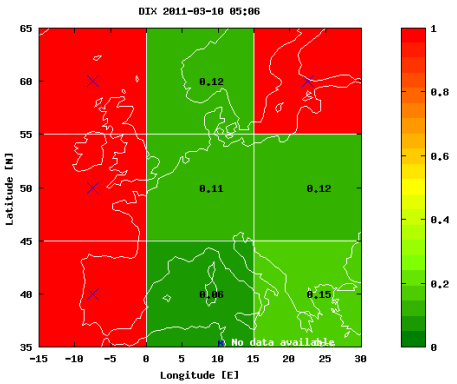
Disturbance Ionosphere Index (DIX) on 10 March 2011



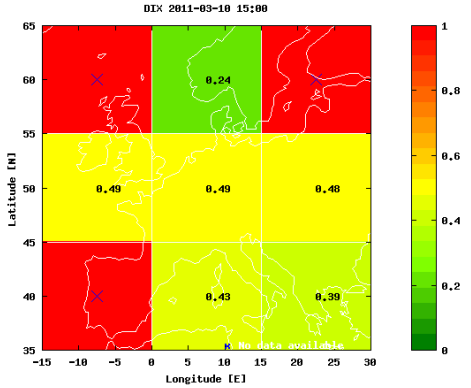
DLR plans to release a provisional European DIX via the Space Weather Application Center - Ionosphere (SWACI) (http://swaciweb.dlr.de) on a regular basis.

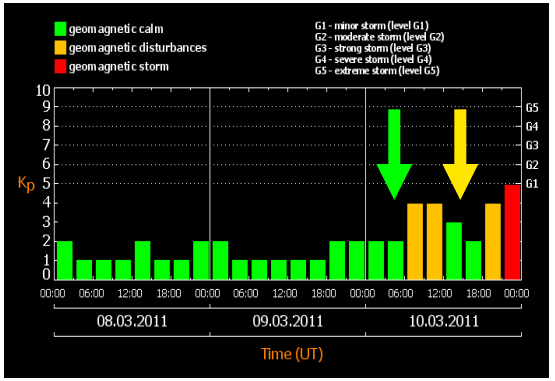
Operational tests to optimize the near real time processing tools and to tune free parameters are currently performed.

Jakowski, N., C. Borries, and V. Wilken, Introducing a new Disturbance Ionosphere Index (DIX), Proc. Ionospheric Effects Symposium, 17-19 May 2011, Alexandria, USA



Source: SOHO





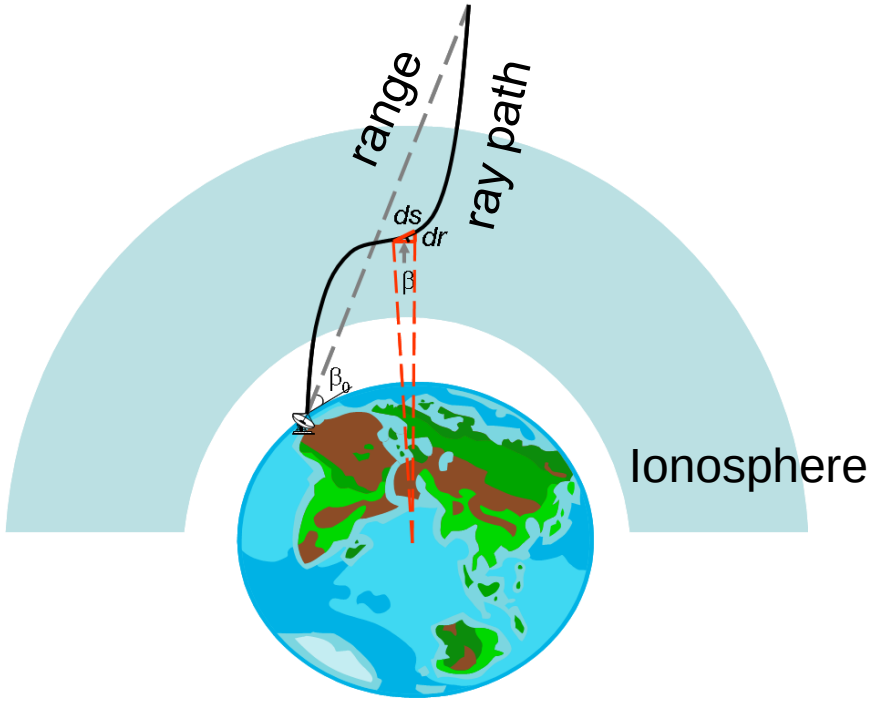
Refraction effects at satellite – ground links

- Geometric distance or true range

$$\rho = \int_S^R ds - d^{len}$$

$$\rho = L + \int_S^R (1-n)ds - d^{len}$$

optical path — phase delay — excess path



ds = ray path element, *n* = refractive index

First and higher order ionospheric terms

Phase refractive index

$$n = 1 - \frac{f_p^{\,2}}{2f^2} \pm \frac{f_p^{\,2} f_g \cos\Theta}{2f^3} - \frac{f_p^{\,4}}{8f^4}$$

Phase delay

$$\int_S^R (1-n)ds = \frac{40.3}{f^2} TEC + \frac{2.26\times10^{12}}{f^3} \overline{B\cos\Theta} \cdot TEC + \frac{2437}{f^4} \int n_e^2 ds$$

First order term | **Second order term** | **Third order term**

- Estimation of higher order errors and development of correction formulas based on TEC input

f_p: plasma frequency, f_g: gyro frequency, n_e: electron density, B: magnetic induction, f : frequency, Θ : angle between ray direction and B field, ds: ray segment, TEC: total electron content

Higher order ionospheric terms

$$\Phi = \rho + c(dt - dT) - d_I + d_A + d_{MP} + dq + dQ + N\lambda + \varepsilon_0$$

Simplified carrier-phase equation

$$\Phi = \rho - \int_S^R (1-n)ds$$

$$\frac{f_1^2}{f_1^2 - f_2^2}\Phi_1 - \frac{f_2^2}{f_1^2 - f_2^2}\Phi_2 = \rho \underbrace{+ \Delta s_{TEC} + \Delta s_2 + \Delta s_3 - \Delta s_{len}}_{RRE}$$

- **TEC difference**

$$\Delta s_{TEC} = \frac{40.3 \times (TEC_2 - TEC_1)}{\left(f_1^2 - f_2^2\right)}$$

- **excess path length**

$$\Delta s_{len} = \frac{d_2^{len} f_2^2 - d_1^{len} f_1^2}{\left(f_1^2 - f_2^2\right)}$$

- **second order**

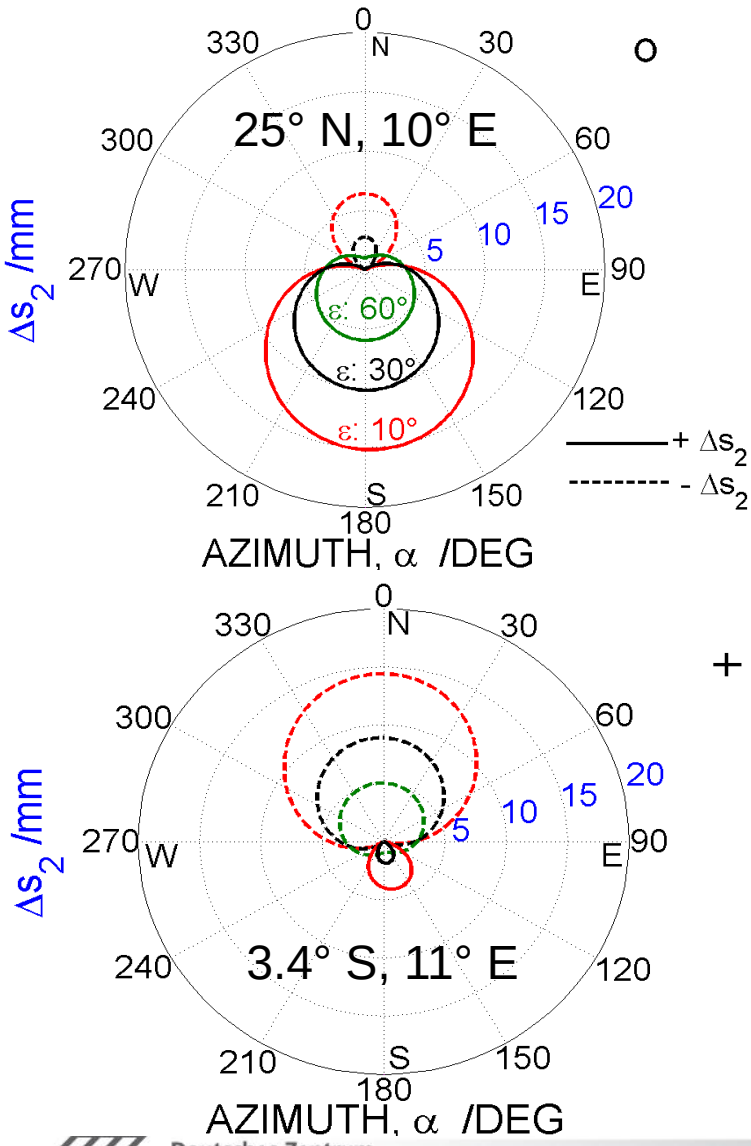
$$\Delta s_2 = \frac{1.13 \times 10^{12} \cdot \overline{B\cos\Theta} \cdot TEC}{f_1 f_2 (f_1 + f_2)}$$

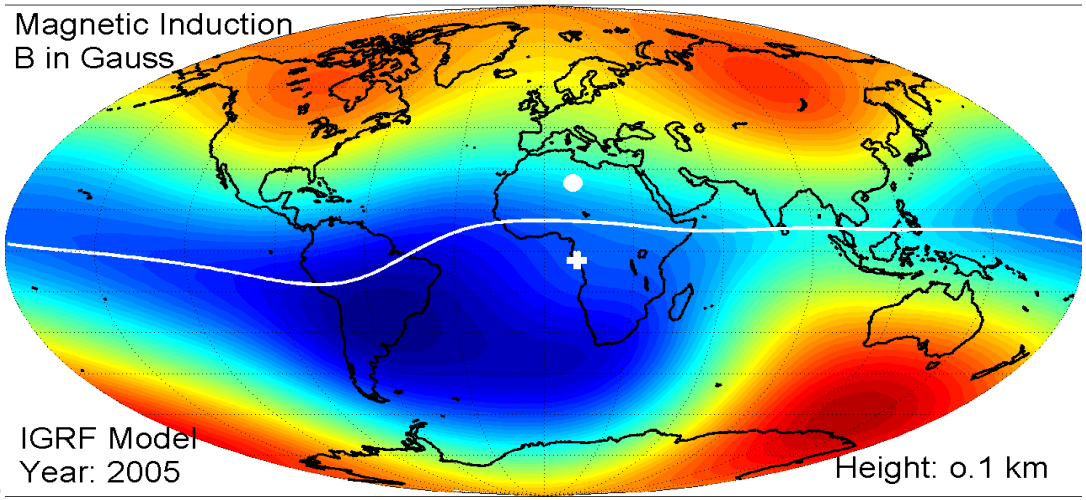
- **third order**

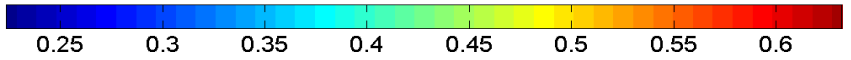
$$\Delta s_3 = \frac{812.3}{f_1^2 f_2^2} \int_S^R n_e^2 ds$$

Hoque, M. M., Jakowski, N. (2008), Estimate of higher order ionospheric errors in GNSS positioning, *Radio Sci.*, *43*, RS5008

Second order ionospheric term







+

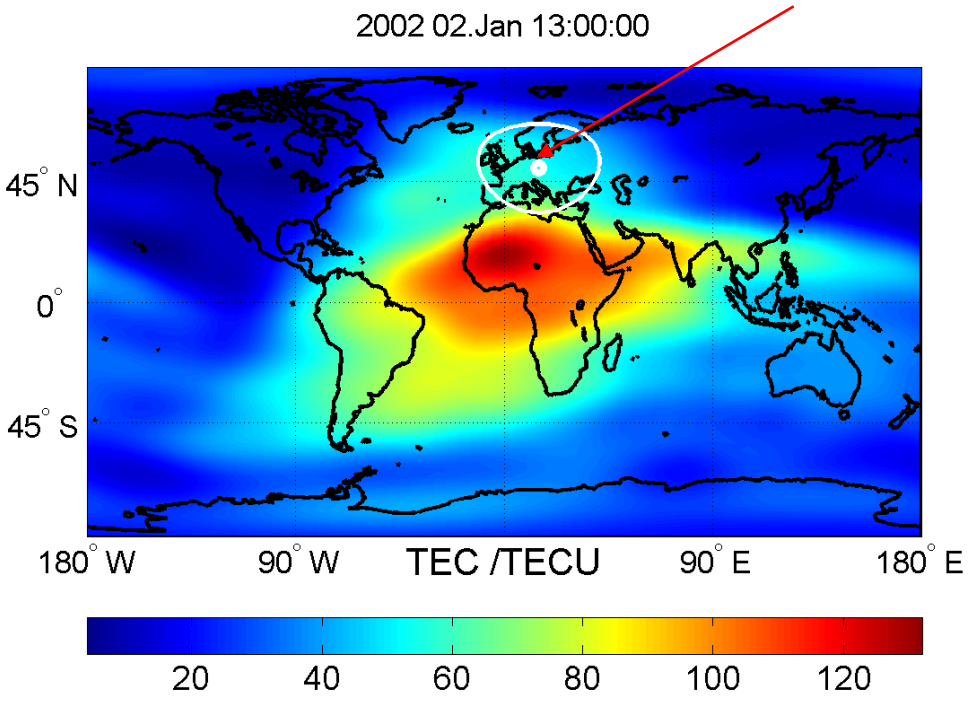
Position:	Conjugate position:
lat: 25° N	lat: 3.4° S
lon: 10° E	lon: 11° E

TEC_V: 100 TECU

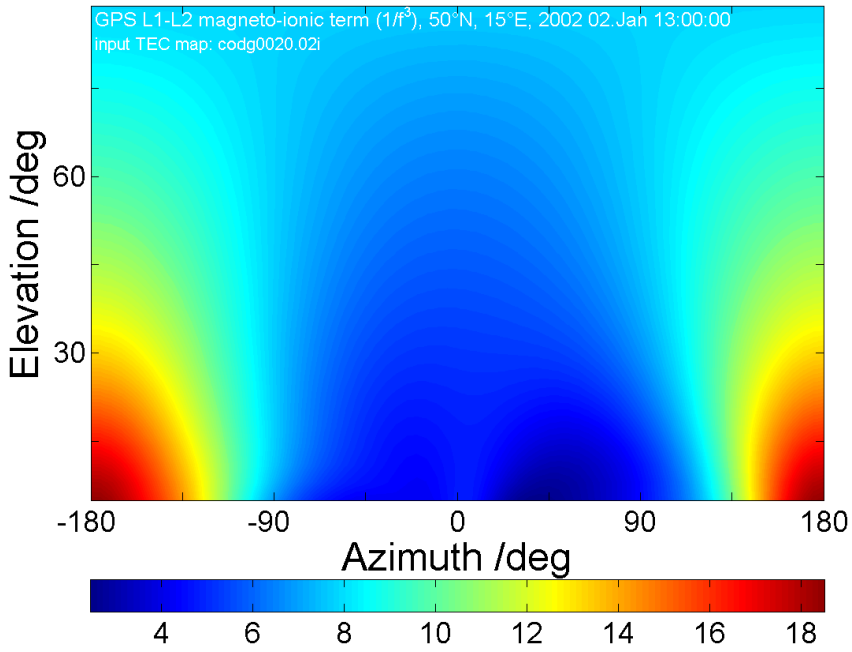
ε : elevation

Estimates of GPS L1-L2 second order term

50°N, 15°E



2002, 2 Jan,13:00 UT

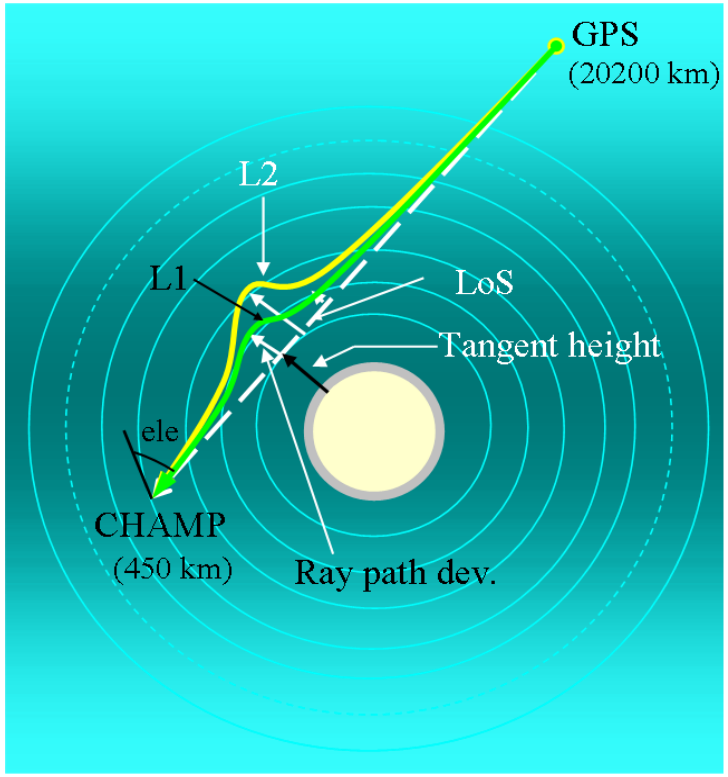


Second order term /mm

Hoque, M. M. and N. Jakowski (2006), Higher-order ionospheric effects in precise GNSS positioning, *Journal of Geodesy*, *81*(4), Hoque, M. M., Jakowski, N. (2007), Mitigation of higher order ionospheric effects on GNSS users in Europe, *GPS Solut*., *12*(2)

Refraction effects at satellite – satellite links during radio occultation

- Estimation of higher order errors and development of correction formulas based on TEC input
- Correction model for radio occultation measurements has been developed.
  - In the limb sounding mode significant ray path bending may cause errors in retrieving techniques.
  - The model enables correcting measured TEC.
  - Ray paths of L1 and L2 may deviate from each other by more than 1 km.
  - The same is valid for the deviation from the line of sight



M M Hoque and N Jakowski, Ionospheric bending correction for GNSS radio occultation signals, Radio Science, 2011

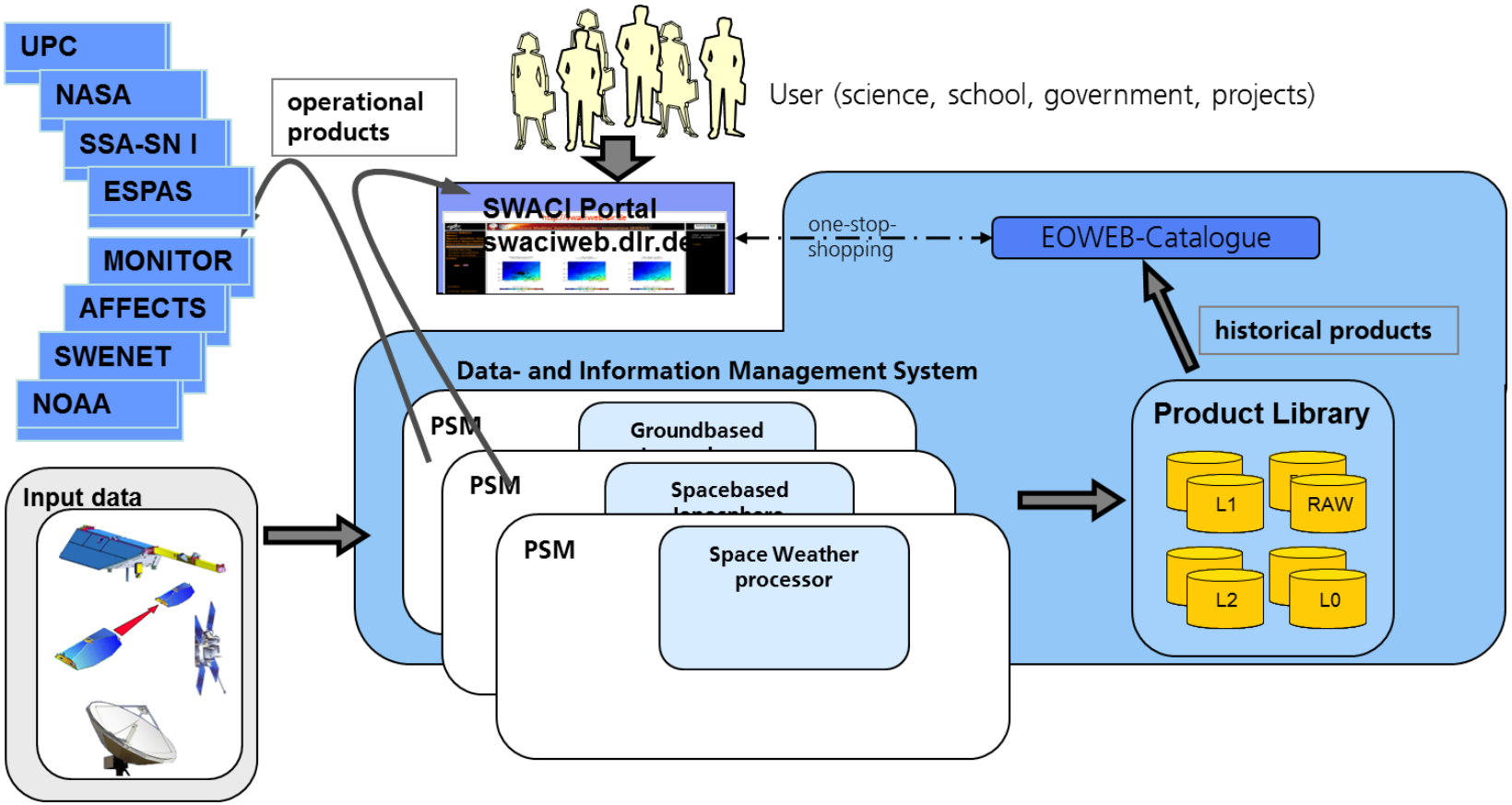
Space weather Application Center - Ionosphere SWACI

- SWACI is a research project for establishing a space weather center focused on ionospheric issues at DLR Neustrelitz
- SWACI is essentially supported by the German State Government of Mecklenburg-Vorpommern

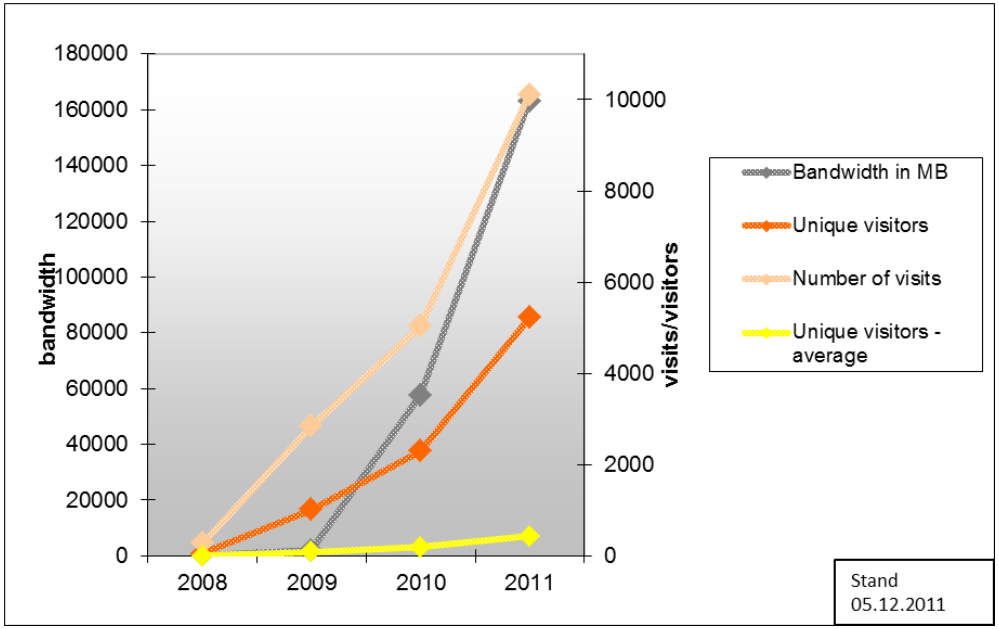
  Funding period: 2004 – 2011

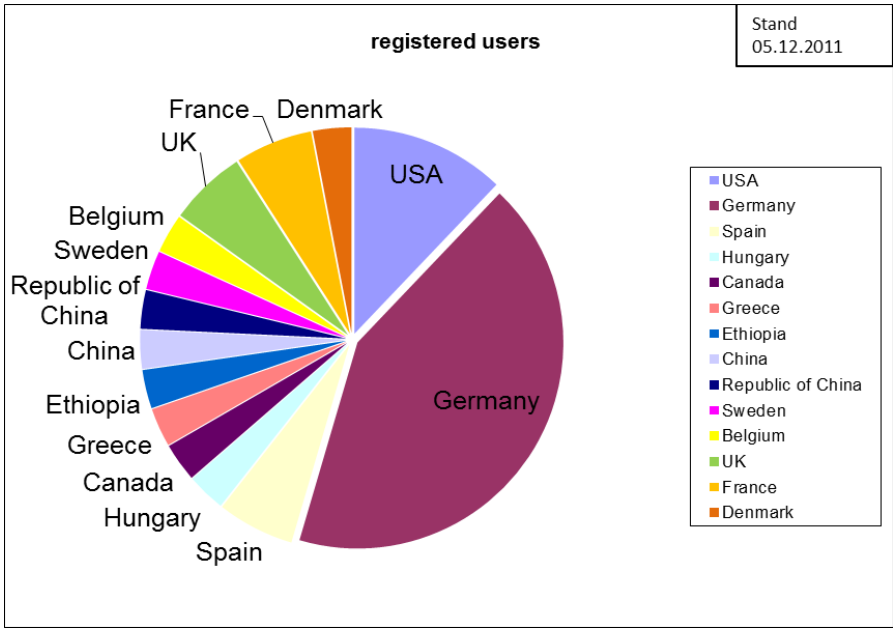
- Service shall provide near real time information on the ionospheric state
  - Monitoring
  - Forecast
  - Data distribution and archiving
- Informations and products are provided via the internet portal http://swaciweb.dlr.de

SWACI Service

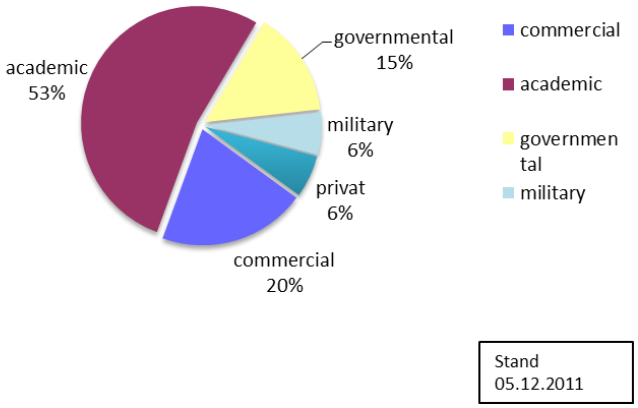


SWACI- Data use





- Access number grows up continuously
- Most users are from academic



Summary

- The „Space Weather Application Center – Ionosphere“ (SWACI) at DLR Neustrelitz provides ionospheric information and data on a routine basis, e.g.
  - Ground based TEC and derivatives over Europe (5 min update)
  - TEC forecast (1 hour in advance) and quality control
  - Scintillation data over Europe (1 min update)
- Ionospheric storms can be monitored by ionospheric services like SWACI to draw conclusions on concrete applications.
- Test of Disturbance Ionosphere Index (DIX) at SWACI Websites available in February 2012
- Estimation of higher order errors and development of correction formulas based on TEC input for ground and space based reception of GNSS signals

Thank you for your attention !