Space Weather Impact on Radio Systems

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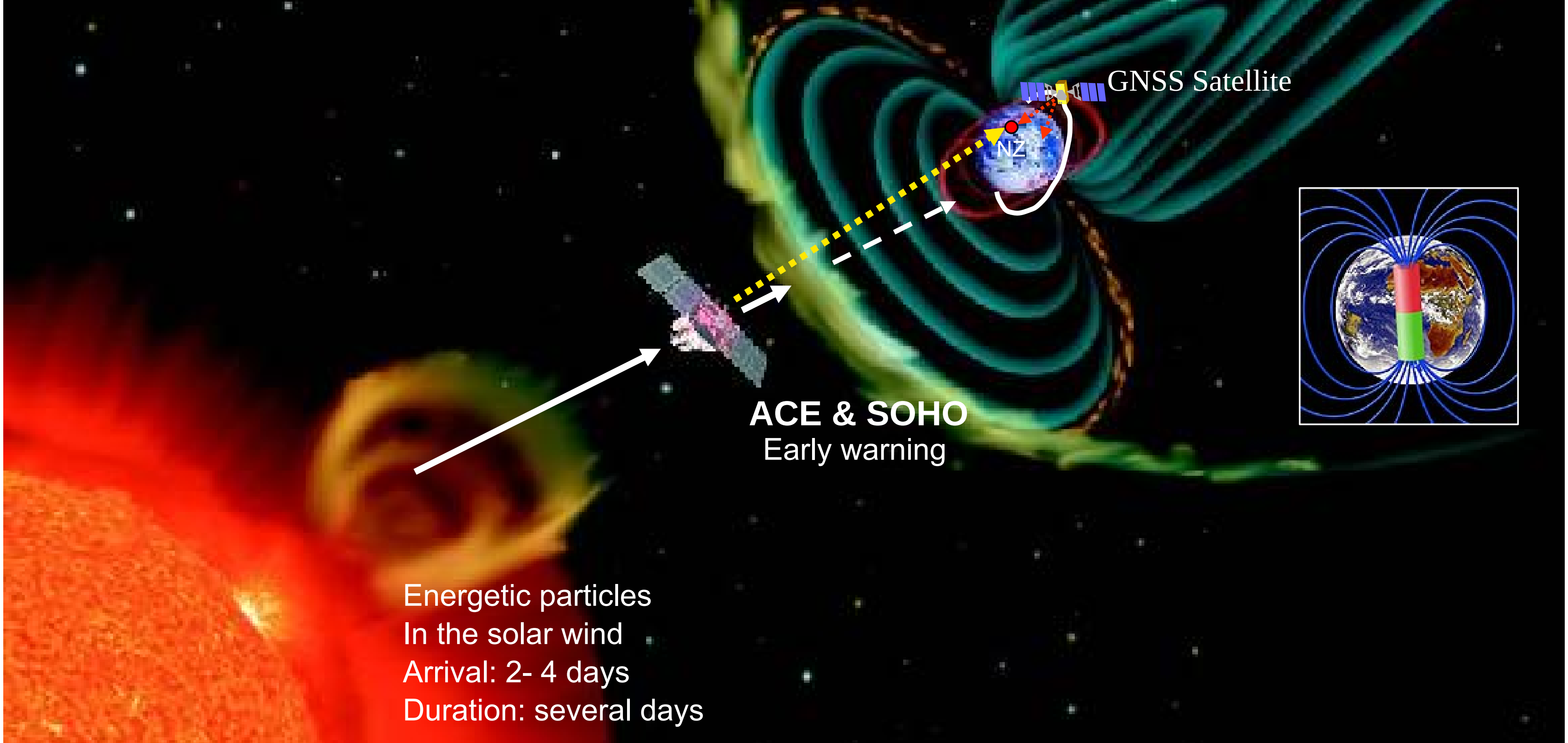
OUTLINE

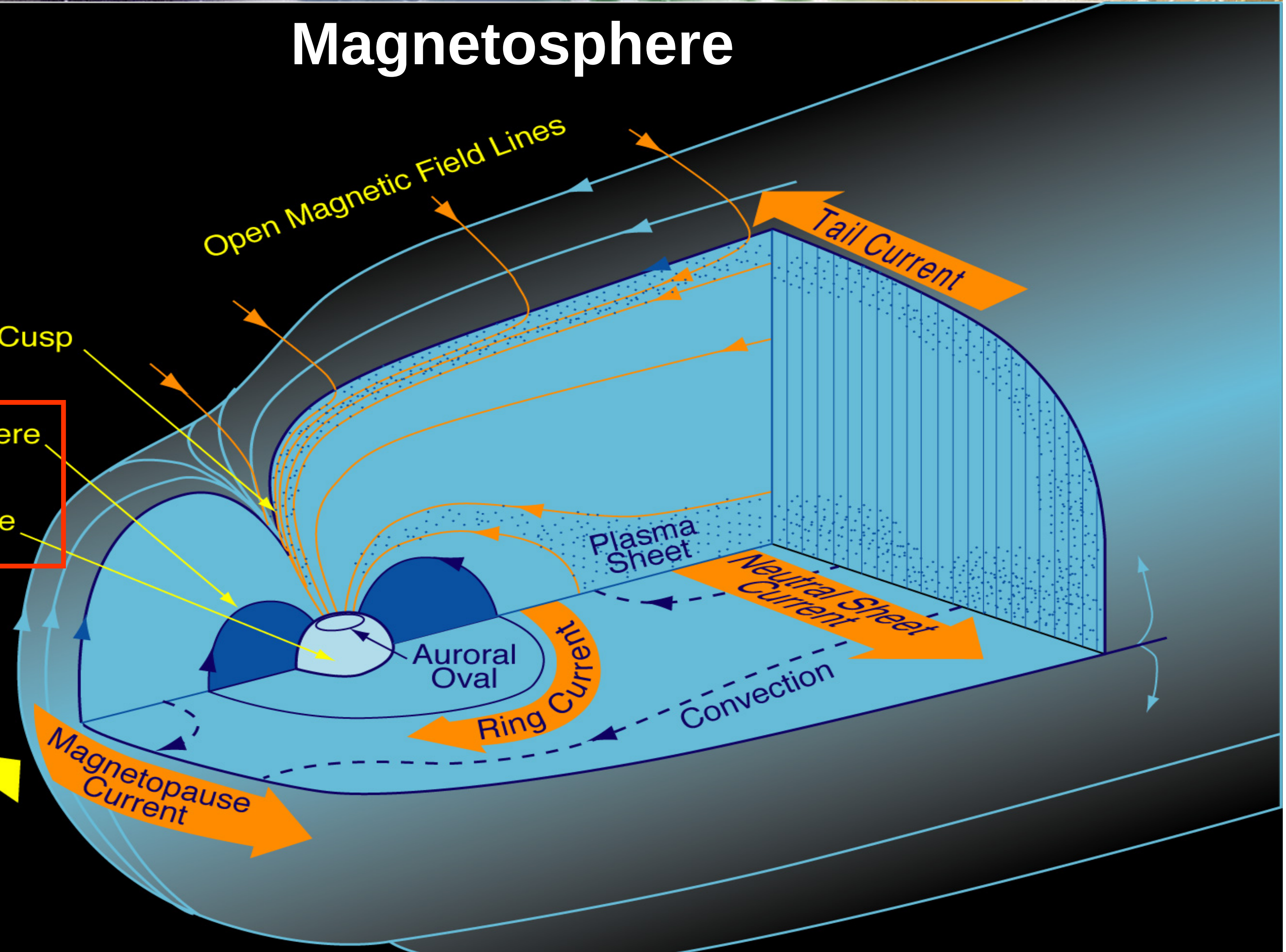
- Space weather impact
  - Ionosphere/plasmasphere
  - Radio wave propagation
- Radio systems
  - Navigation
  - Communication
  - Remote sensing
- Mitigation of space weather impact
  - Monitoring and modelling space weather
  - Space weather services
- Summary

- Space weather refers to the conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. (Definition NSWP, USA, 1996)



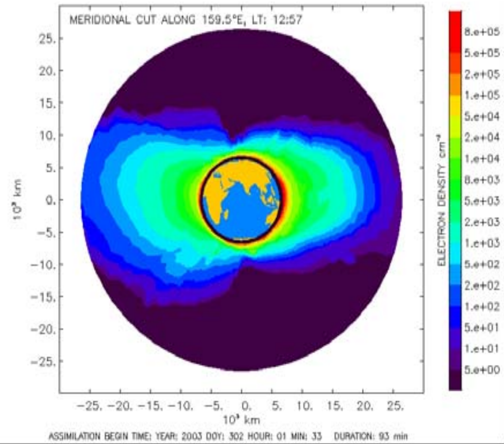
GNSS - Global Navigation Satellite System

Magnetosphere

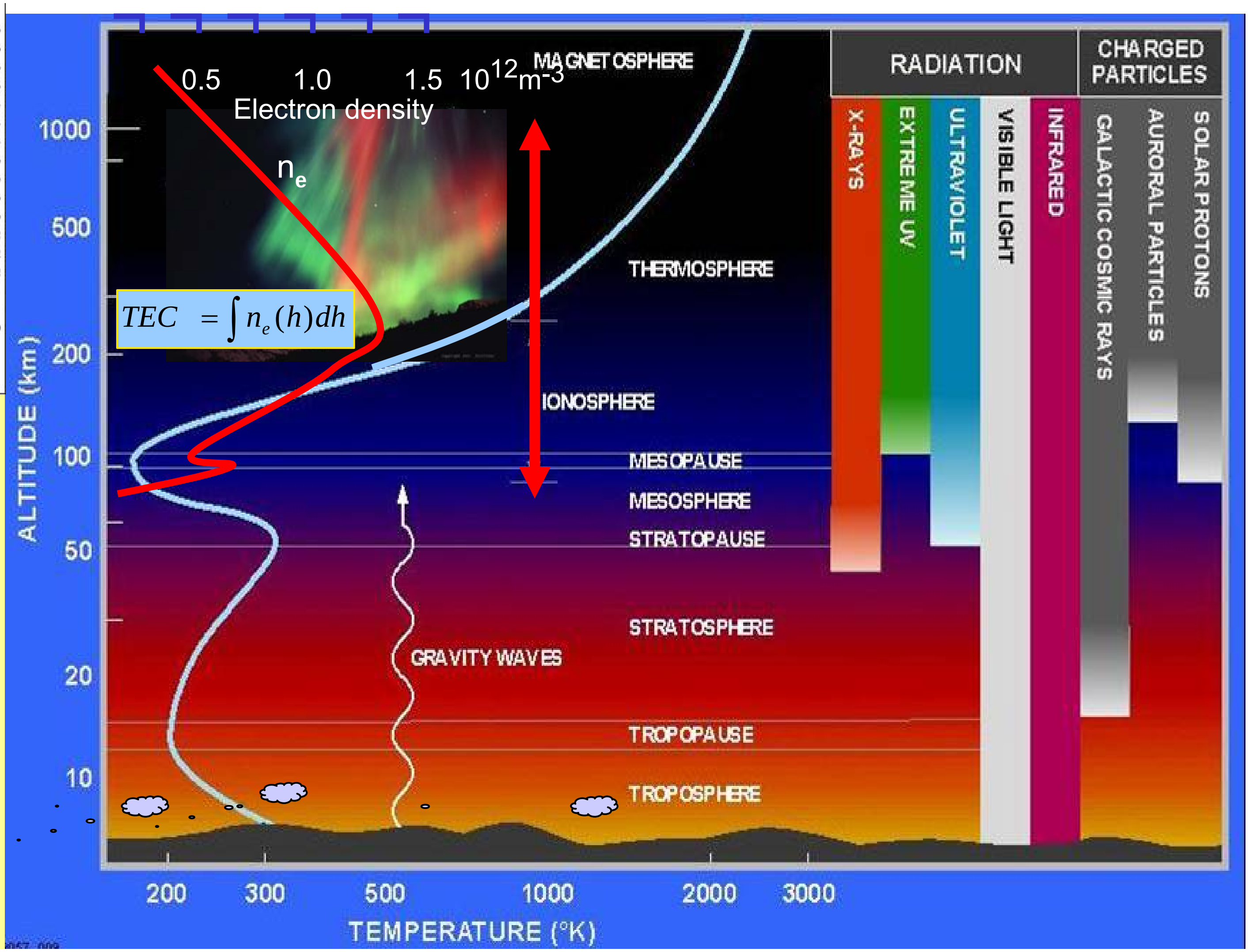


Das ionospheric weather is strongly coupled with processes in the magnetosphere

Structure of the Earth's atmosphere

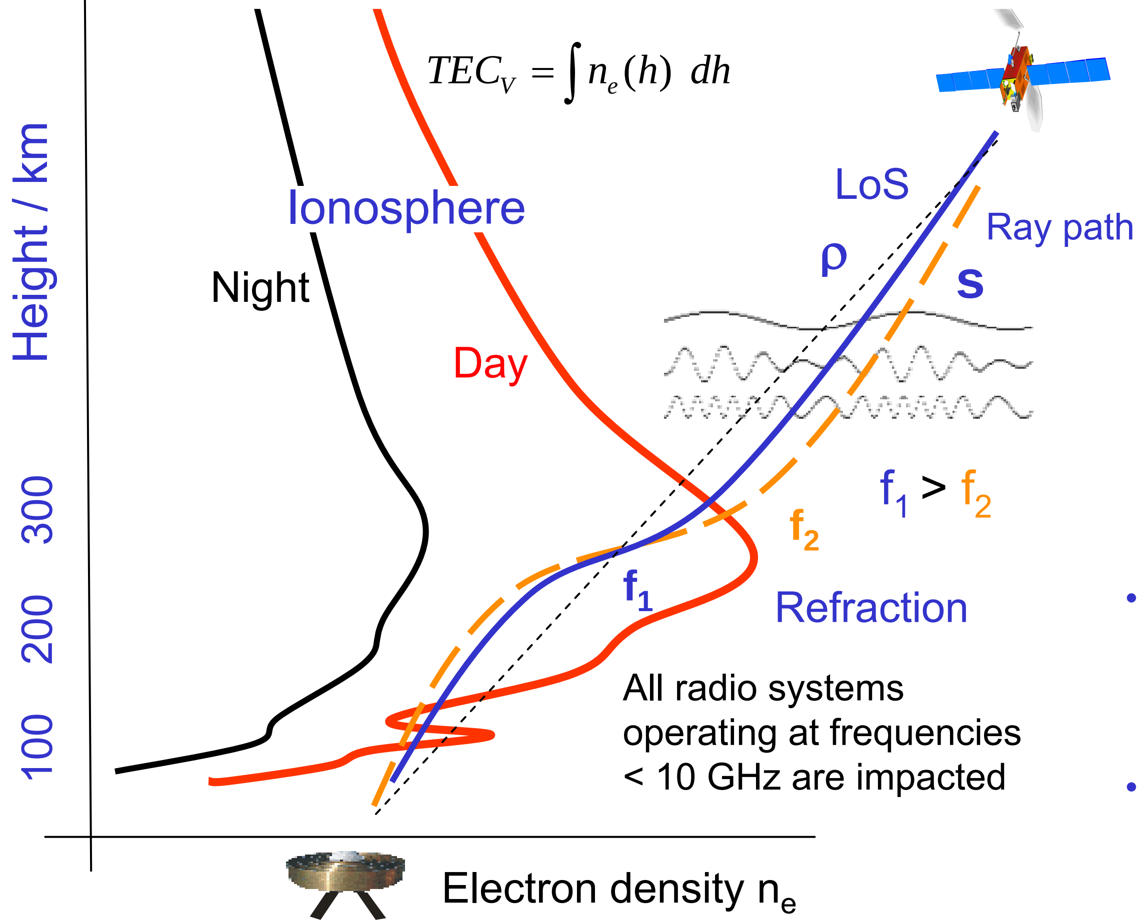


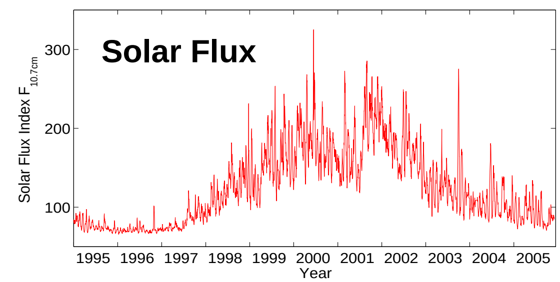
The ionosphere is part of the complex dynamics of the near Earth space. The understanding of interdisciplinary coupling processes of the Geo-Plasma is important to forecast space weather effects and their impact on radio systems

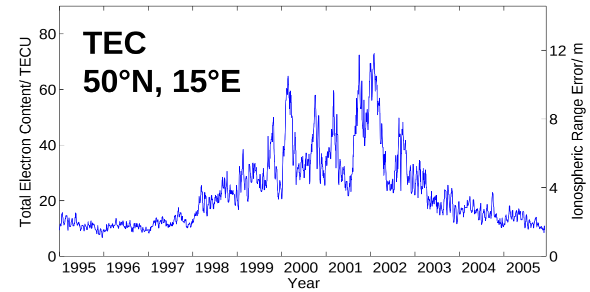


Radio wave propagation in the ionosphere

Electron density n_e & Total Electron Content (TEC) are closely related to the solar irradiance



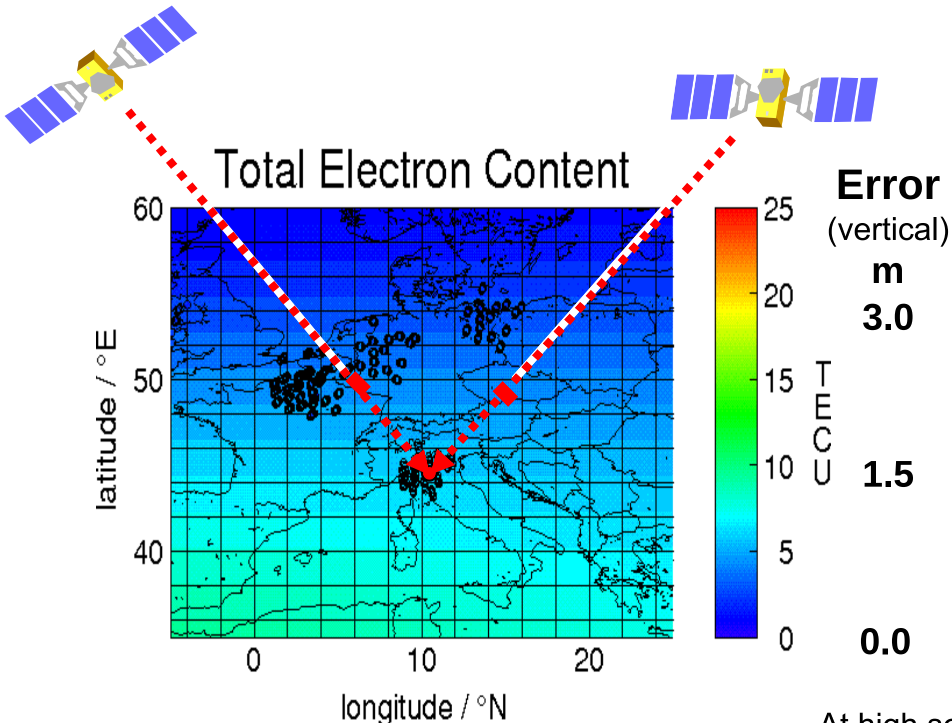




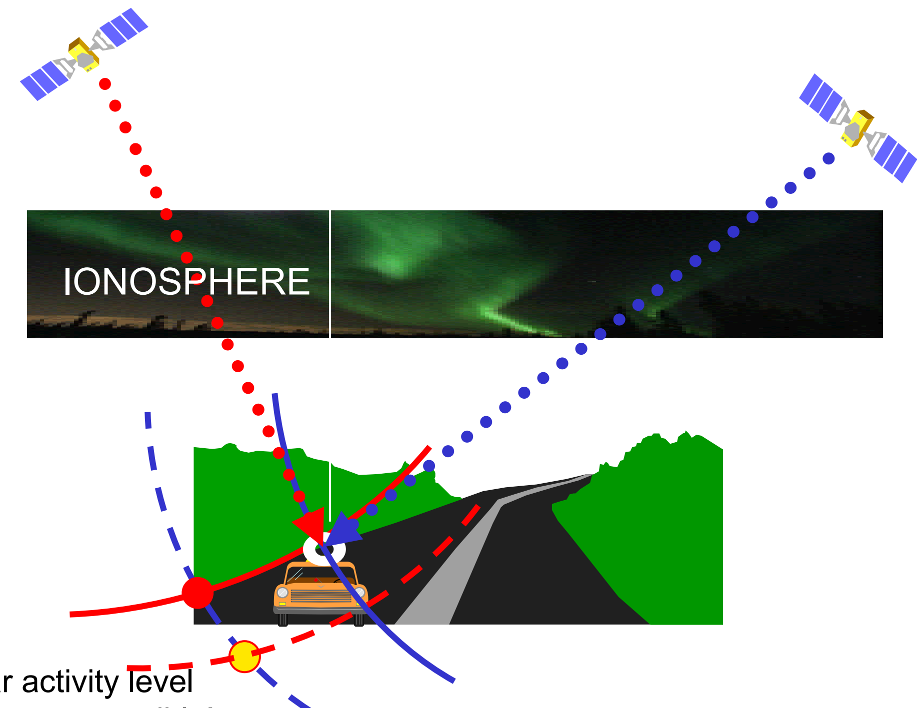
Ionosphere causes

- Regular effects due to the presence of plasma
  - signal delay
  - rotation of polarisation
- Irregular effects due to plasma distortions, turbulences
  - misinterpretation of data due to horizontal gradients (HMI)
  - Radio scintillations

TEC – monitoring - Navigation errors



Sample:16 GPS stations Time: 01:04:00 UT



At high solar activity level errors up to **35 m** possible!

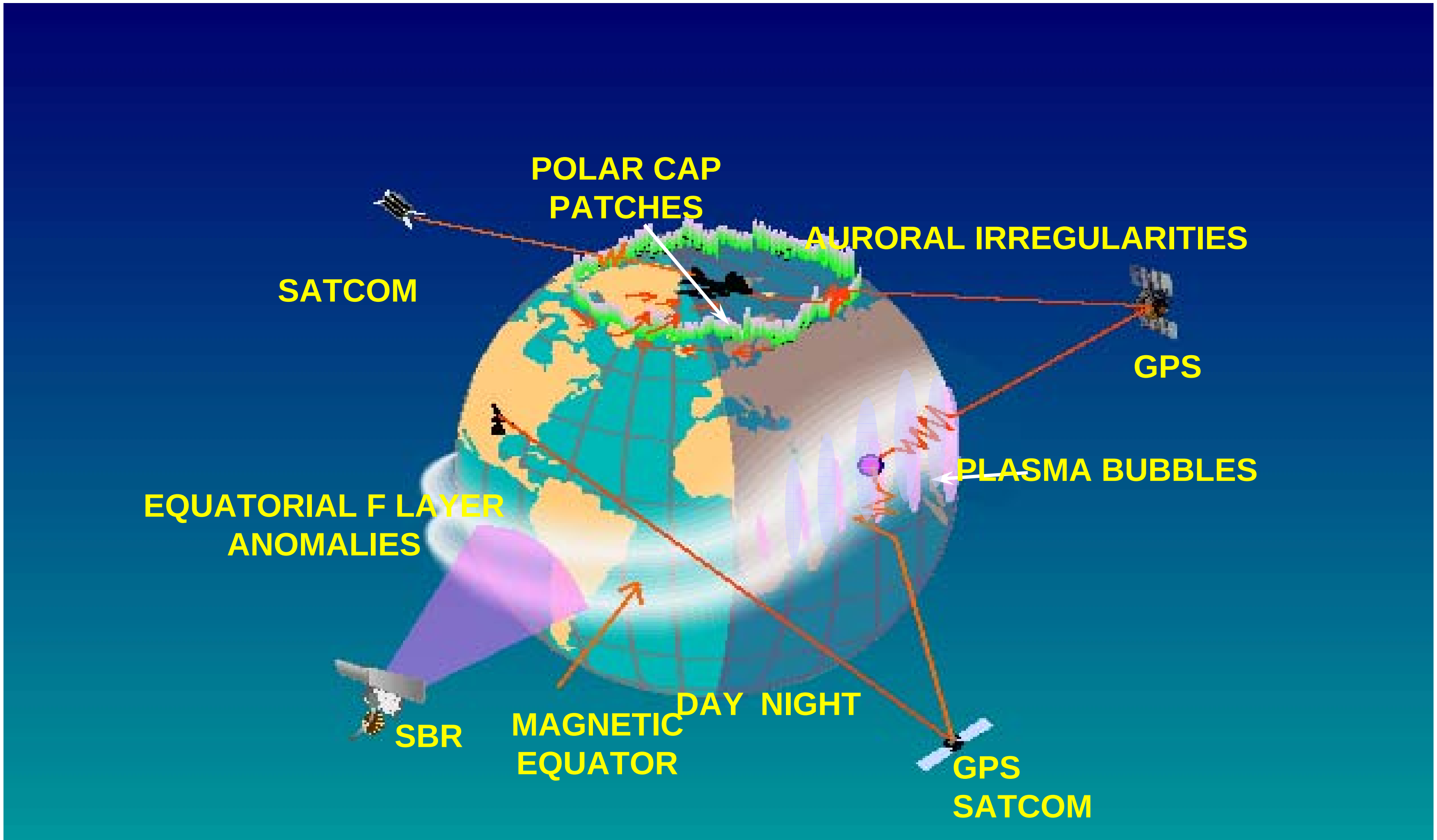
$$d_I^{(1)} = \frac{K}{f^2}\int n_e ds = \frac{K}{f^2}\cdot TEC$$

Ionospheric first order range errror d_I is proportional to TEC

- GNSS*-Data obtained from geodetic networks for TEC Monitoring in streaming mode (IGS, EUREF)
- Empirical modelling of the ionosphere (in DLR: Europe, polar regions, global)
- Near real time monitoring possible

*GNSS- Global Navigation Satellite System

Ionospheric perturbation regions where radio wave propagation may seriously be affected



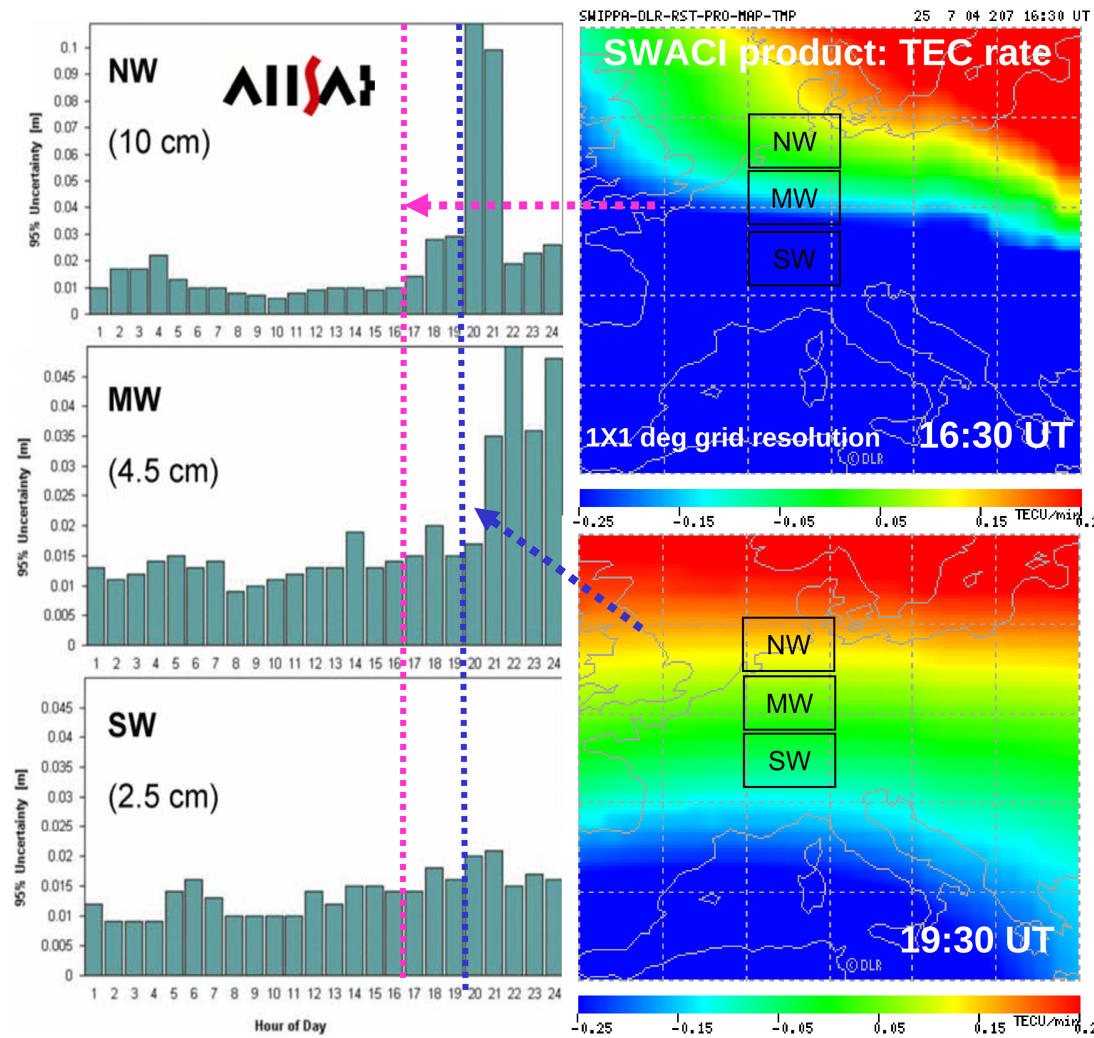
Source: AFRL

Performance degradation of the GPS reference network of ascos on 25 July 2004

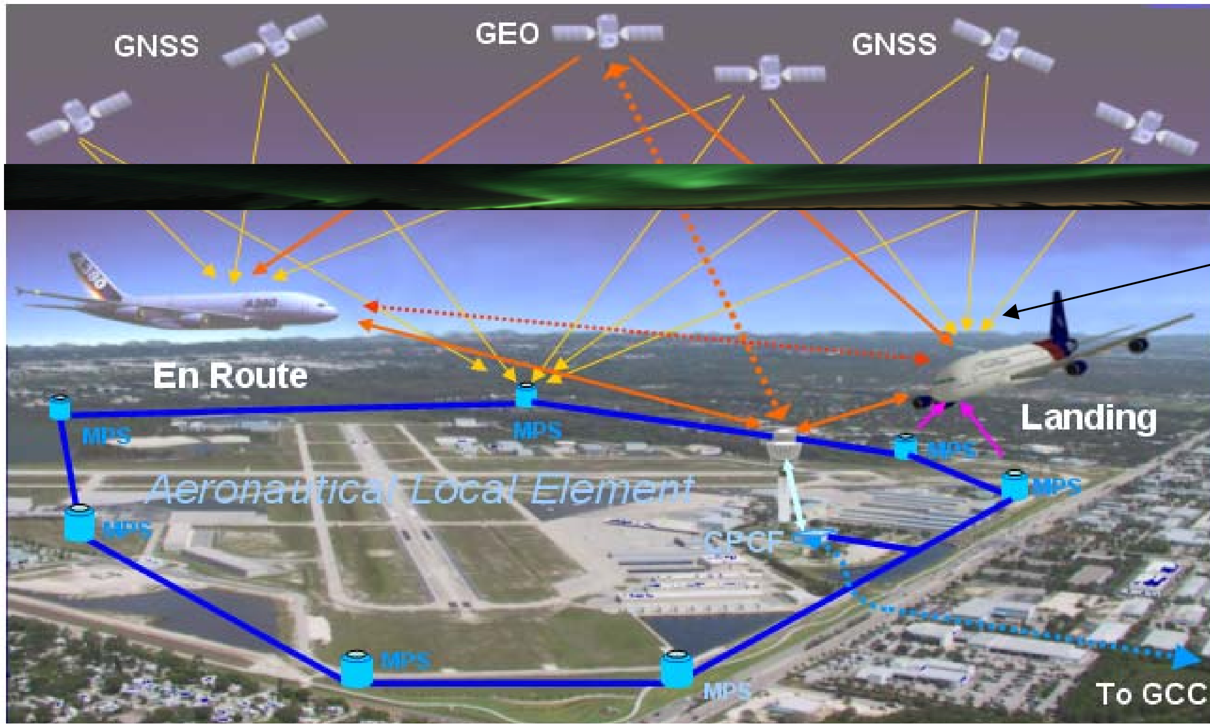
Performance of the GPS reference network of Allsat GmbH, Hannover degrades during the ionospheric storm on 25 July 2004

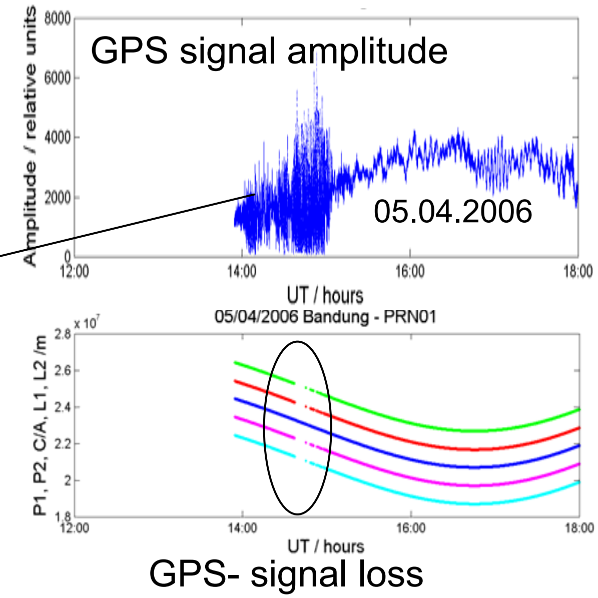
Different effects in different network areas over Germany

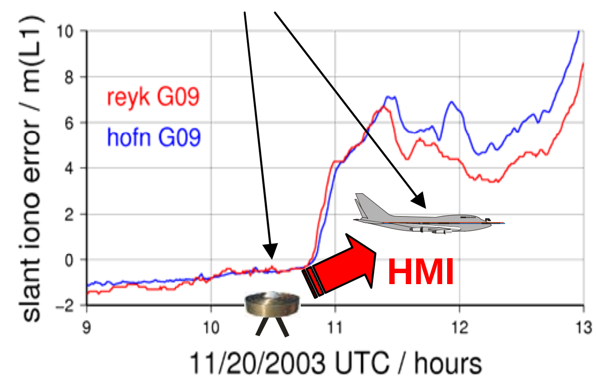
- Propagation of perturbation from high to mid-latitudes
- Provision of ionospheric now- and forecast information valuable for users
- Perturbation degree should be quantified by a perturbation index that can directly be used by customers



Safety of Life (SoL) application - aviation





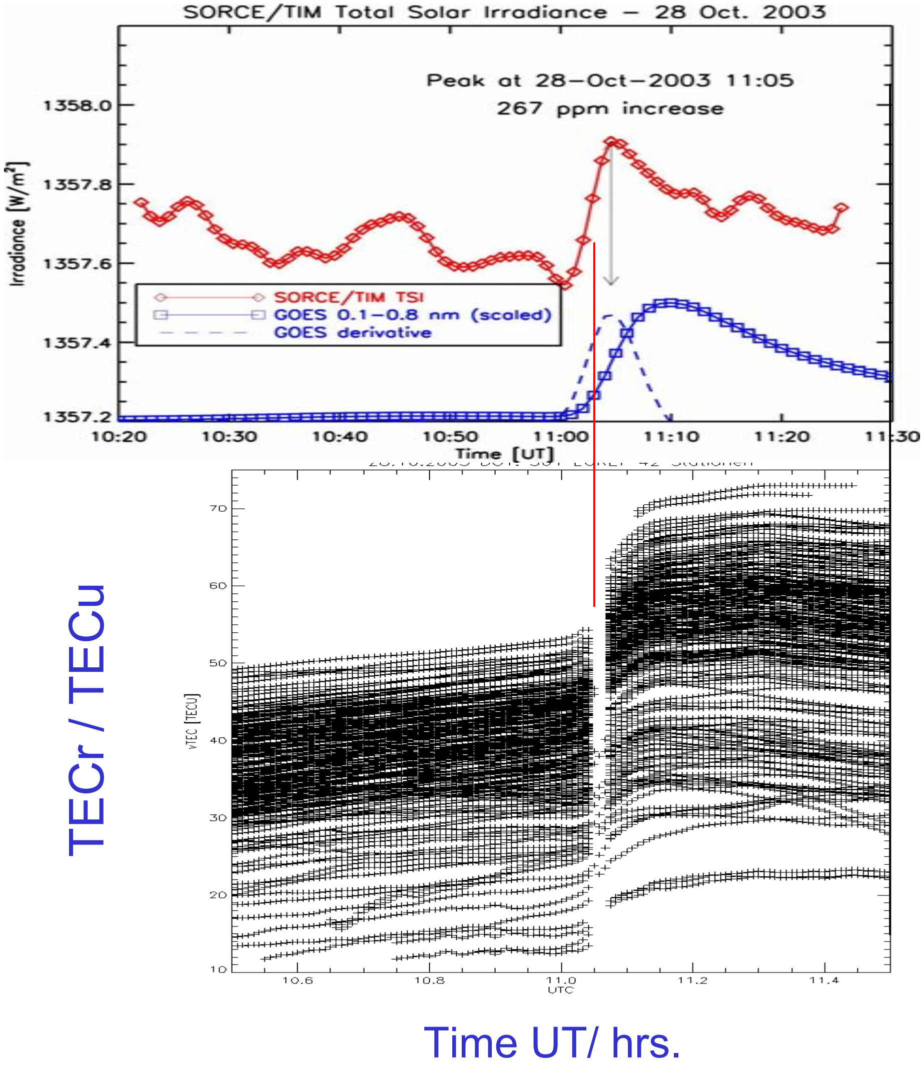


HMI: Hazardous Misleading Information

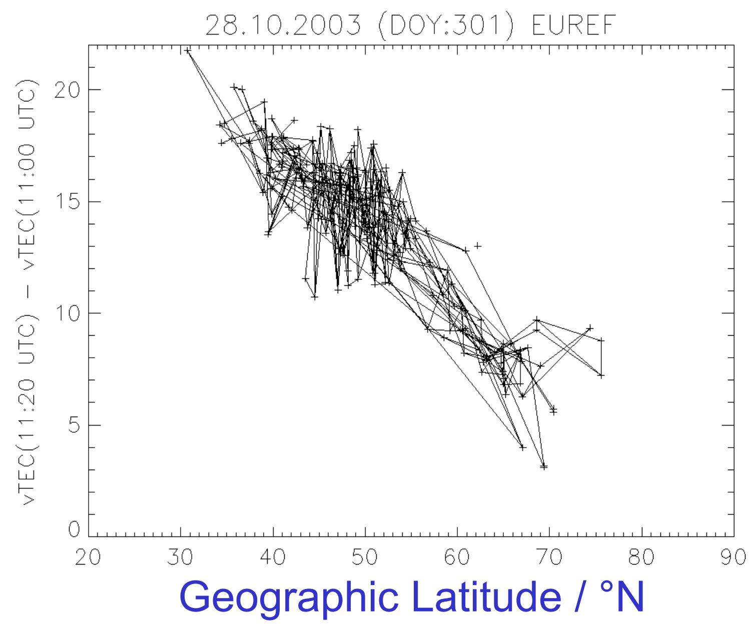
- Degradation of accuracy, integrity, availability and continuity of signals
- HF Communikation disturbed or interrupted

➡ Operational **detection** and modelling of ionospheric **perturbations** needed
Ionospheric "**Threat-Model**"required

Solar flare induced storm on 28 October 2003

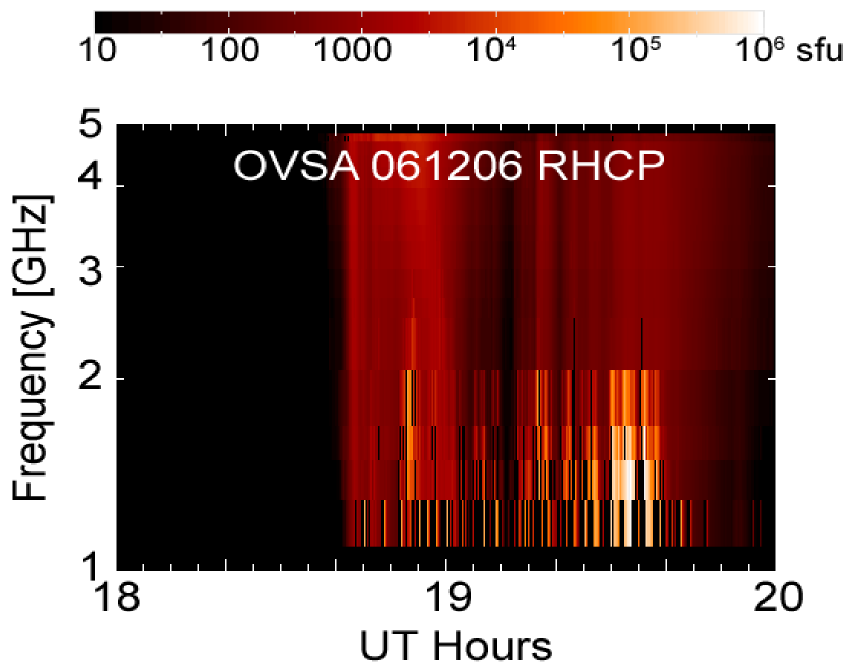


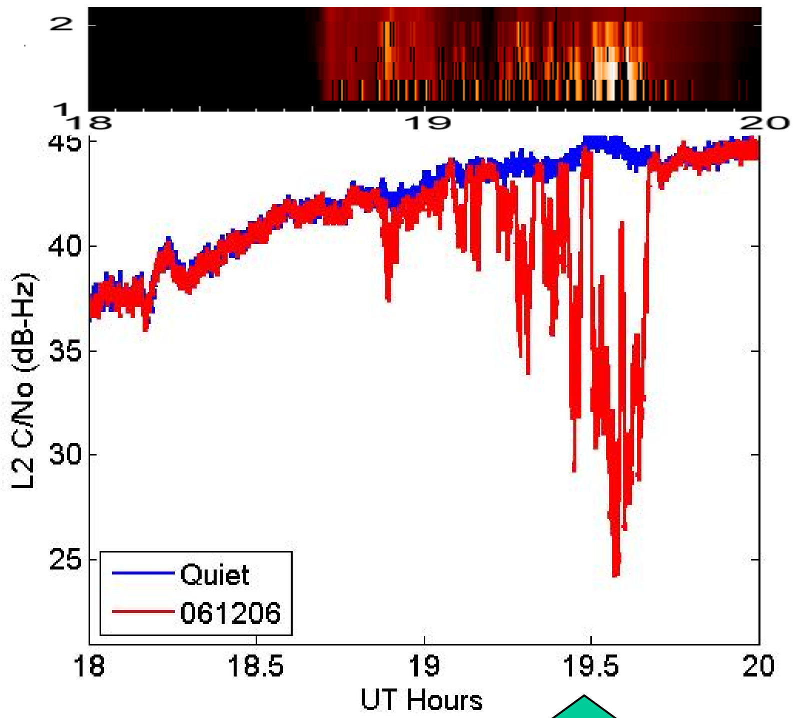
- Strong Solar Flare was observed on 28 October 2003 at 11:05 UT
- Total solar irradiation enhances within a few minutes by 267 ppm
- Rapid and strong increase of TEC at all GPS measurements (range error up to 3.5 m)
- Number of usable GPS measurements dropped down from 30 to 7



Impact of Solar Radio Bursts on GPS signal reception

December 6, 2006



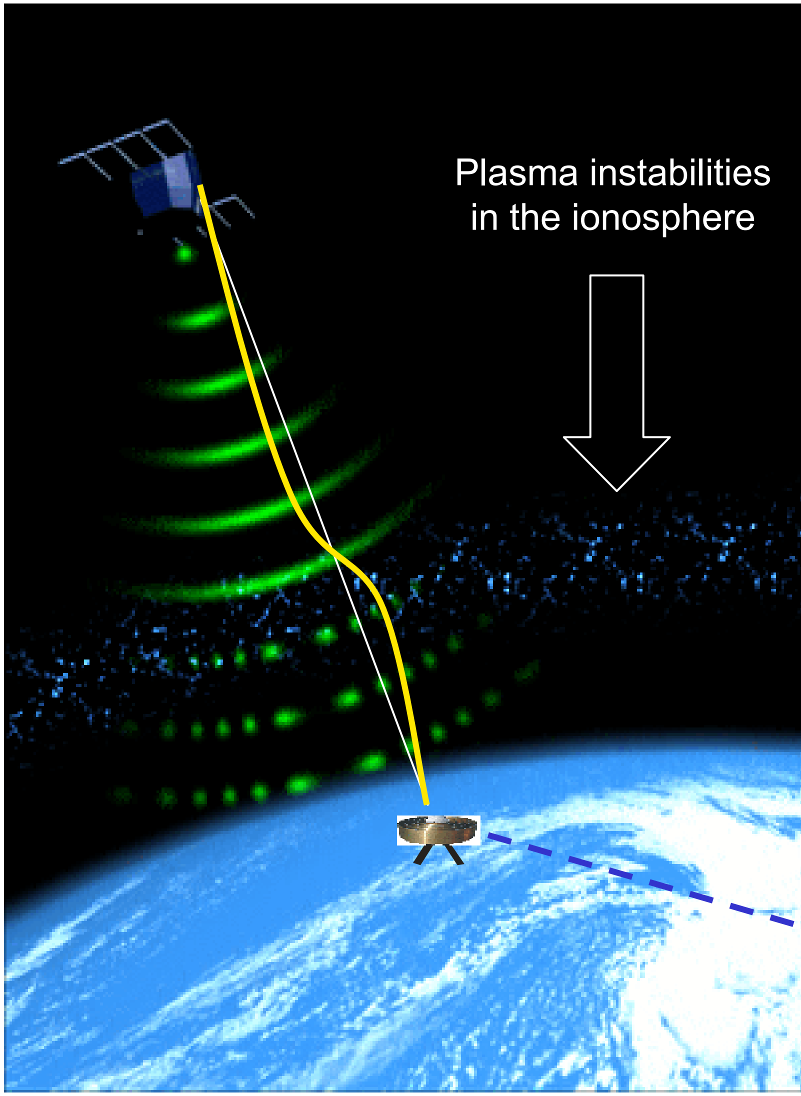


Solar Radio Burst

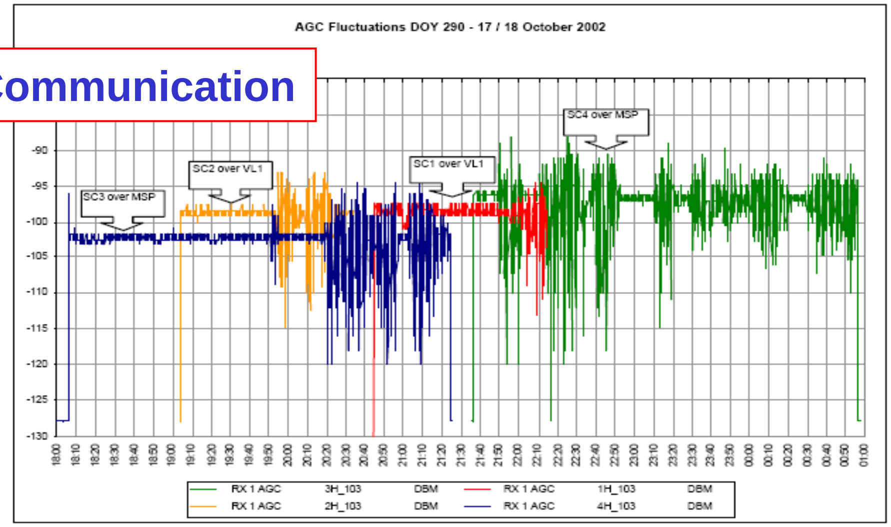
Effect on GPS Receivers

Source: P. Doherty

Ionospheric impact on transionospheric radio waves

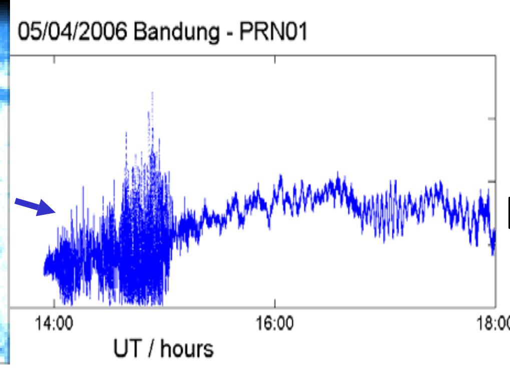


Communication



AGC fluctuations affecting all four CLUSTER spacecrafts at different ground stations
(Source: ESOC Report CL-COM-RP-1001-TOS)

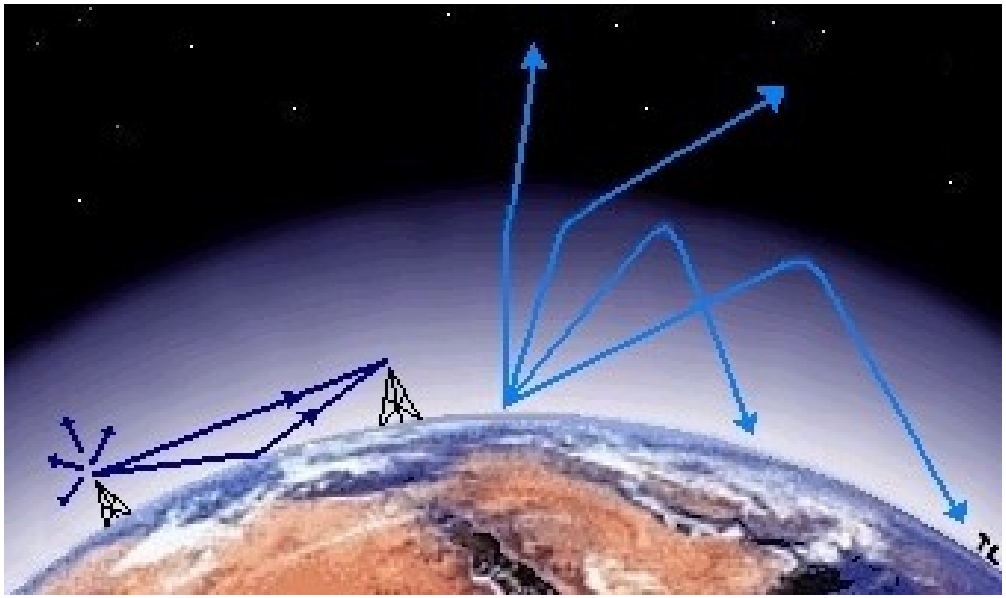
Navigation



Plasma instabilities cause rapid signal strength fluctuations

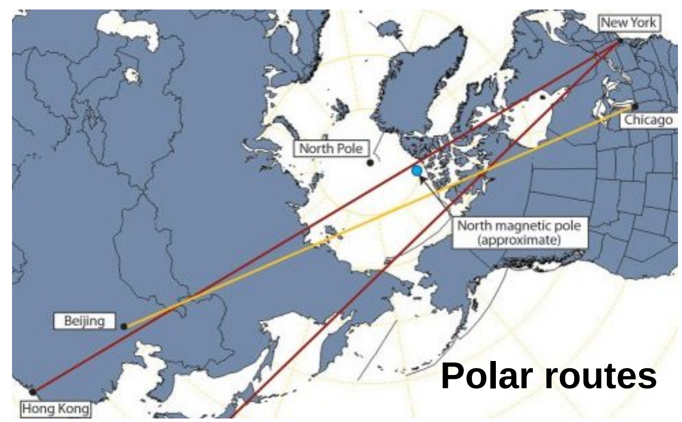
Loss of lock possible

Terrestrial Telecommunication - Ionosphere



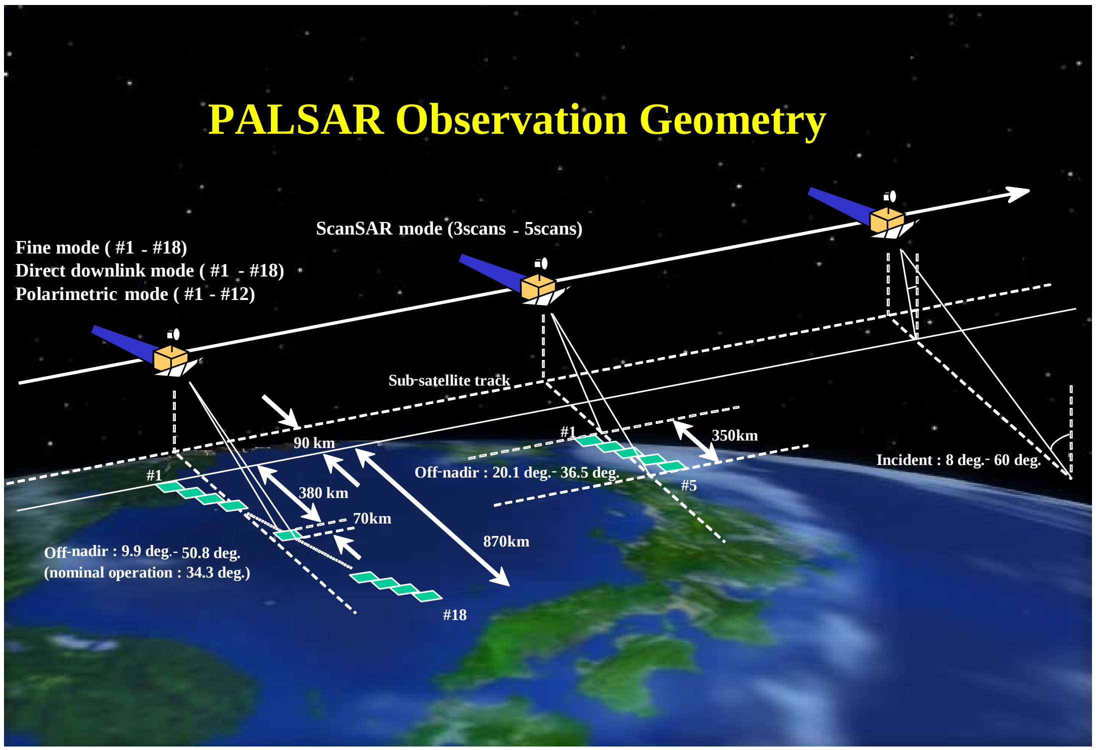
- Radio waves at frequencies below 10 MHz are mostly reflected by the ionosphere
- This results in a long distant propagation of waves
- Solar flares and particle precipitation can prevent the ionosphere from reflecting or refracting radio waves

- Short wave radio waves may be absorbed by enhanced plasma density in the lower ionosphere leading to a blackout in radio communications (Short wave fading)
- Ionospheric disturbance may enhance long wave radio propagation (measurements of Sudden Ionospheric Disturbances - SIDs)



Remote sensing - Radar measurements

The ionospheric plasma impacts the phase and polarisation angle of transionospheric radio waves in C-, L- und P- bands, i.e. numerous radar



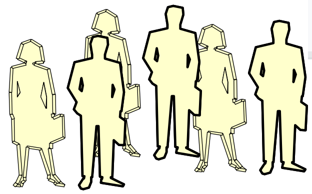
Band	f (GHz)	Ω_F [°] (100 TECu)
C	5.0	2
L	1.2	25
P	0.4	200

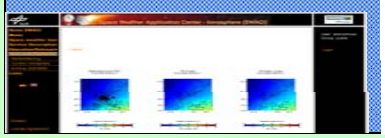
Development of methods and algorithms for correction and mitigation of ionospheric propagation errors needed

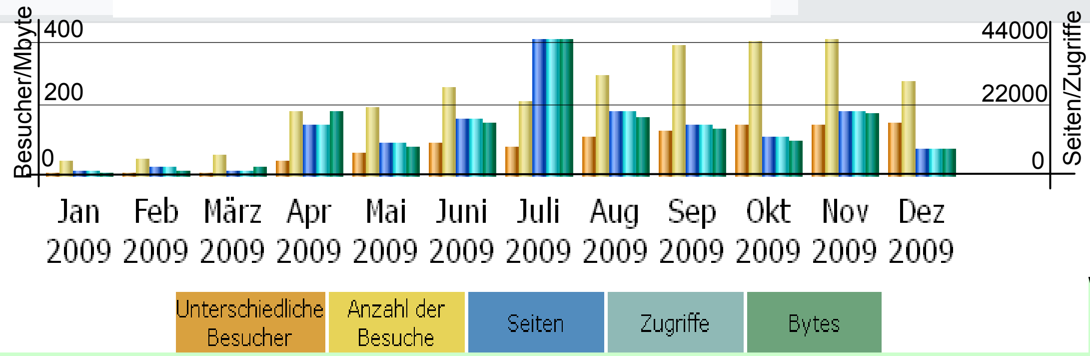
- Plasma turbulences cause defocussing effects in particular in L- and P- band radars
- Planned ESA Biomass Explorer will use P-band radar

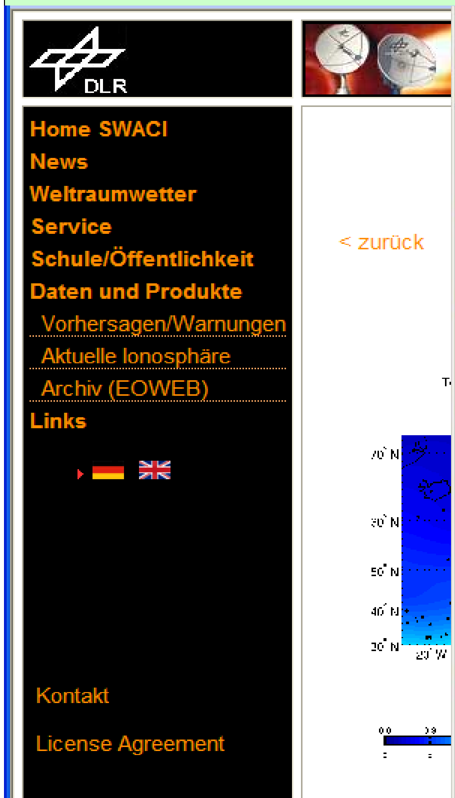
SWACI Service - Data access

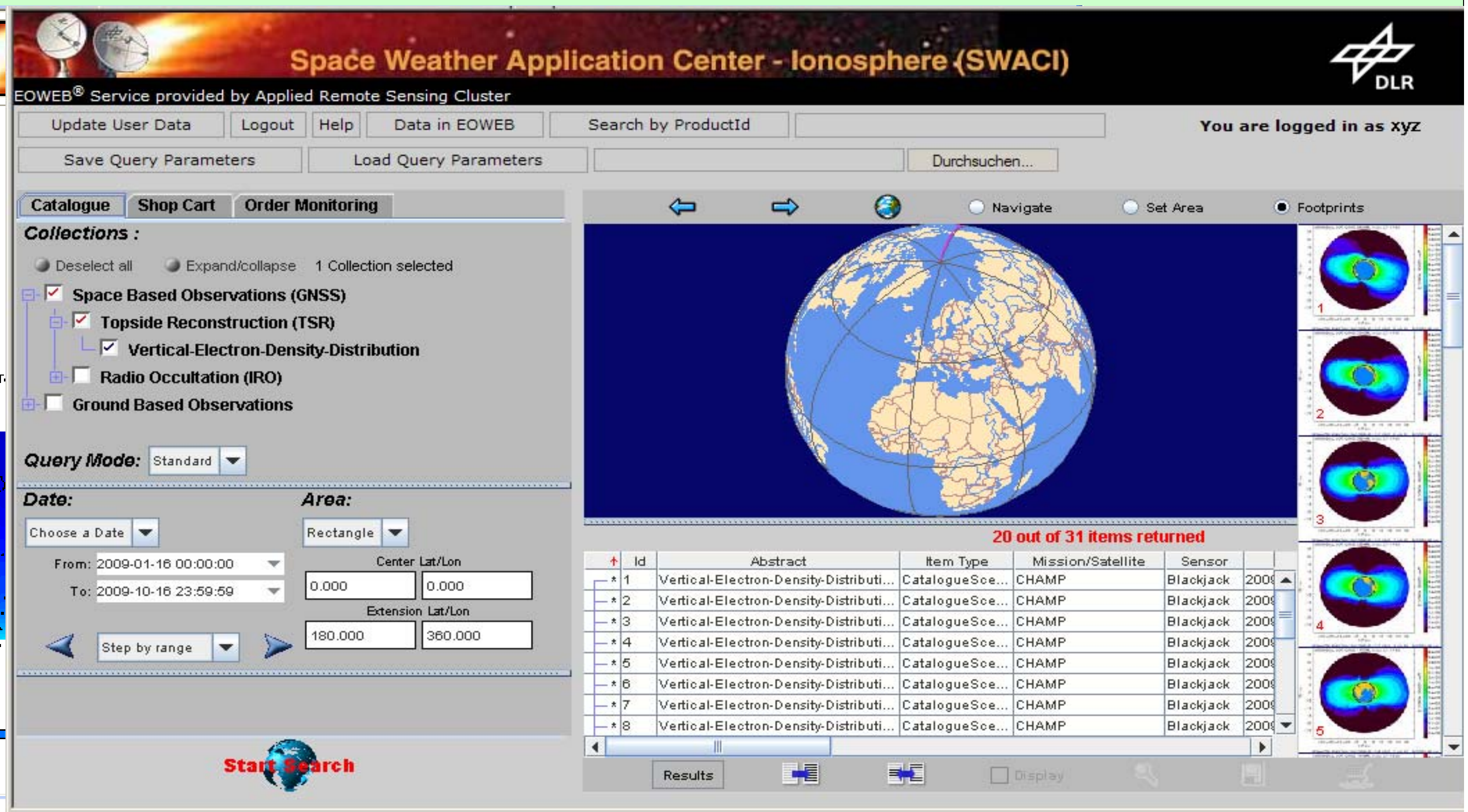
http://swaciweb.dlr.de





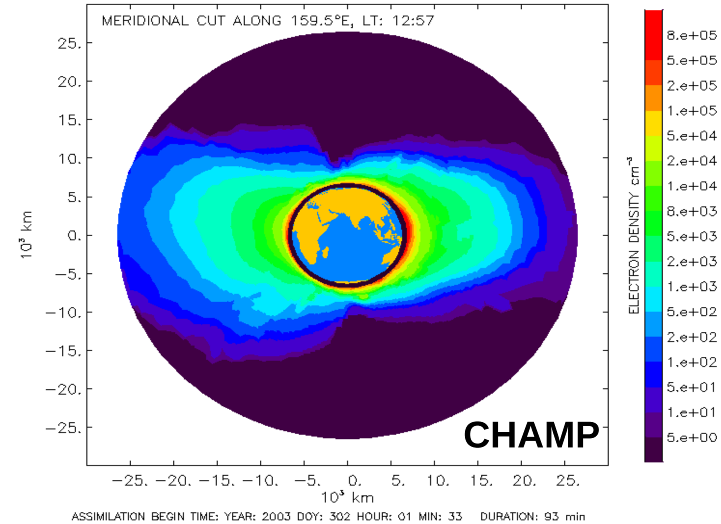


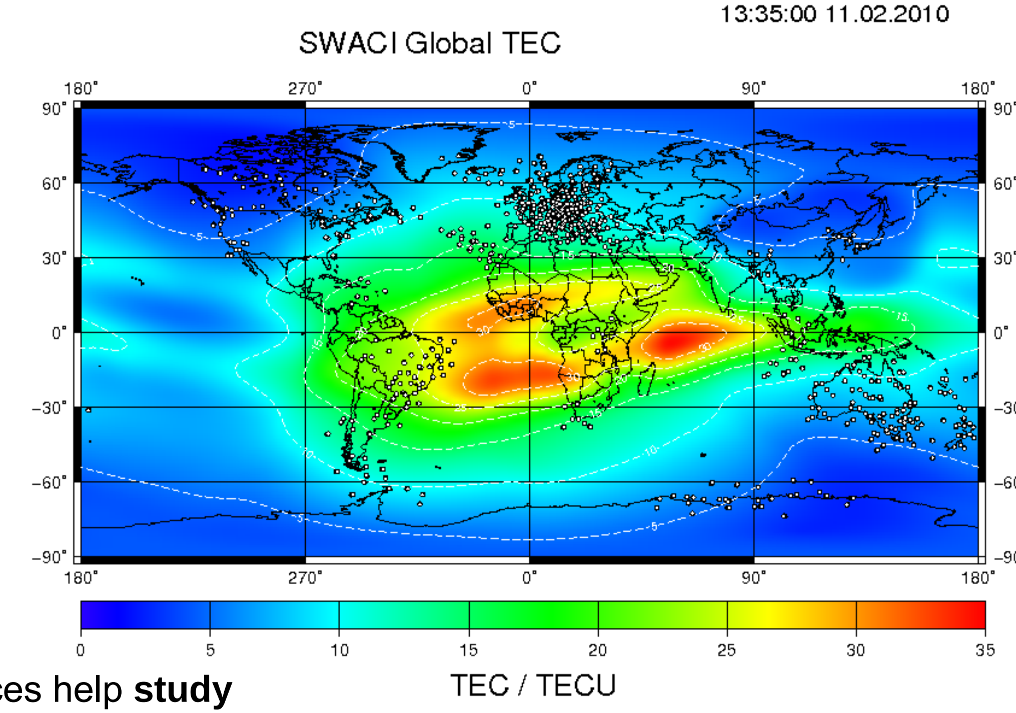


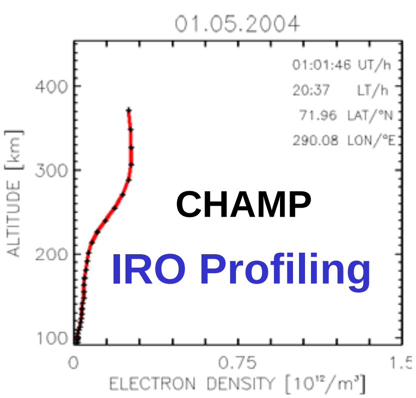


Ground and space based ionosphere service products

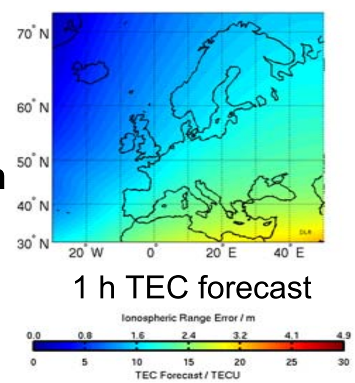
Topside reconstructions
28 / 29 October 2003



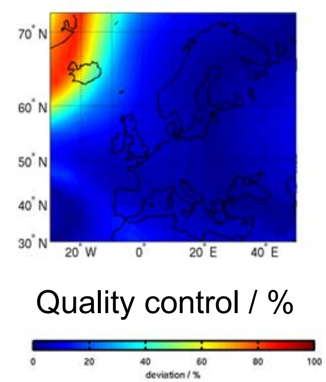




- Ionospheric services help **study** the ionosphere and relationships between ionosphere and space weather, to **correct/mitigate** propagation errors, to **detect** ionospheric perturbation, to **warn** and **forecast** users
- Services: ISES, Space Weather Prediction Center Boulder, Int. GNSS Service (IGS), SWACI

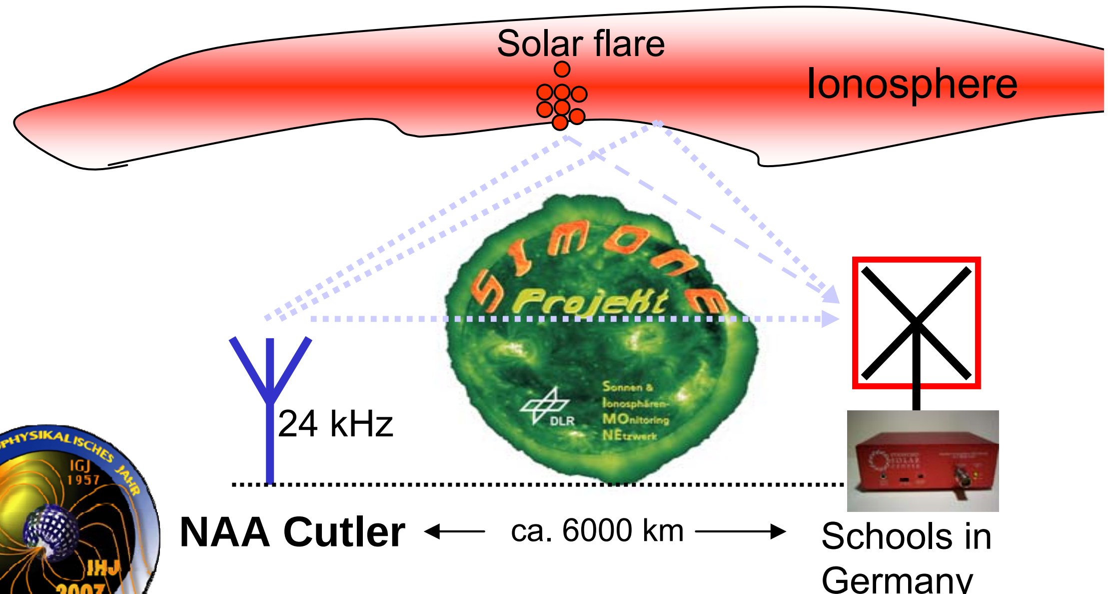


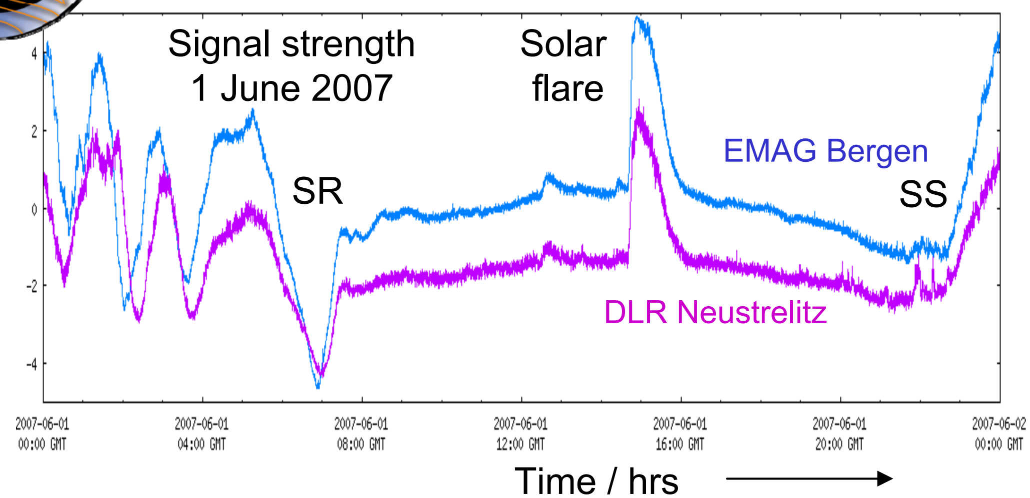
1 h TEC forecast



Quality control / %

Sun & Ionosphere MOnitoring NEtwork - SIMONE





Summary

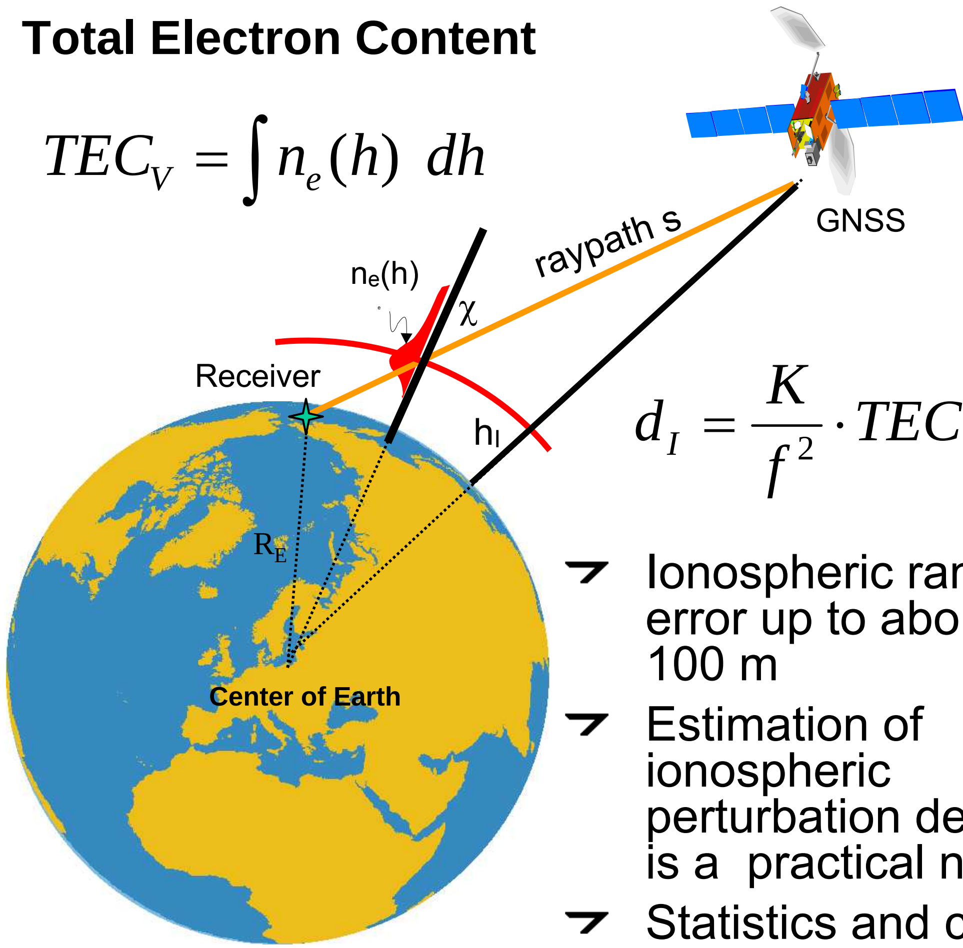
- Radio wave propagation is strongly affected by space weather effects via their interaction with the non-isotropic ionospheric plasma
- Impacted are technical systems related to:
  - Terrrestrial radio wave propagation
    - Telecommunication
    - Radar systems
  - Transionospheric radio wave propagation
    - Telecommunication
    - Satellite navigation /positioning
    - Remote sensing, altimetry
    - Research facilities
- Space weather / ionospheric monitoring and provision of actual and forecasted information helps to mitigate the space weather impact
- A number of ionospheric data and information services exist (e.g. ISES, SWPC, SWACI), data products with higher temporal and spatial resolution are required to improve the Space Situational Awareness (SSA)
- The International Space Weather Initiative (ISWI) is a unique opportunity to improve our understanding of space weather effects.

Thank you for your attention

Dual frequency GNSS measurements

Total Electron Content

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



$$d_I = \frac{K}{f^2} \cdot TEC$$

- Ionospheric range error up to about 100 m
- Estimation of ionospheric perturbation degree is a practical need
- Statistics and case studies required

$$\Delta P = P_2 - P_1 = K \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} TEC + \varepsilon_{off}$$

TEC can be derived from dual frequency GNSS measurements.

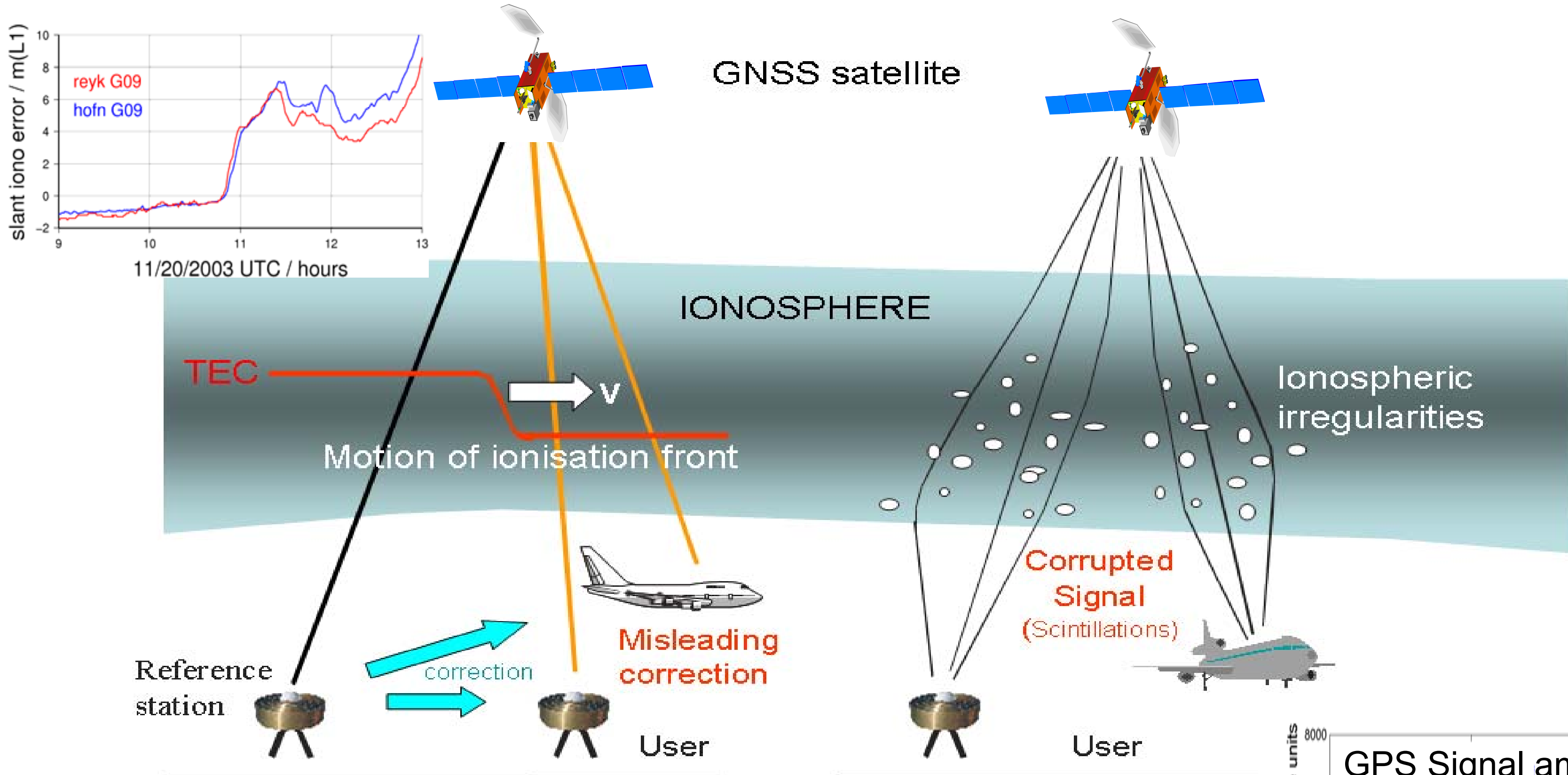
GPS based TEC measurements and mapping in DLR Neustrelitz

Europe
post proc. (1 day) since 1995
http://www.kn.nz.dlr.de/daily/tec-eu

operational (5 min) since 2005
http://swaciweb.dlr.de

North Pole
post proc. (1 day) since 2002
http://www.kn.nz.dlr.de/daily/tec-np

Impact of Ionospheric perturbations on navigation and positioning



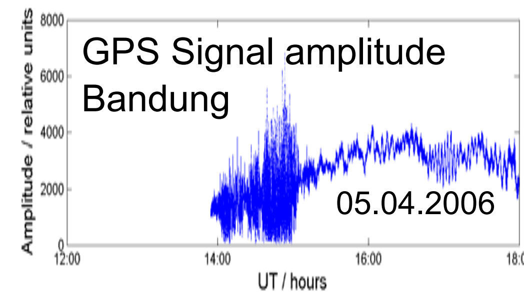
Differential GNSS

Integrity

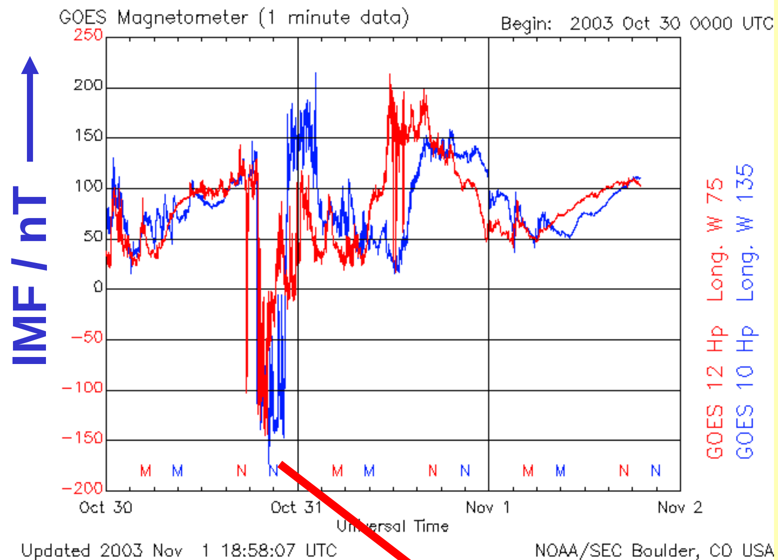
Risk of undetected failures resulting in the violation of the protection level

Single point user

Availability, continuity

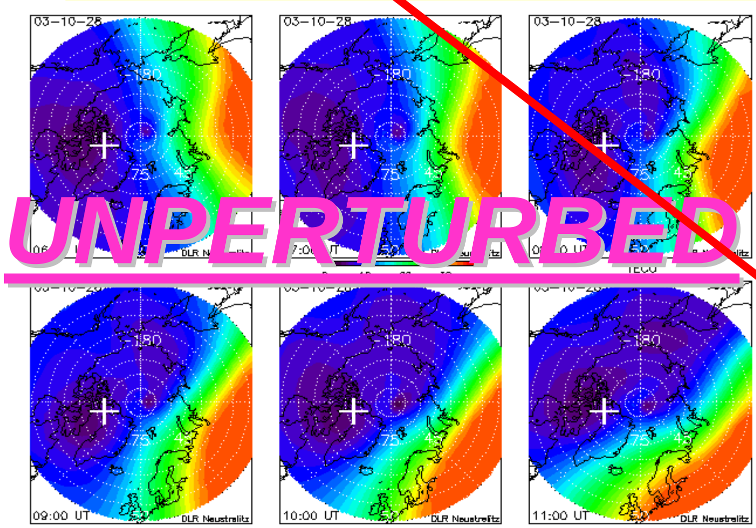


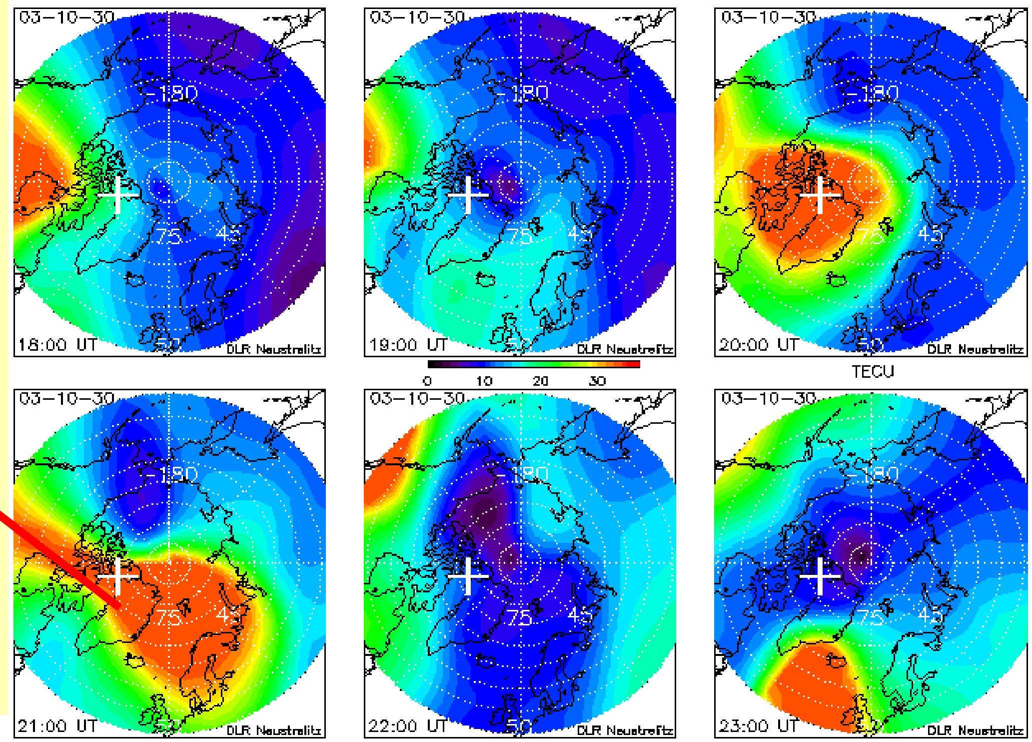
Ionospheric perturbations on 29 / 30 October 2003



Numerous perturbations in Com/Nav Systems in Europe and in the USA

Close correlation of TEC behaviour with the southward component of the IMF





Higher-order refraction effects

Ionosphere phase refractive index

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

first-order | **second-order** | **third-order**

plasma frequency:

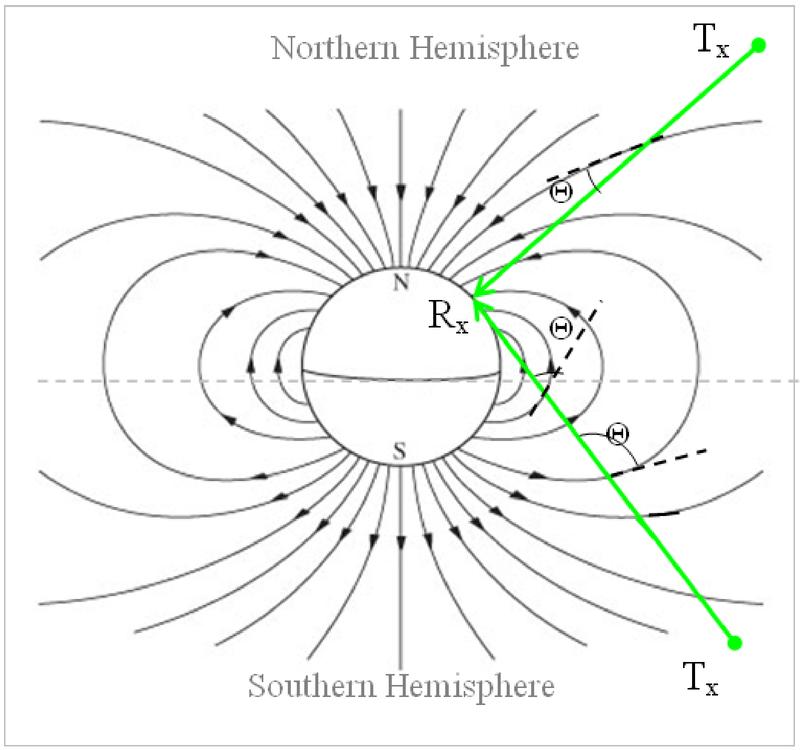
$$f_p = \sqrt{e^2 n_e / (4\pi^2 m_e \varepsilon_0)}$$

gyro frequency:

$$f_g = eB / (2\pi m_e)$$

Θ: angle between wave direction and B field vector
n_e: electron density
m_e: electron mass
B: magnetic induction
ε_0: free space permitivity
f : signal frequency

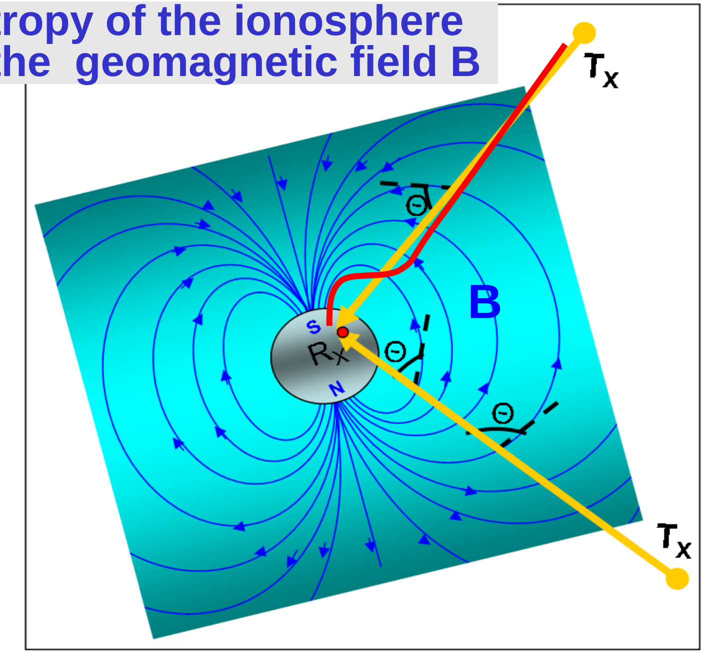
First-order effect removable via L3 phase combination, second order effect remains uncompensated

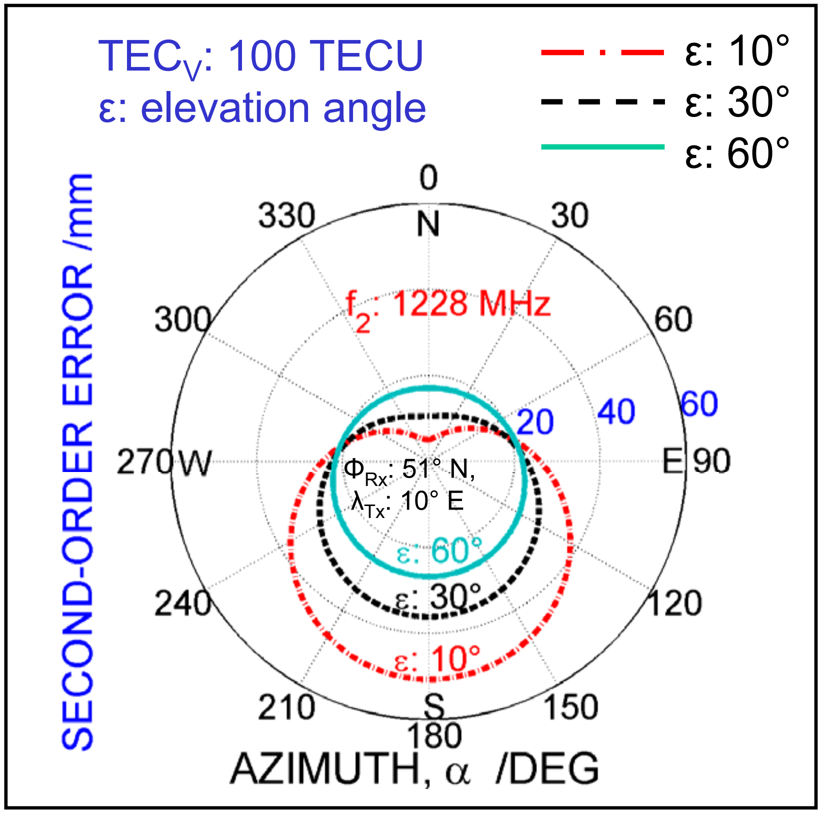


$$d_I^{(2)} = \frac{K_F}{f^3} \int B \cos\Theta \cdot n_e ds$$

Second-order error,

Ionospheric Range Error – 2nd order (1)





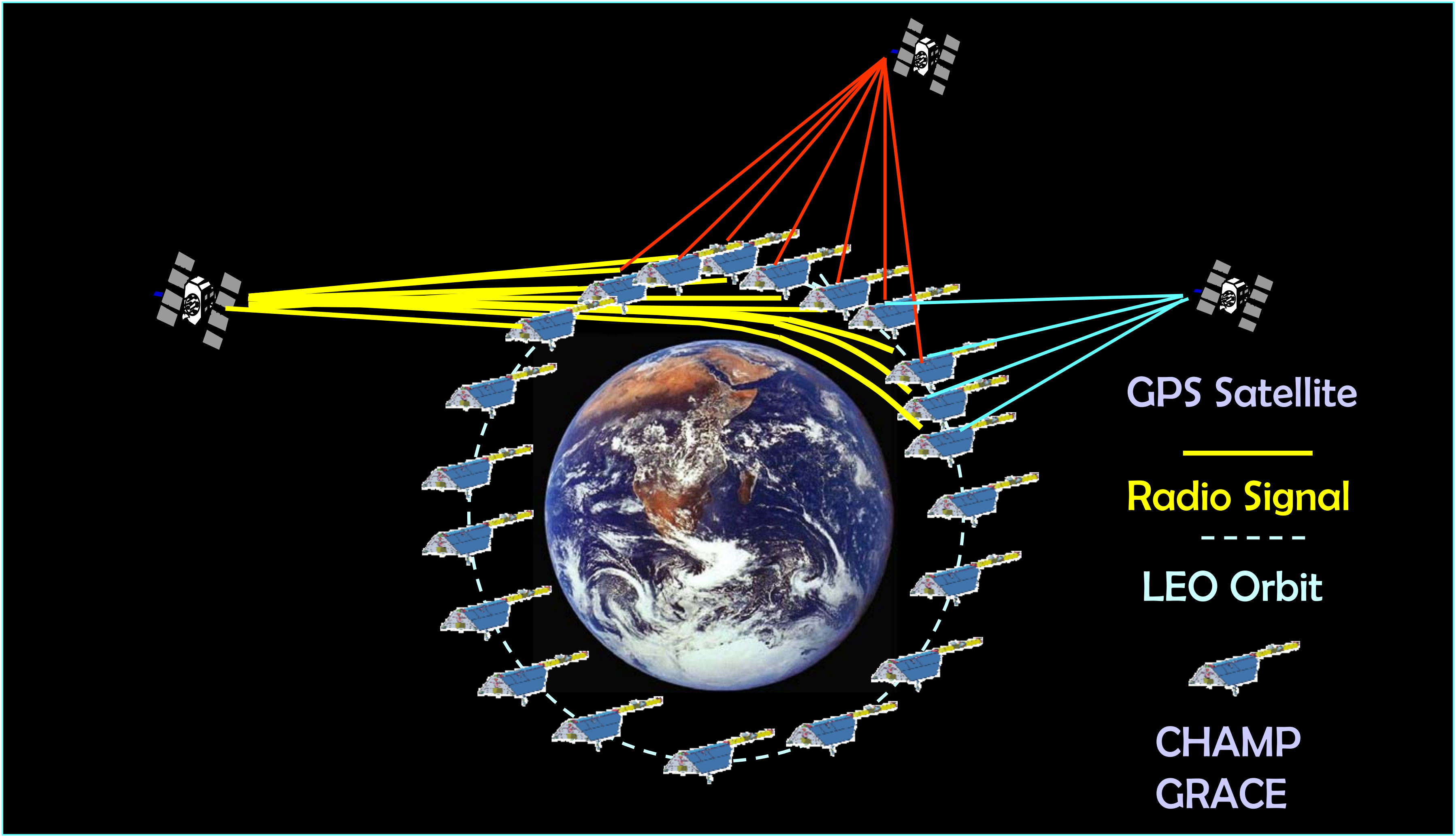
- Ionospheric 2nd order errors are usually ignored in the measurement praxis (< 20 cm).
- When Galileo becomes operational, these errors have to be routinely mitigated in precise applications

$$d_I^{(2)} = \frac{K_F}{f^3} \int B \cos\Theta \cdot n_e \, ds$$

Hoque,M.M., N. Jakowski, Mitigation of higher order ionospheric effects on GNSS users in Europe, GPS Solutions, DOI 10.1007/s10291-007-0069-5, 2007

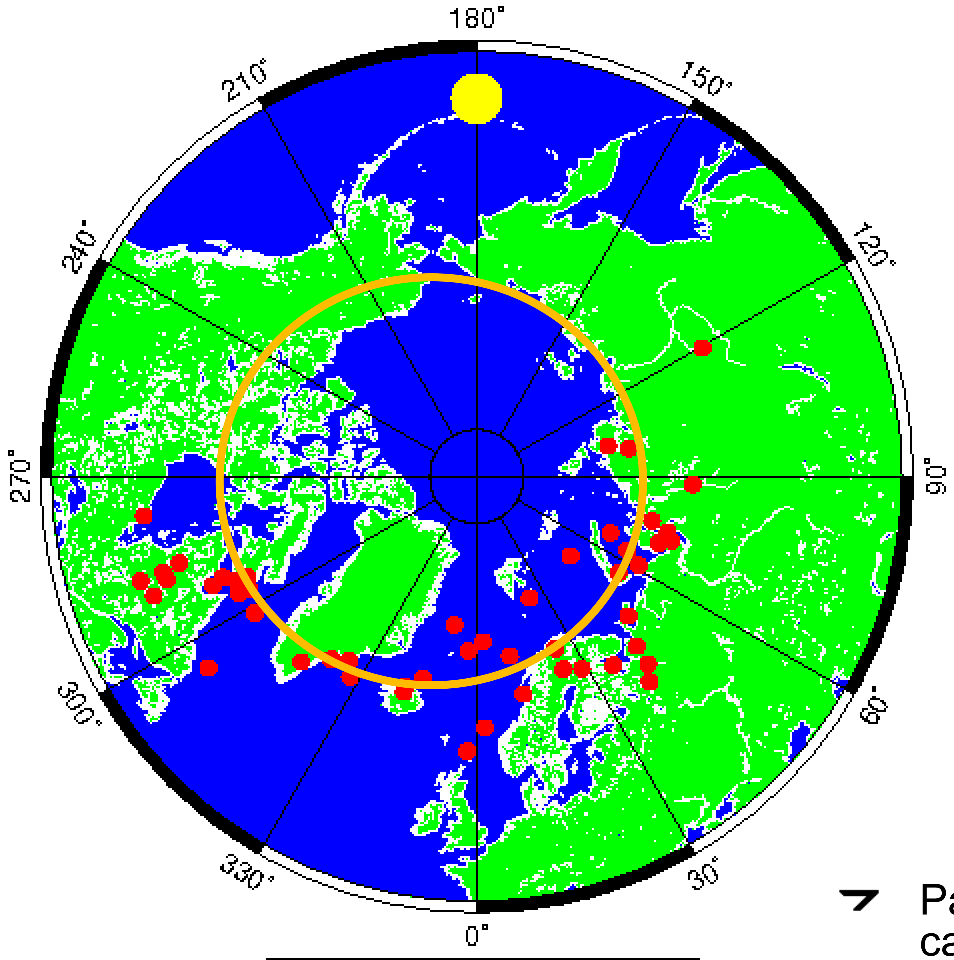
Hoque, M. M., N. Jakowski, Estimate of higher order ionospheric errors in GNSS positioning, Radio Science, 2008

GPS sounding of the Ionosphere onboard a LEO satellite

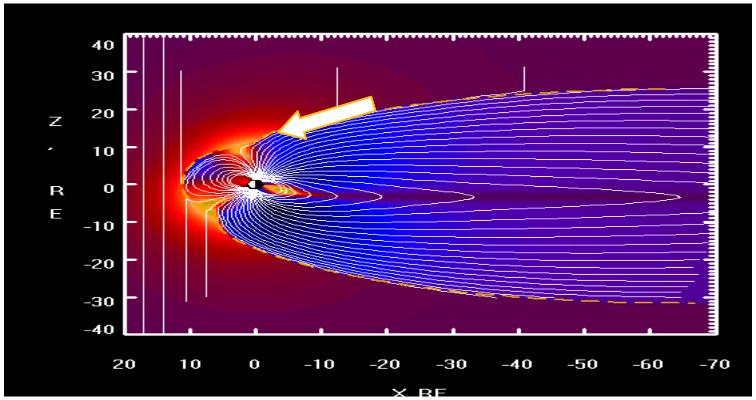


Auroral particle precipitation - ELDI

COSMIC Profiles with E–Layer 2007.001–2007.030

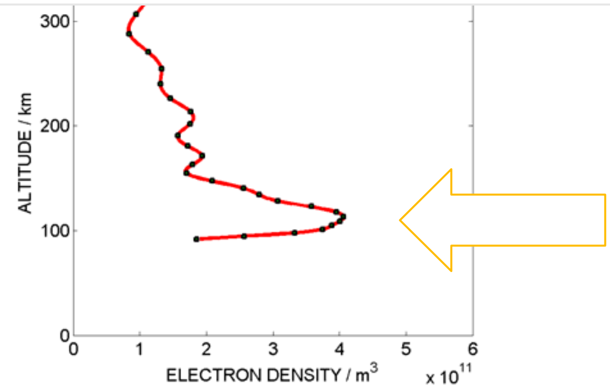


UTC=00h, #profiles= 50



CHAMP Profile
2003 DOY: 302, 23:31:12 LT

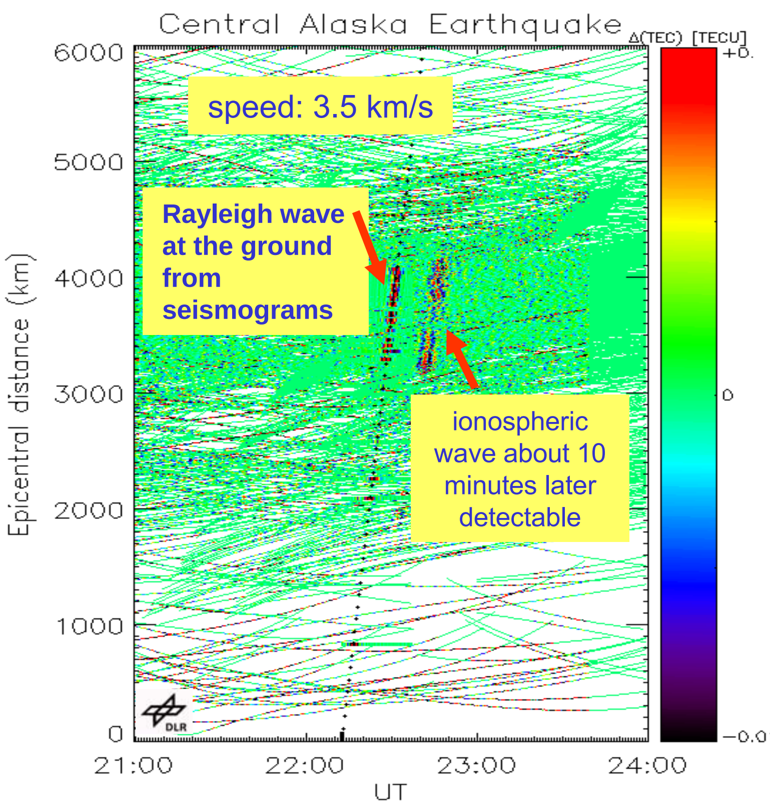
ELDI : E-Layer Dominated Ionosphere



- Particle precipitation from the magnetosphere causes a locally enhanced ionization in the lower ionosphere

Anwendung – Fernerkundung (1)

Alaska Earthquake on November 3, 2002
(M=7.9 ; 63.5N /147.4 W)



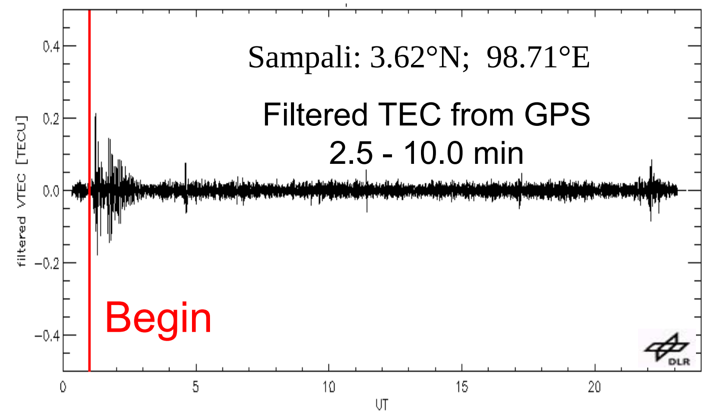
Weg-Zeit-Diagramm

GITEWS
Nachweis ionosphärischer Erdbeben / Tsunami - Signaturen in der Ionosphäre (ETSI)

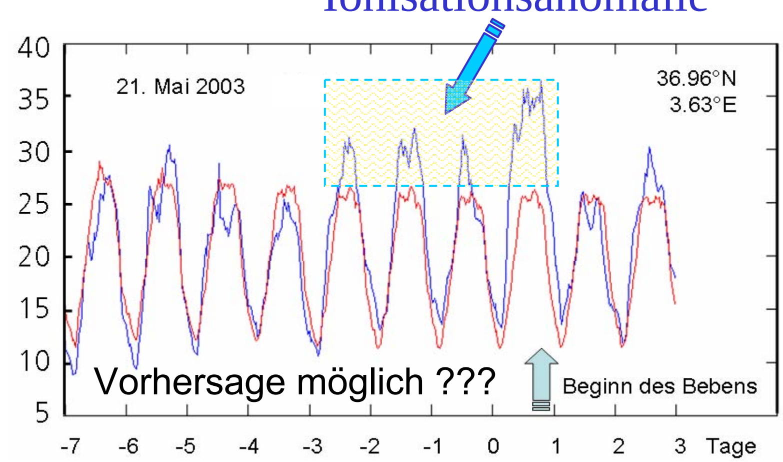
TEC-Messungen (blau) über dem Ort des Epi-zentrums bis zu 7 Tage vorher im Vergleich zu 27-tägigen Median-werten (rot).

Wettbewerb der Visionen des DLR

Sumatra earthquake
on 26 December 2004



Ionisationsanomalie

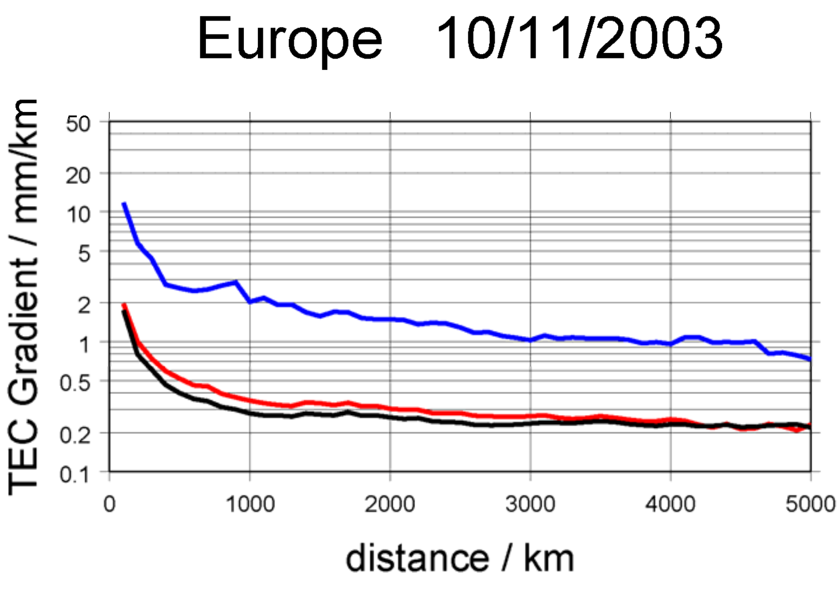


Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

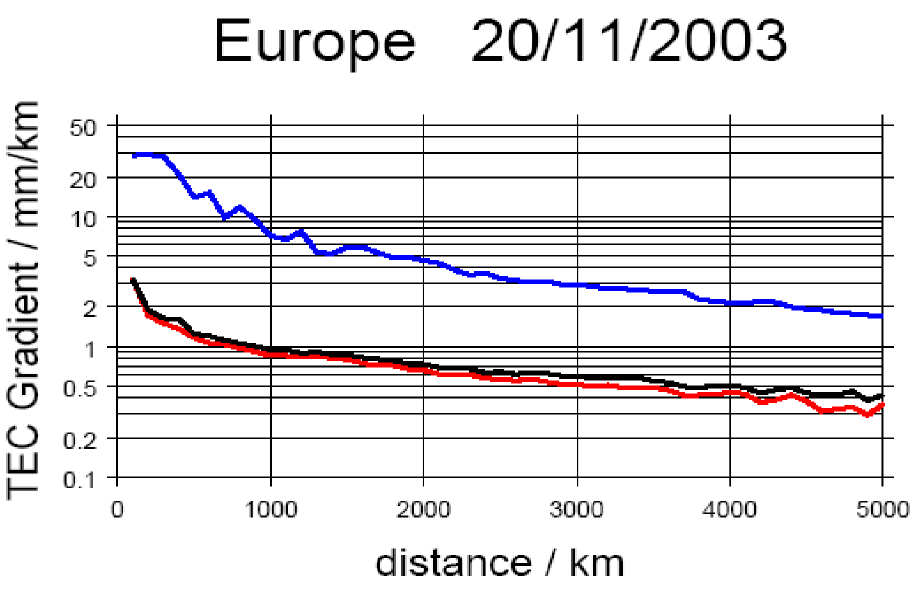
Gradient statistics

- Strong enhancement of gradients on 20 November 2003 observed (up to about 30 mm/km at L1)
- Average values at 1000 km distance:
  about 1mm/km (quiet day 0.3mm/km)
- Maximum level at 1000 km distance: 7 mm/km

Unperturbed day



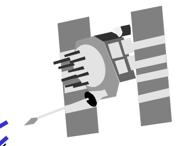
Perturbed day

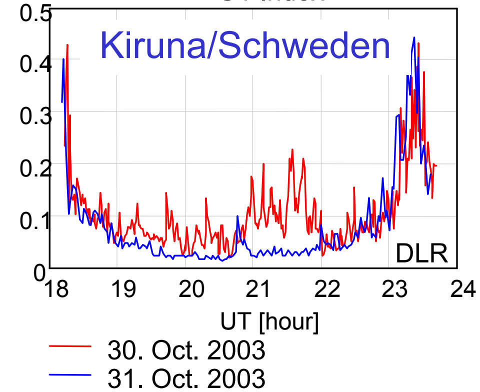


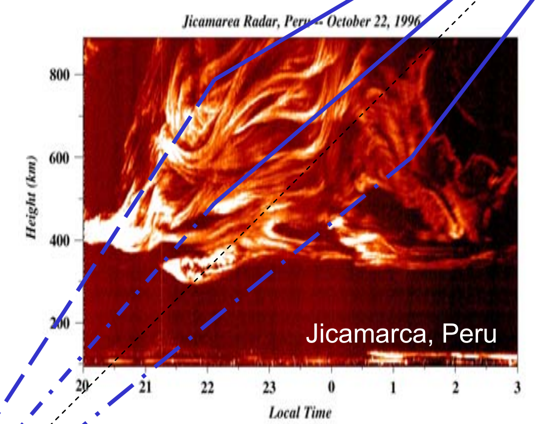
Ionosphärisch bedingte Radioszintillationen

Plasmaturbulenzen

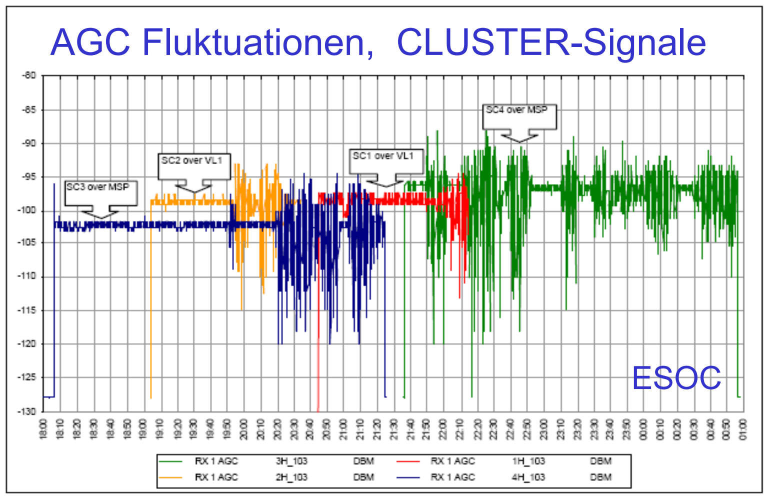
- Hohe Breiten
  - Teilchenpräzipitation
- Niedere Breiten
  - ‚Bubbles'







$$S_4 = \left(\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \right)^{1/2}$$

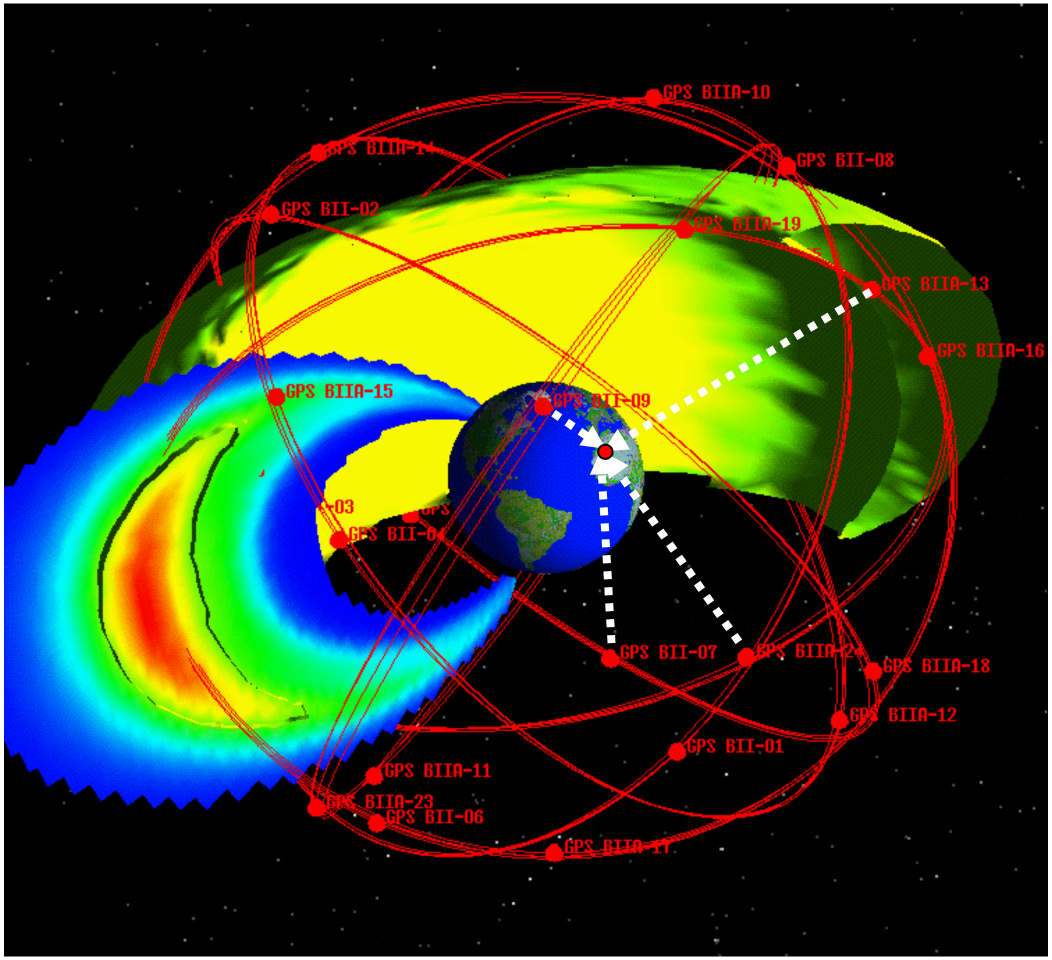


Superposition von Radiowellen
Starke Feldstärkeschwankungen
Signalverlust möglich

(Source: ESOC Report CL-COM-RP-1001-TOS)

➜ Radioszintillationen stellen auch für Galileo ein Problem dar.

Satellitennavigation



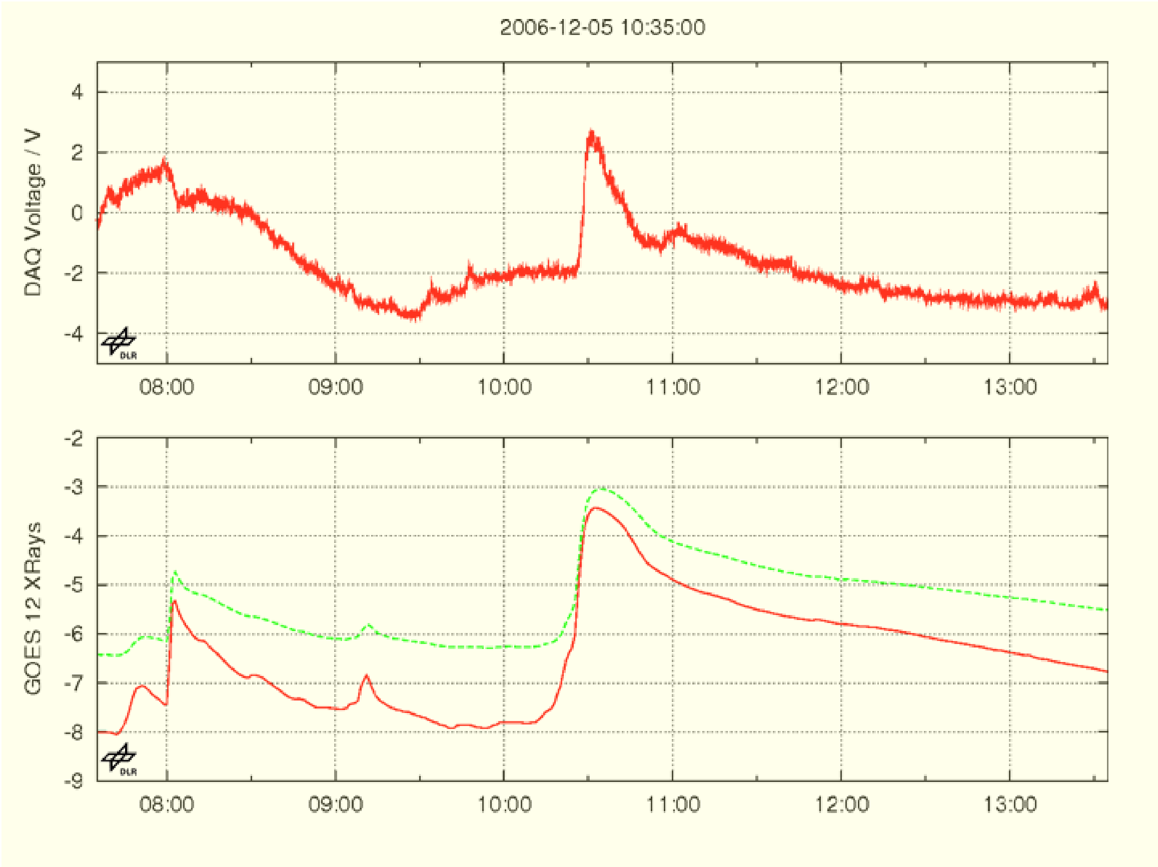
Operationelle und geplante satellitengestützte Navigationssysteme

GPS	(USA)
GLONASS	(Russland)
Galileo	(Europa)
Compass	(China)

„Anwendungsbeispiel“ für präzise Navigation

- Die Entfernungsmessung basiert auf der Messung der Signallaufzeit

Weltraumwetterprojekt SIMONE (Sonnen & Ionosphären MOnitoring NEtzwerk)



- An Schulen in Niedersachsen, Hamburg und Mecklenburg-Vorpommern werden kontinuierlich Messungen durchgeführt, archiviert und analysiert.