Space Weather Impact on Satellite Navigation and Positioning

Norbert Jakowski

Institute of Communications
and Navigation

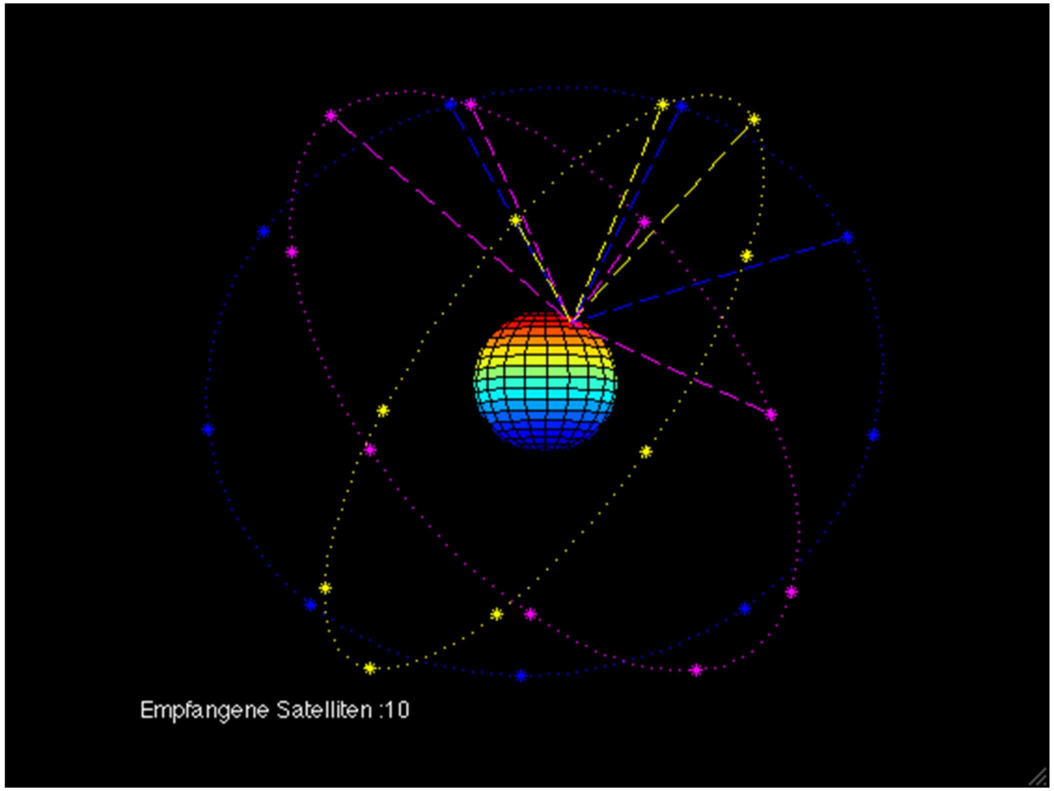
DLR

Outline

- Space weather
- Transionospheric radio wave propagation
- Space weather effects in the ionosphere
    - Solar radiation / activity / flares
    - CMEs / ionospheric storms
- Space weather / ionosphere impact on GNSS & mitigation
    - Single frequency GNSS for mass market
    - Precise positioning
    - Safety of Life applications
    - Monitoring and forecast service for mitigating ionospheric impact
- Summary

Positioning, Navigation &Timing (PNT) play a significant role in the modern society

Global Navigation Satellite Systems (GNSS)



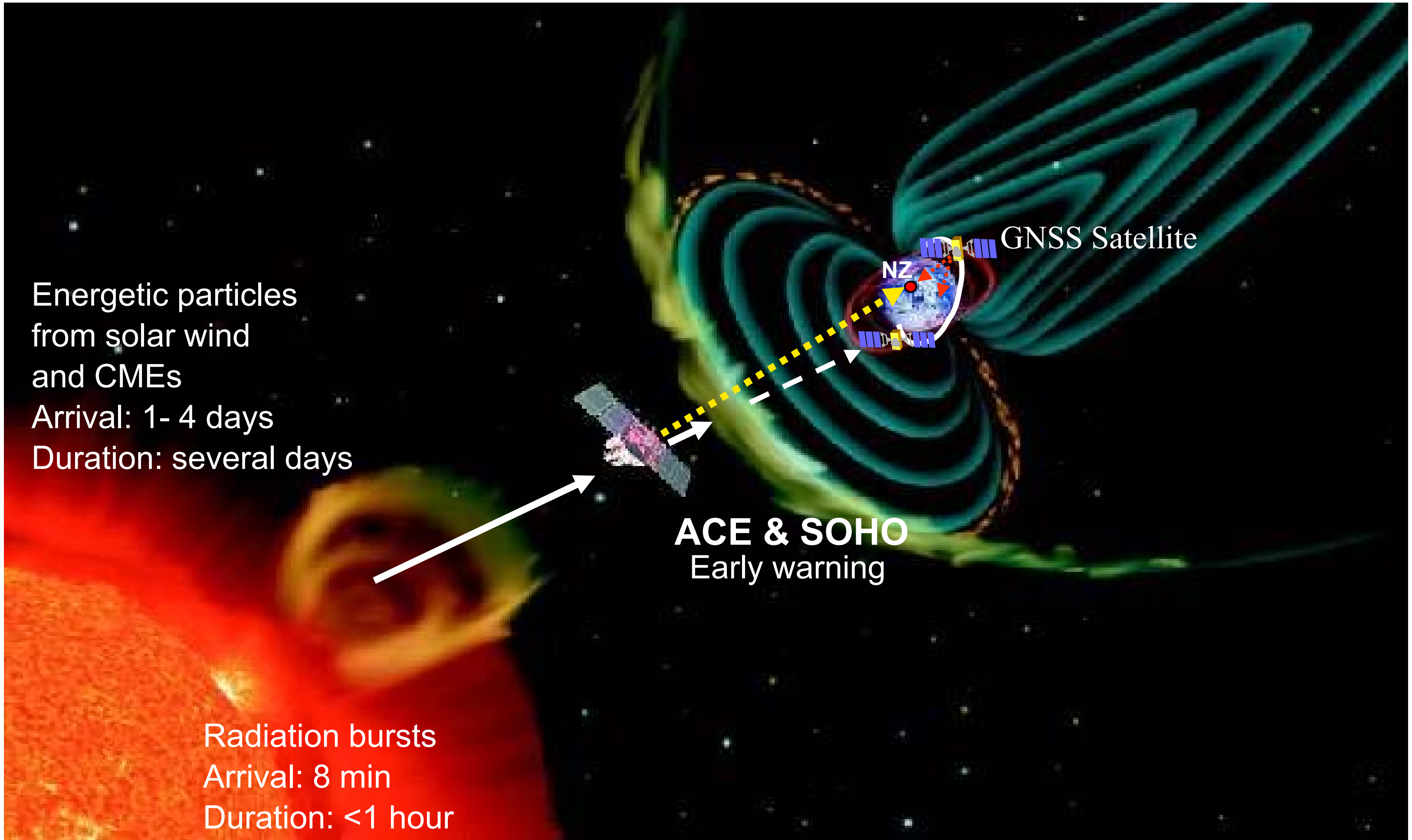
Measurement Principle

- Range ρ is determined by measuring the travel time Δt of radio signals from satellite down to the receiver antenna.

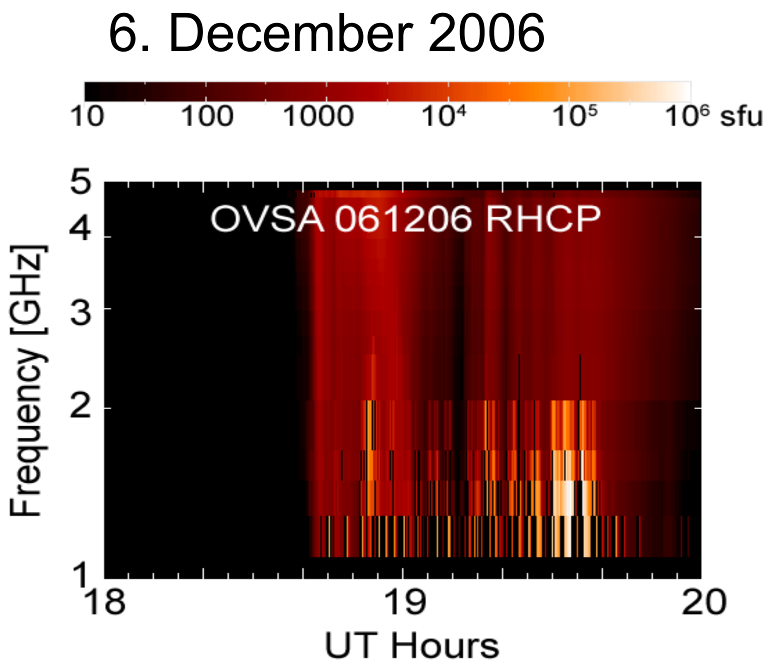
$$\rho = c \cdot \Delta t$$

- Determination of position requires well known orbits, precise clocks, knowledge of radio wave propagation conditions.

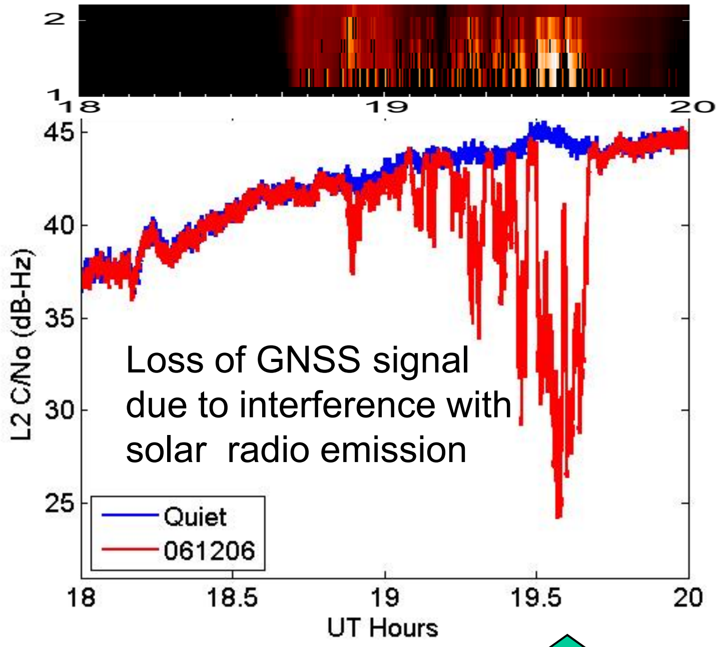
Space Weather



GPS signal interference with solar radio emission during a solar radio burst on 6 December 2006



Solar Radio Burst



Effect on L2- GPS frequency

Source: P. Doherty

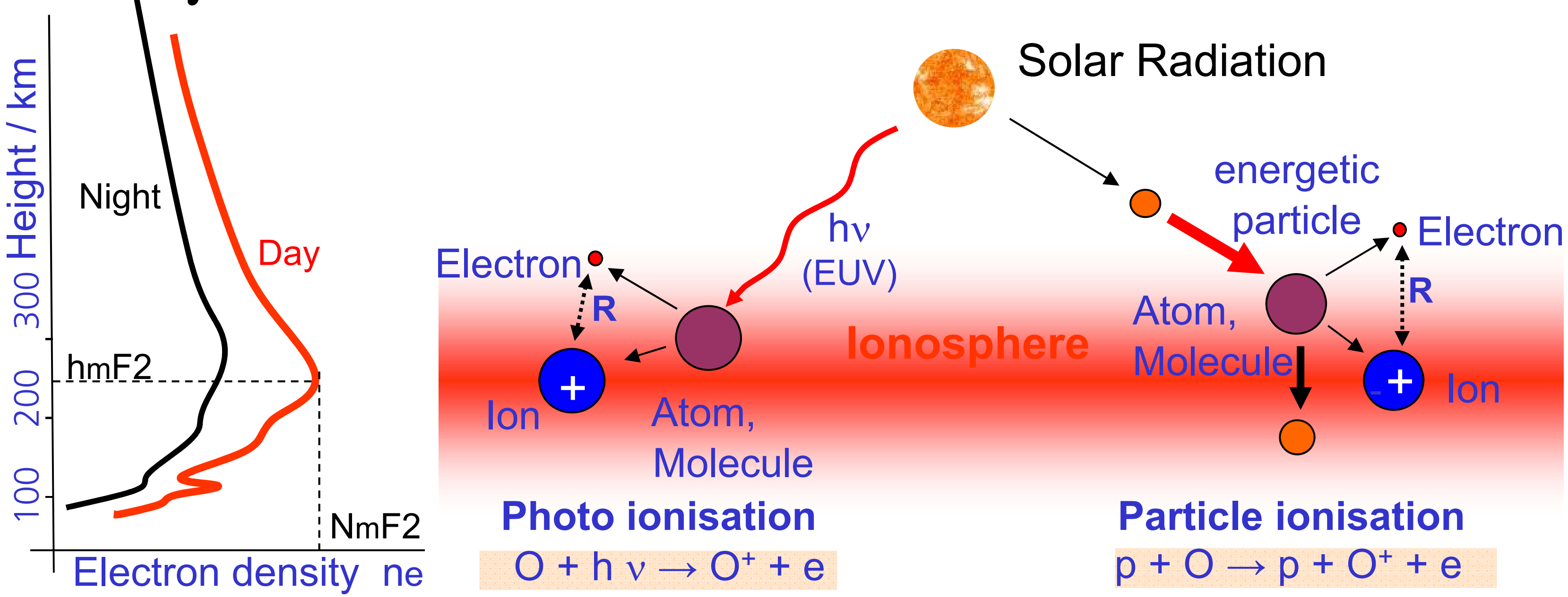
Outline

- Space weather
- **Transionospheric radio wave propagation**
- Space weather effects in the ionosphere
    - Solar radiation / activity / flares
    - CMEs / ionospheric storms
- Space weather / ionosphere impact on GNSS & mitigation
    - Single frequency GNSS for mass market
    - Precise positioning
    - Safety of Life applications
    - Monitoring and forecast service for mitigating ionospheric impact
- Summary

DLR

Ionosphere and radio waves

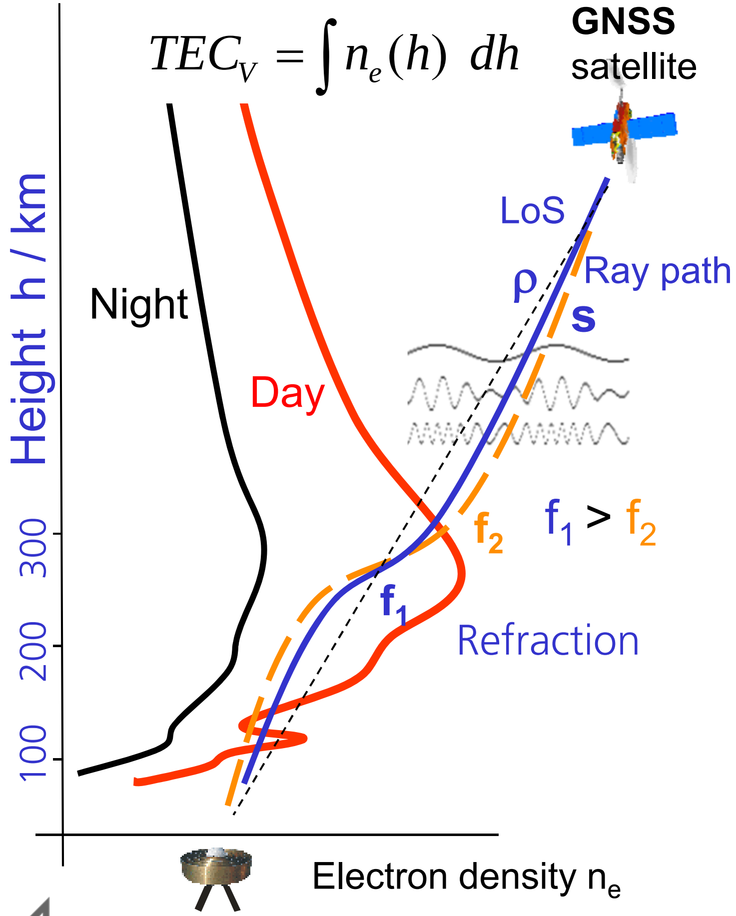
$$TEC_V = \int n_e(h)\ dh$$



- Ionosphere is the ionized part of the Earth's atmosphere
- generated by solar radiation and energetic particles (Space weather dependence)
- strong coupling with other geospheres such as thermosphere and magnetosphere
- ionospheric plasma impacts propagation of electromagnetic radio waves

Transionospheric propagation of radio waves

Ionosphere – vertical structure



Refraction of radio waves transmitted by GNSS satellites

The phase length L along the ray path s is defined by the integral

$$L = \int n\ ds \quad = Min$$

where n is the refractive index and the integral becomes a minimum according to Fermat's principle.

For GNSS, the phase length can be written:

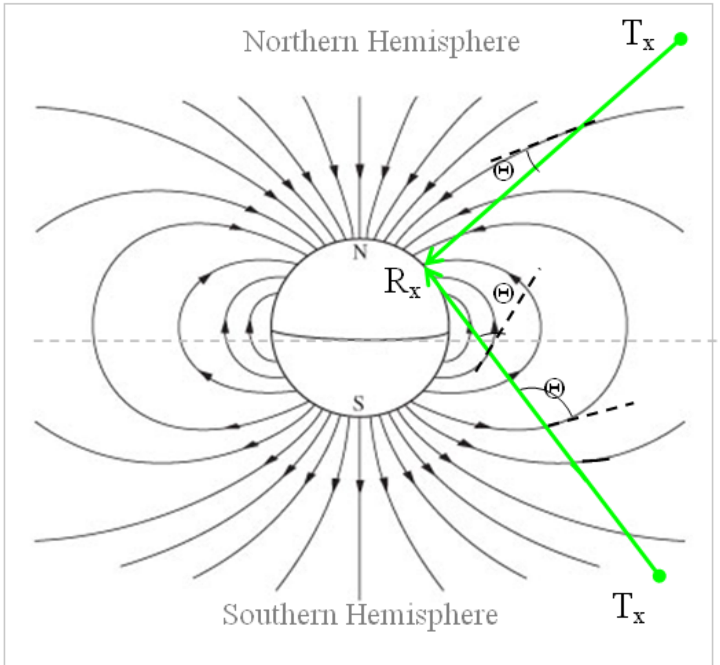
$$L = \int (n - 1)\ ds + \rho + \Delta s_B$$

where ρ is the line of sight and Δs_B means the excess path due to bending

Refractive index of ionospheric plasma

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

first-order **second-order** **third-order** **term**



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

DLR

Observation equations of GNSS measurements

Neglecting higher order terms in the refractive index and bending, the basic GNSS measurements of code phases P_1/P_2 and L_1/L_2 carrier phases can be written:

$$P = \boxed{\rho} + c(\Delta t_{rec} - \Delta t^{sat}) + d_T + \boxed{d_I} + d_{MP} + \varepsilon_P$$

$$\Phi = \boxed{\rho} + c(\Delta t_{rec} - \Delta t^{sat}) + d_T - \boxed{d_I} + d_{MP} + N_a \lambda + \varepsilon_\Phi$$

ρ	**true range between GPS satellite and receiver along ray path s**
c	velocity of light
Δt^{sat}	offset of satellite clock from GNSS Time
Δt_{rec}	offset of receiver clock from GNSS Time
d_I	**ionospheric phase delay along s**
d_T	atmospheric phase delay along s
d_{MP}	error due to multipath
λ	wave length of radio wave
N_a	phase ambiguity number (integer)
ε	Phase noise

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

Ionospheric range error

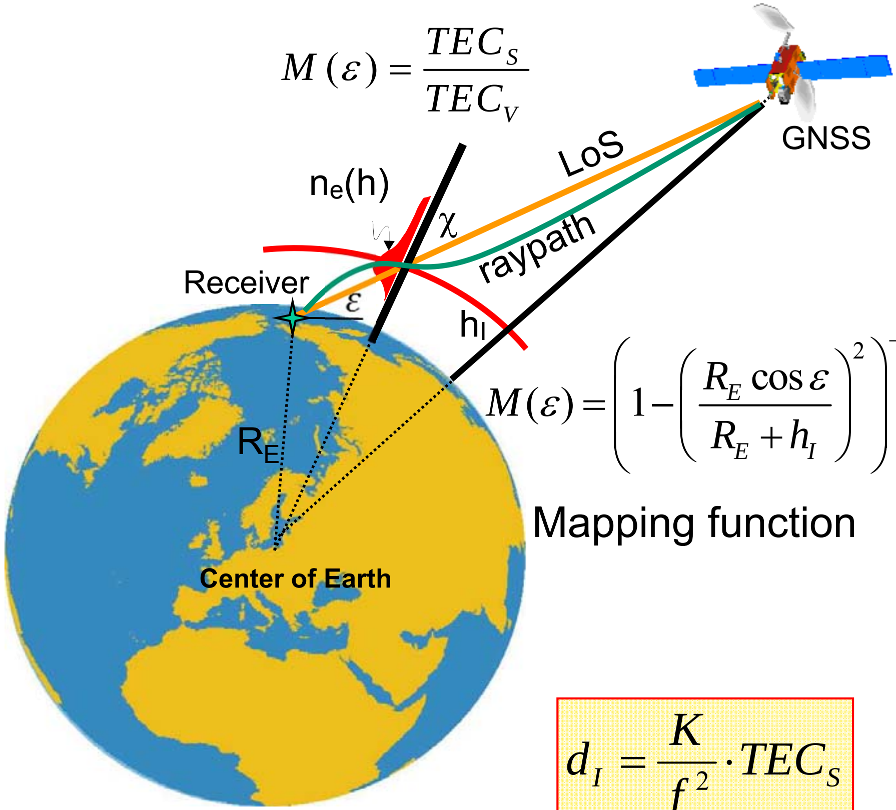
$$K = 40.3 \ m^3 s^{-2}$$

Ionosphere related range errors deduced from dual frequency GNSS measurements

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

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

$$M(\varepsilon) = \frac{TEC_S}{TEC_V}$$



$$M(\varepsilon) = \left(1 - \left(\frac{R_E \cos\varepsilon}{R_E + h_I}\right)^2\right)^{-1/2}$$

Mapping function

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

Due to the dispersive ionosphere TEC can be derived from dual frequency GNSS measurements (differential phases).

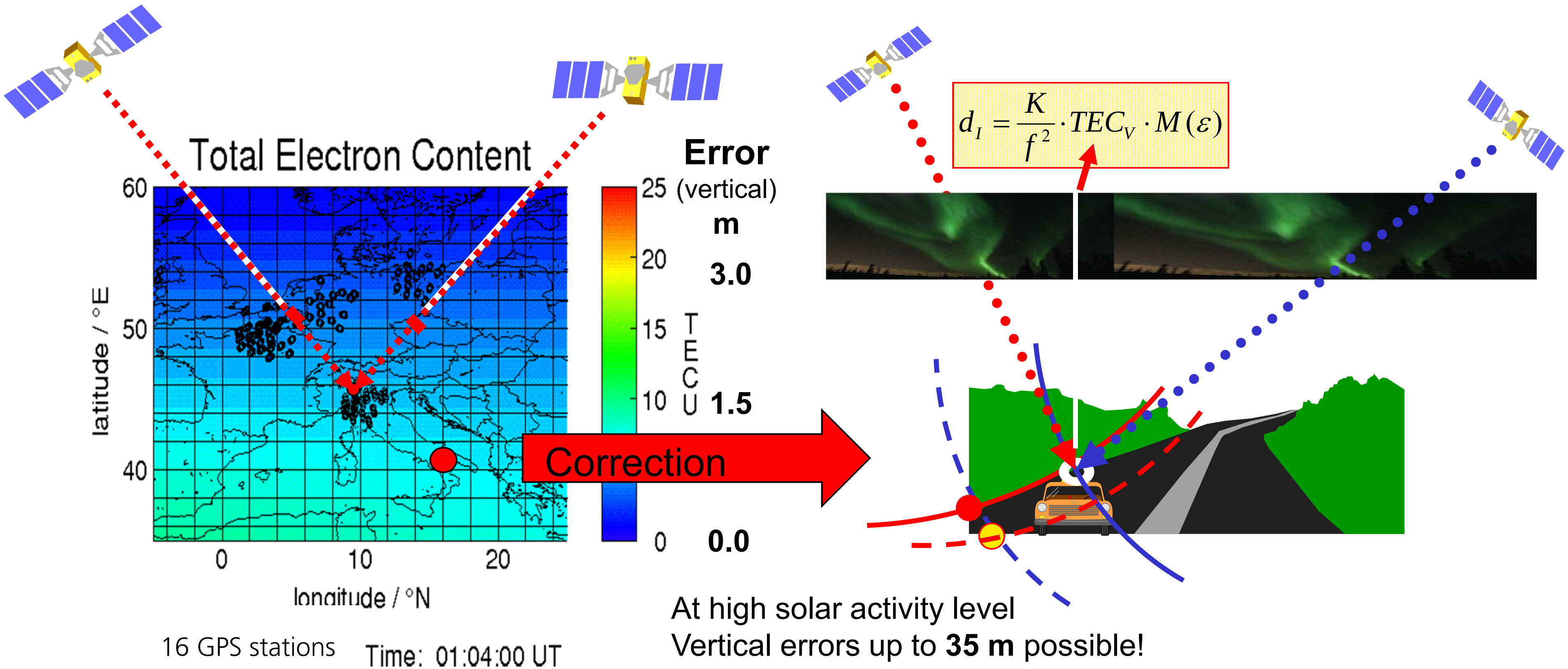
The ionospheric range error d_I is the biggest error source in single frequency GNSS applications (up to 100 m along ray path)

Single frequency measurements need range error correction information from:

- TEC monitoring data (map) or
- TEC model computations

DLR

Near real time correction of navigation errors



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

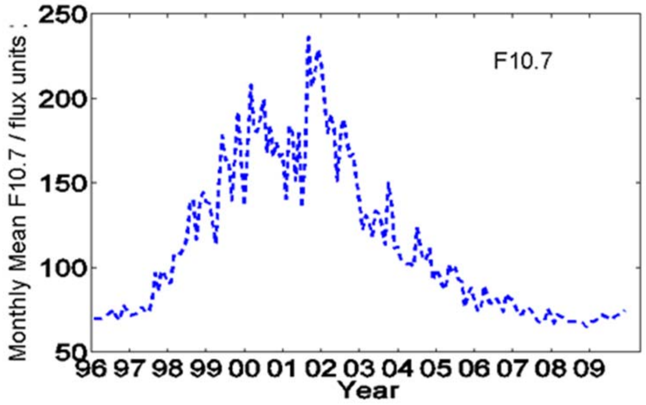
Near real time **TEC monitoring** data can be used for correcting single frequency GNSS measurements.
Data base provided by geodetic networks such as the International GNSS Service (IGS), EUREF and national networks.

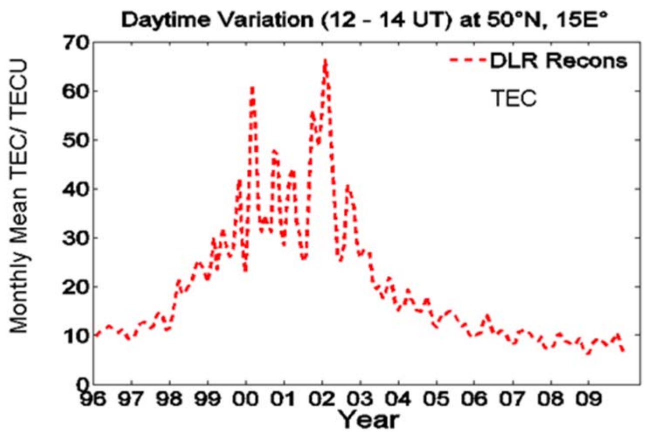
DLR

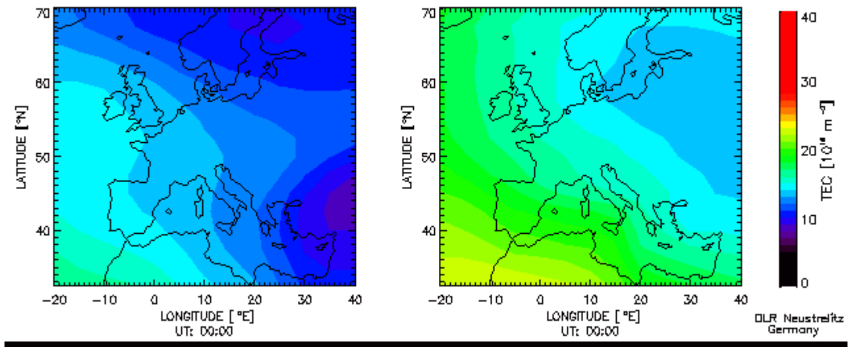
Outline

- Space weather
- Transionospheric radio wave propagation
- **Space weather effects in the ionosphere**
    - Solar radiation / activity / flares
    - CMEs / ionospheric storms
- Space weather / ionosphere impact on GNSS & mitigation
    - Single frequency GNSS for mass market
    - Precise positioning
    - Safety of Life applications
    - Monitoring and forecast service for mitigating ionospheric impact
- Summary

TEC dependence from solar radiation







[Total solar eclipse](#) Monthly medians

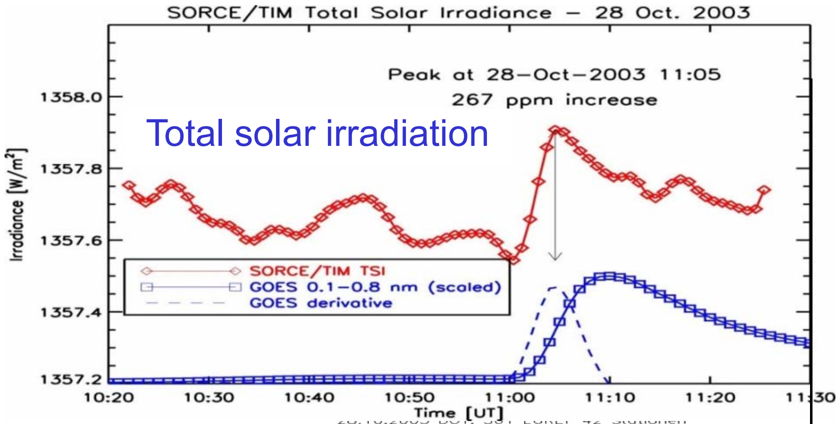
11. August 1999 August 1999

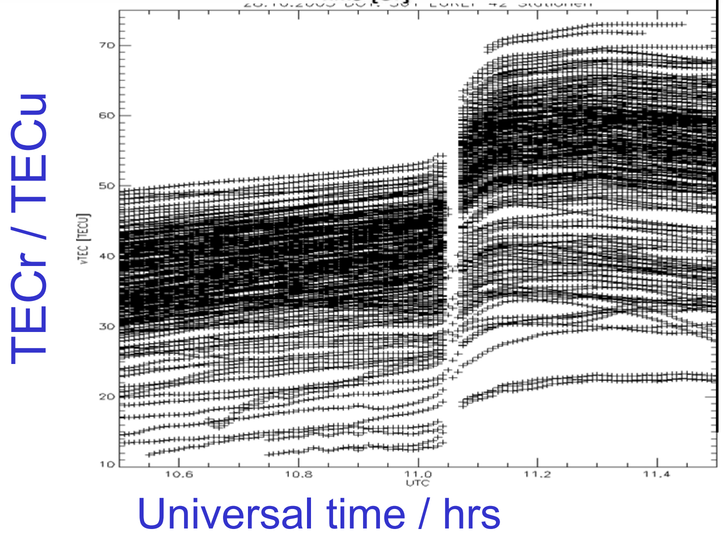
- TEC depends on solar irradiation conditions and solar activity.
- Electron density is strongly correlated with current space weather conditions.

Jakowski, N., S. Schlüter, S. Heise, J. Feltens, Satellite Technology Glimpses Ionospheric Response to Solar Eclipse, EOS, Transactions. American Geophysical Union, 80, 51, 21 December 1999

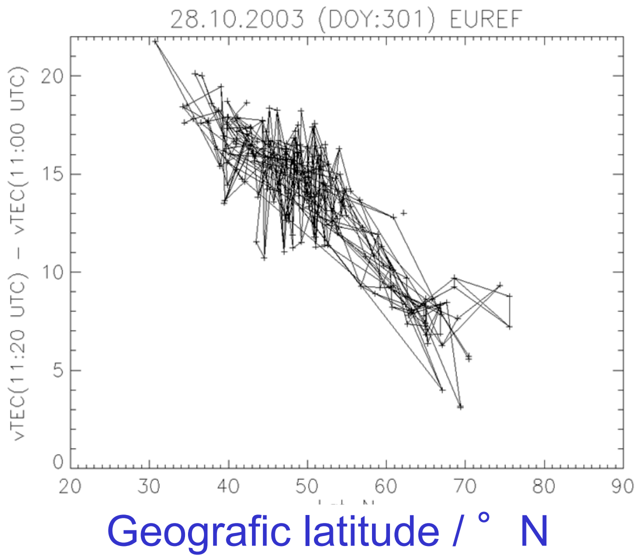
DLR

Solar flare effect in TEC on 28 October 2003

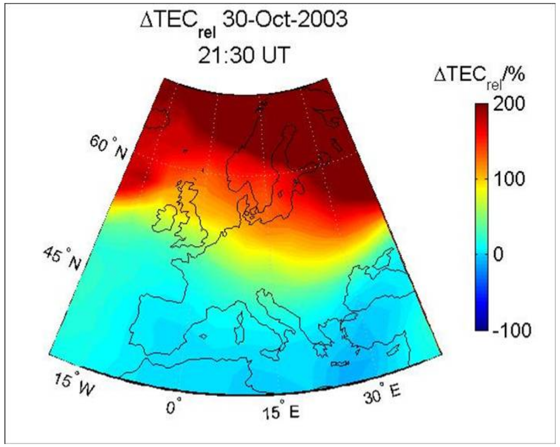


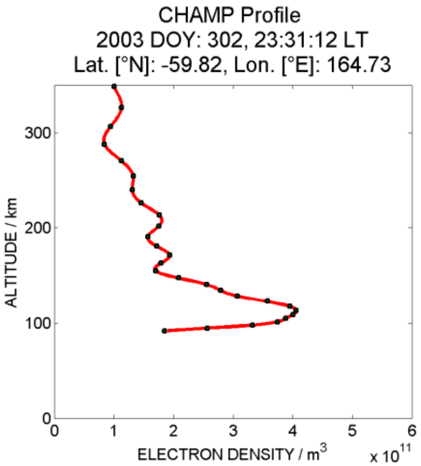


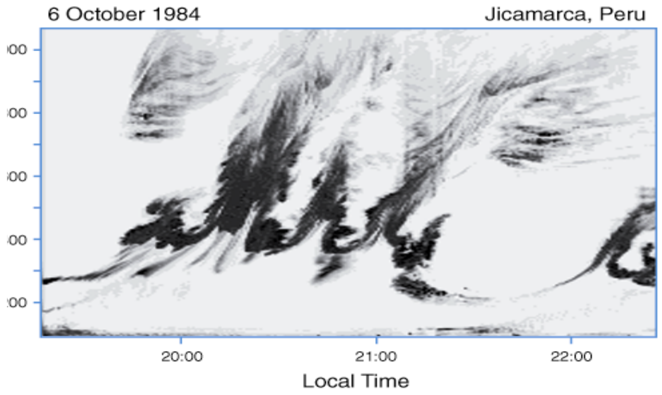
- Strong solar flare was observed on 28 October 2003 at 11:05 UT
- Total solar irradiation enhances within a few minutes by 267 ppm
- Rapid and strong increase of TEC at all GPS measurements (range error up to 3.5 m)



Ionospheric perturbations impacting GNSS







Large scale

- ≈1000 km
- hours
- Propagating Ionisation front
- Horizontal gradients up to 2TECU/km

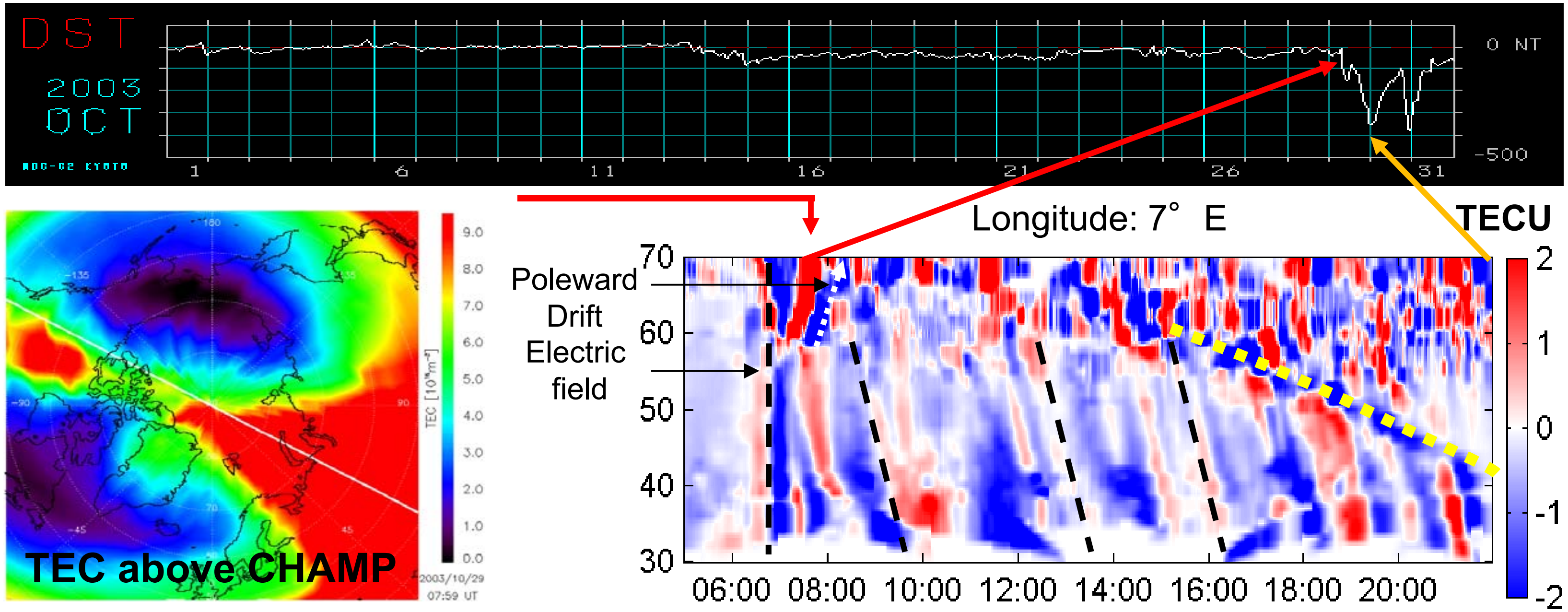
Mid-scale

- ≈100 km
- minutes
- Wavelike phenomena
- Ionisation patches
- Plasma bubbles

Small scale

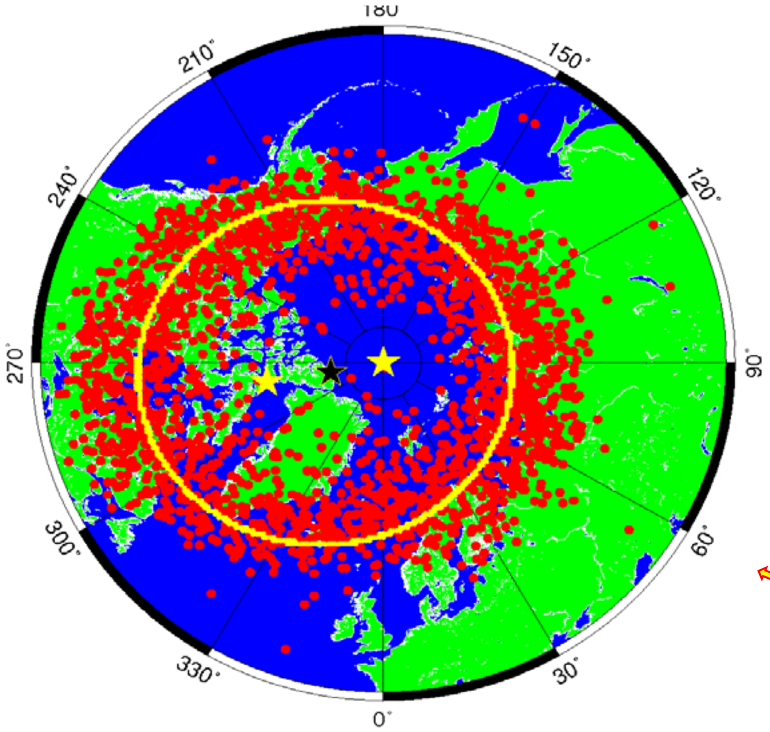
- ≤ 10 km
- seconds
- Plasma turbulences
  - Plasma instabilities
  - Particle precipitation

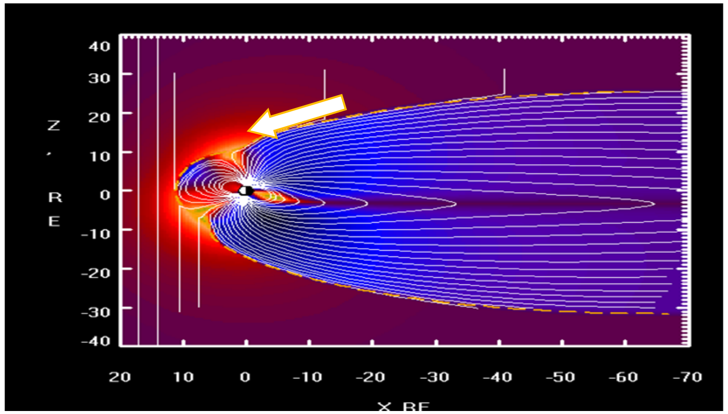
Ionospheric storm generation and propagation



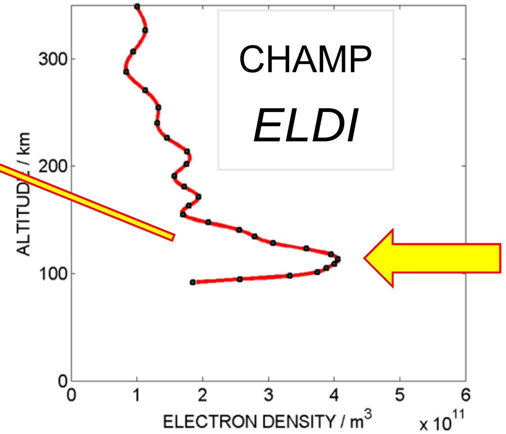
- Immediate response at all latitudes at storm onset
- Tongue of ionization across the Pole
- Wavelike propagation of disturbances during the main phase
- High latitude disturbance zone (northward of the trough) moves equatorward

Auroral particle precipitation





E-Layer Dominated Ionosphere



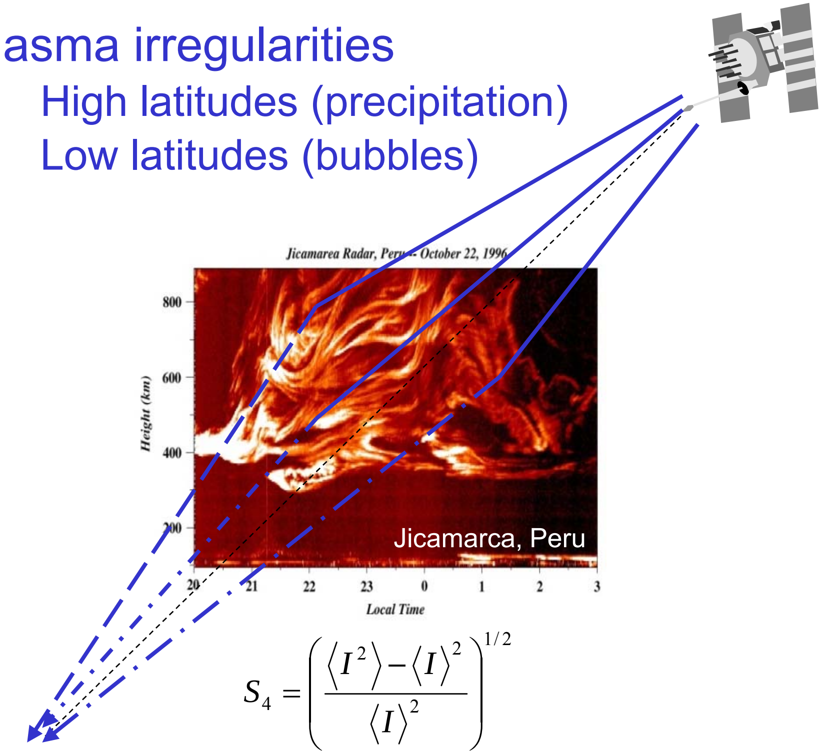
- Particle precipitation from the magnetosphere causes a locally enhanced ionization in the lower ionosphere → gradients, dynamic irregularities

Mayer, C. and N. Jakowski, Enhanced E layer Ionization in the Auroral Zones Observed by Radio Occultation Measurements Onboard CHAMP and Formosat-3/COSMIC, Annales Geophysicae, 27,1207-1212, 2009

Ionospheric irregularities – radio scintillations

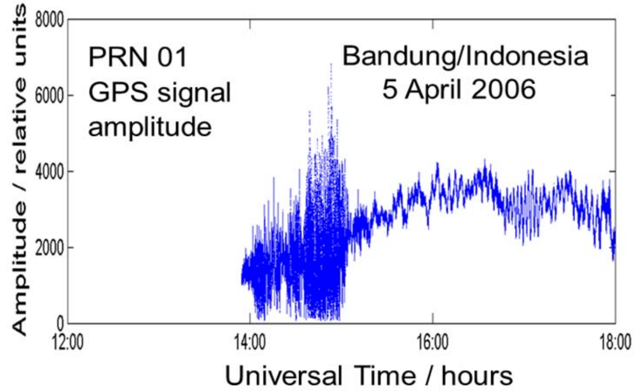
Plasma irregularities

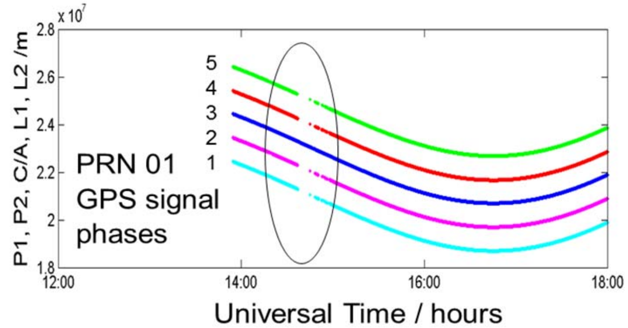
- High latitudes (precipitation)
- Low latitudes (bubbles)



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

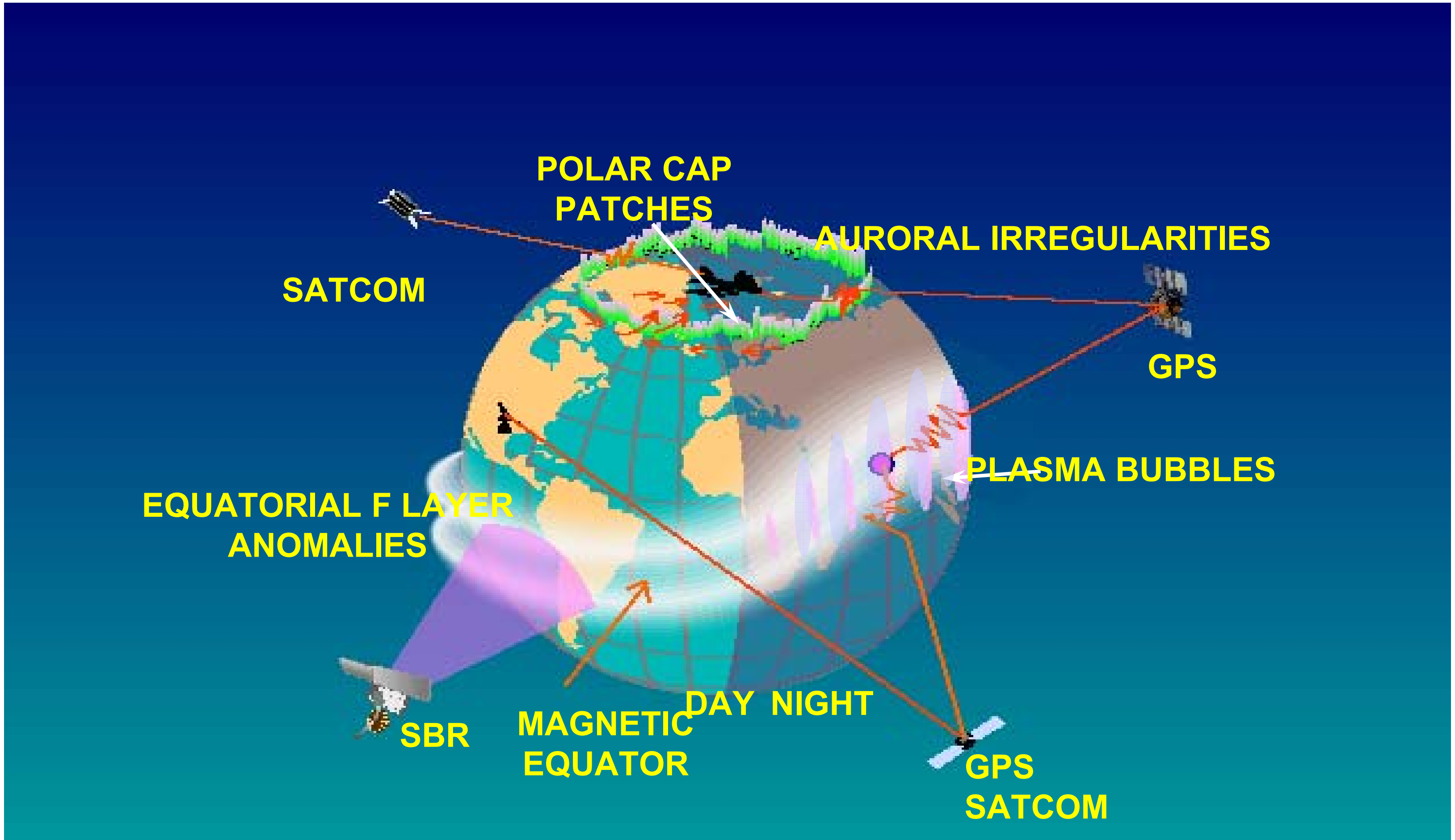
- Superposition of radio waves
- High variability of signal strength
- Loss of lock possible





Key parameters are S4 index and carrier phase noise σ_φ

Review of space weather related ionospheric effects



Source: AFRL

Outline

- Space weather
- Transionospheric radio wave propagation
- Space weather effects in the ionosphere
    - Solar radiation / activity / flares
    - CMEs / ionospheric storms
- **Space weather / ionosphere impact on GNSS & mitigation**
    - Single frequency GNSS for mass market
    - Precise positioning
    - Safety of Life applications
    - Monitoring and forecast service for mitigating ionospheric impact
- Summary

DLR

Use of ionospheric models in single frequency GNSS applications for correcting ionospheric errors

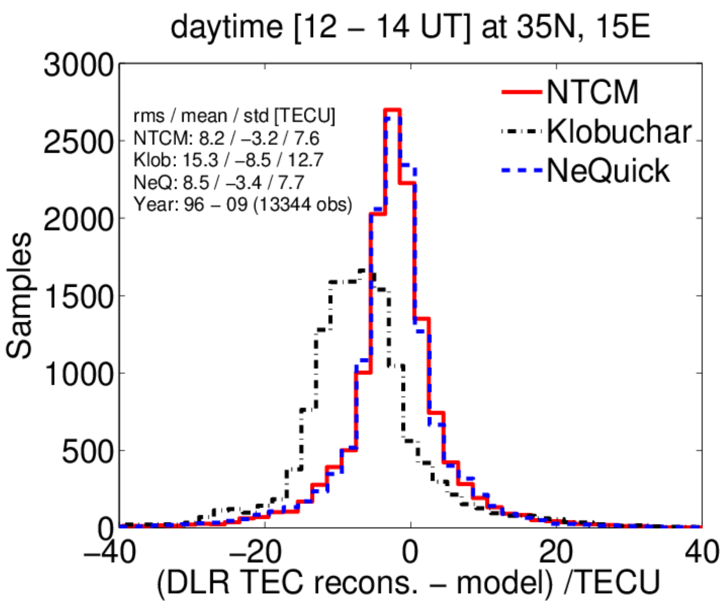
- Empirical models of the ionosphere provide a climatological estimation of the ionospheric ionization. Storm models capable to describe severe perturbations of the electron density and its distribution are not yet available.

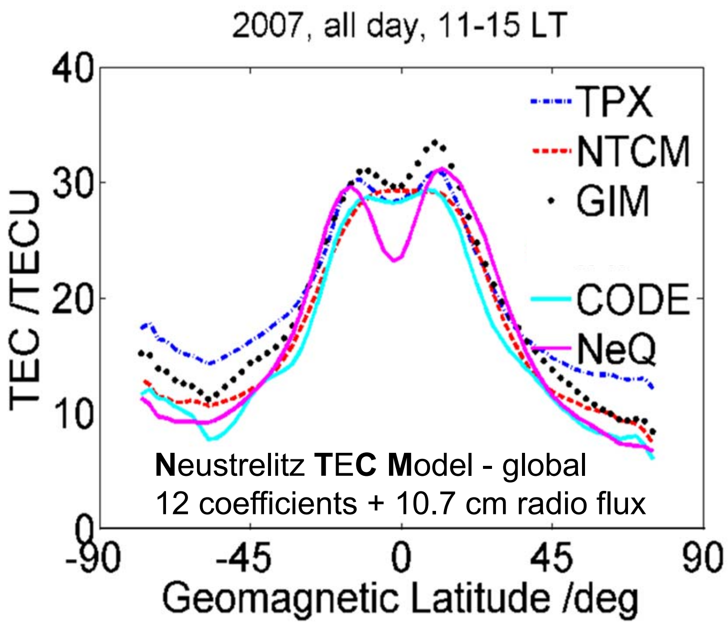
$$TEC_v = f(\varphi, \lambda, t, F10.7) \rightarrow d_I = \frac{K}{f^2} \cdot TEC_V \cdot M(\varepsilon)$$

- For estimating the transionospheric time delay or range error, several ionospheric models are currently available e.g.:

  - **GPS correction model** or Klobuchar model used for GPS
  - **NeQuick** 3 D model planned to be used for Galileo.
  - International Reference Ionosphere (**IRI**)
  - Family of TEC models developed in DLR
    Neustrelitz **TEC M**odels (NTCM-**EU**, -**NP**,-**SP**, -**GL**)

TEC model NTCM-GL for correcting single frequency GNSS measurements





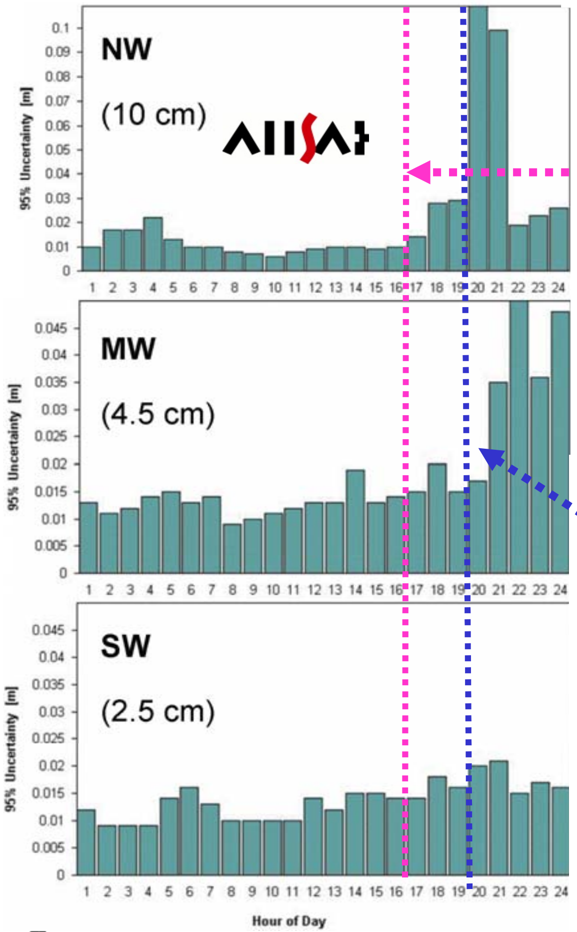
Comparison of TEC estimations obtained from three ionospheric models: GPS (Klobuchar) model, NeQuick and NTCM-GL in comparison with TEC at 35N;15E for daytime from 1996-2009.

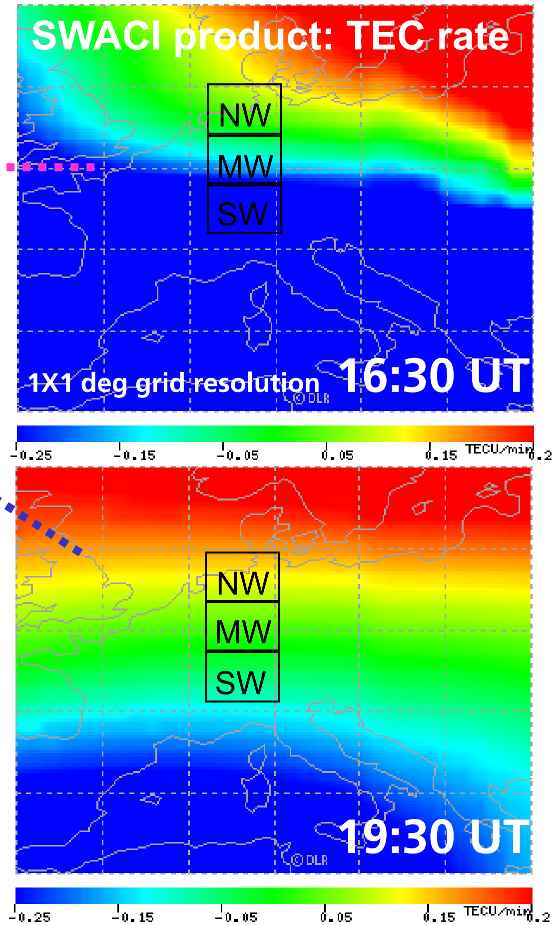
Comparison of TEC data derived from ionospheric models NeQuick (NeQ) and NTCM-GL with TEC reconstructions and measurements from TOPEX, GIM and CODE for global daytime TEC data.

Jakowski N, M.M. Hoque and C. Mayer (2011), A new global TEC model for estimating transionospheric radio wave propagation errors, Journal of Geodesy, 10.1007/s00190-011-0455-1

DLR

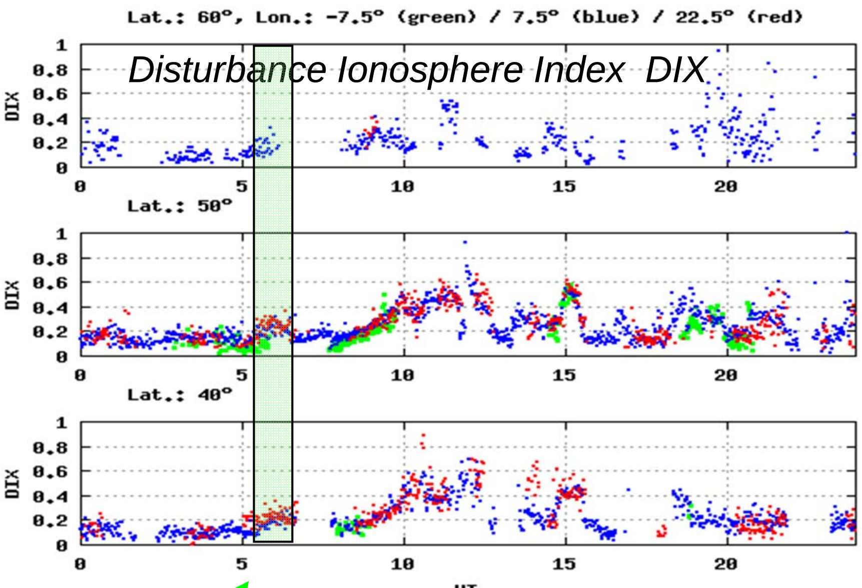
Impact on differential GNSS networks for precise positioning - I

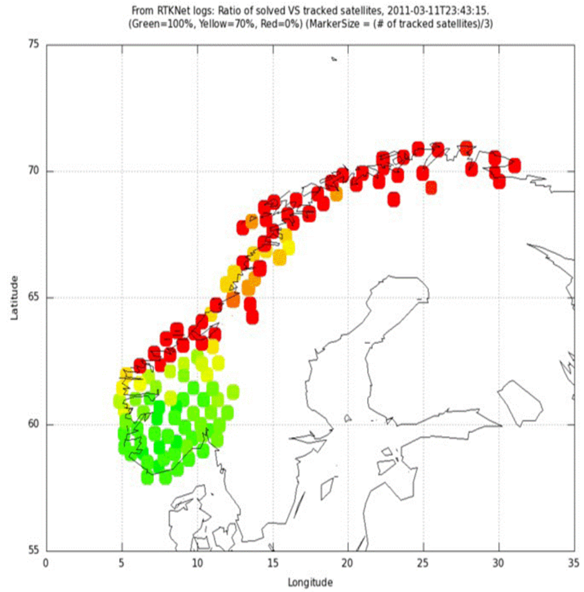




- Performance of the DGPS network of Allsat/Germany (left panel) compared with TEC rate maps from SWACI over Europe on 25 July 2004 at 16:30 and 19:30 UT.
- Accuracy reduces in the same way as the Travelling Ionospheric Disturbance (TID) propagates southward.
- Forecast of TIDs would allow forecasting performance changes.

Impact on differential GNSS networks for precise positioning - II





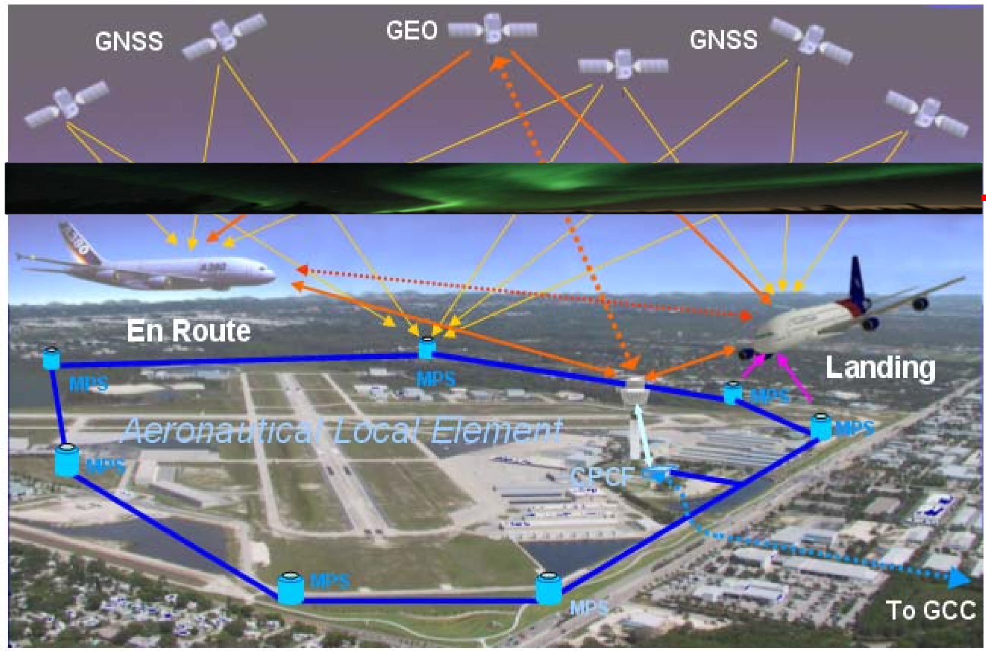
≈ 6:30 UT CME arrived at Earth

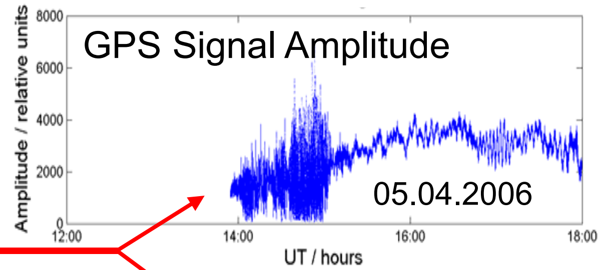
Disturbance Ionosphere Index (DIX) indicates perturbations over Europe which lead to performance degradation at higher latitudes.

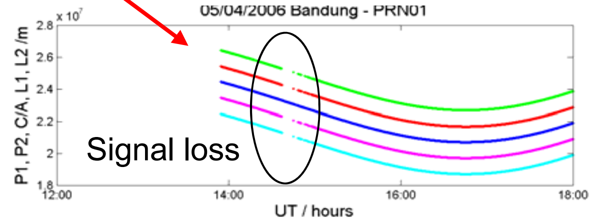
Performance degradation of Norwegian geodetic network CPOS (green: corrections for 100% of satellites, red: 0 %,no solution possible.

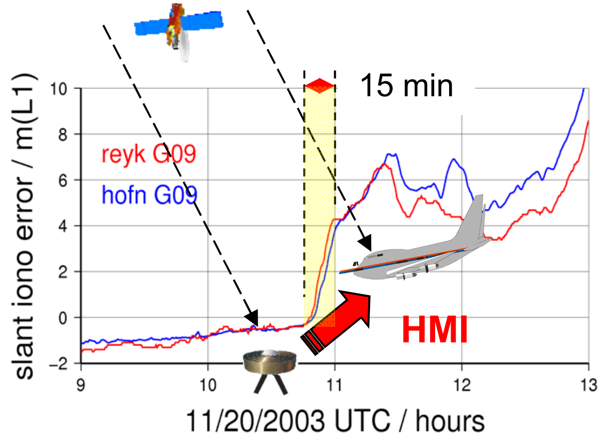
Jakowski, N.,V. Wilken, C. Borries, K. S. Jacobsen, and S. Schaefer, Monitoring of the ionospheric storm on 10/11 March 2011 and related impact on the Norwegian positioning network CPOS, ESWW 8 , Namur, Belgium, 2011

Ionospheric impact on Ground Based Augmentation Systems (GBAS) for GNSS guided aircraft landing



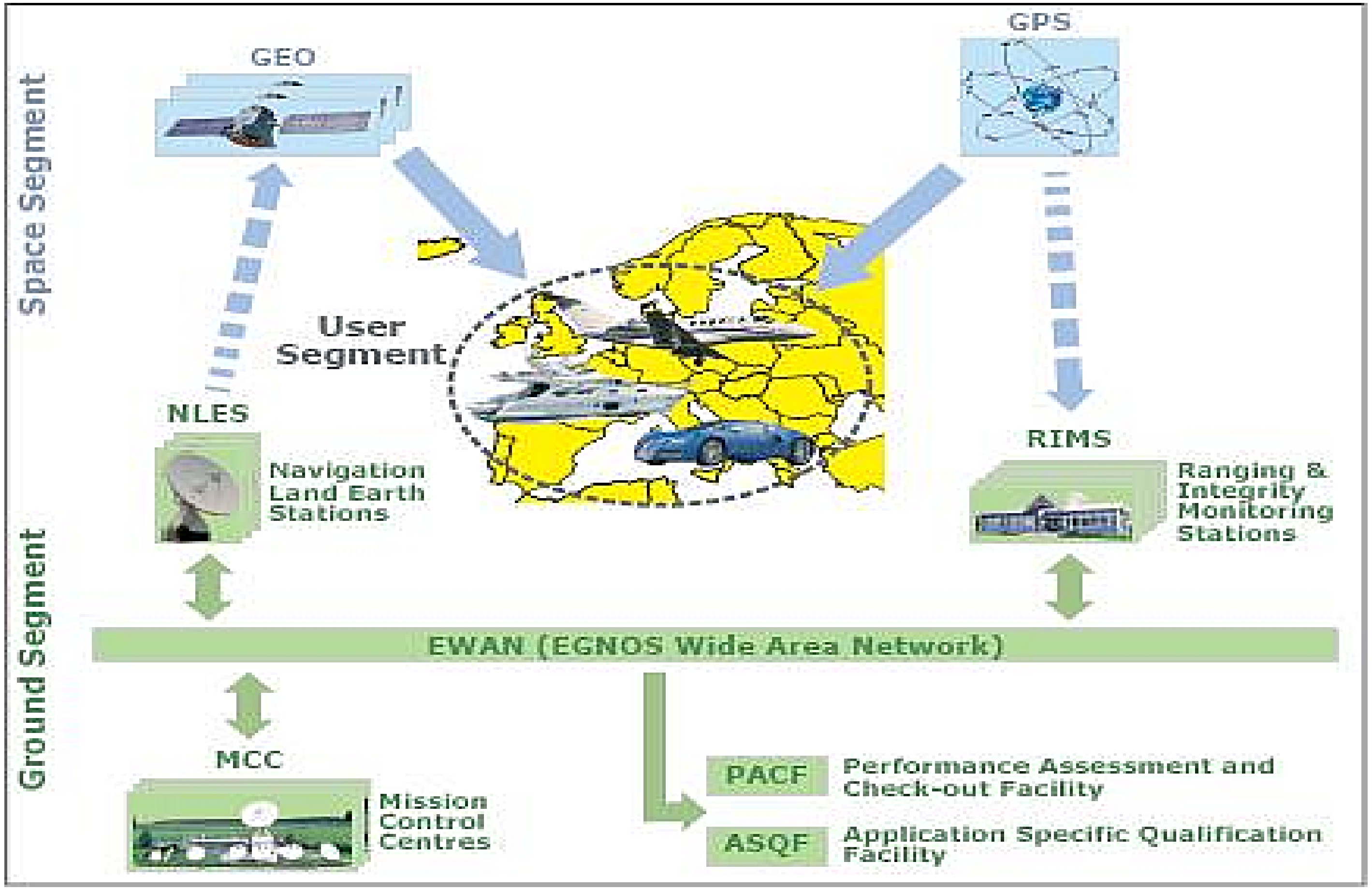






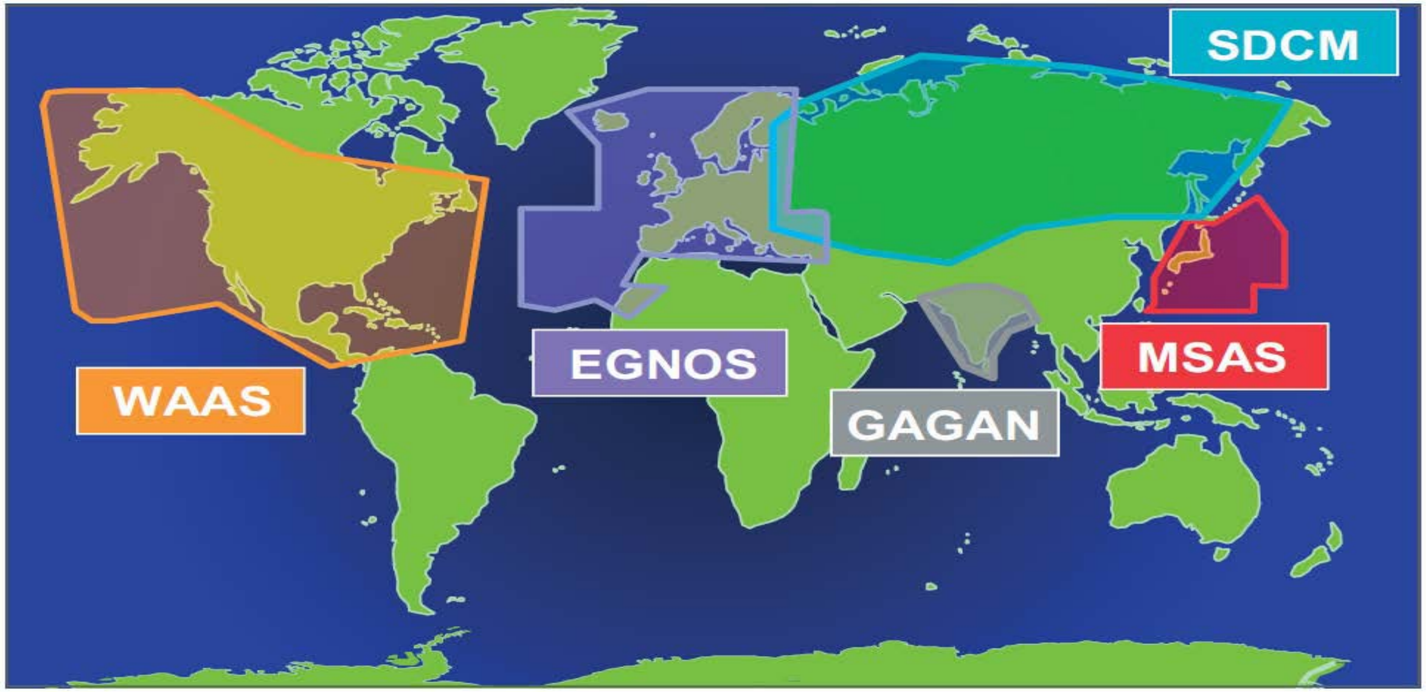
- Degradation of accuracy, integrity, availability and continuity of GNSS-signals possible
- Ionospheric threat model needed

Space Based Augmentation Systems (SBAS) - European Geostationary Overlay System (EGNOS)



Source: ESA

Space Based Augmentation Systems (SBAS)



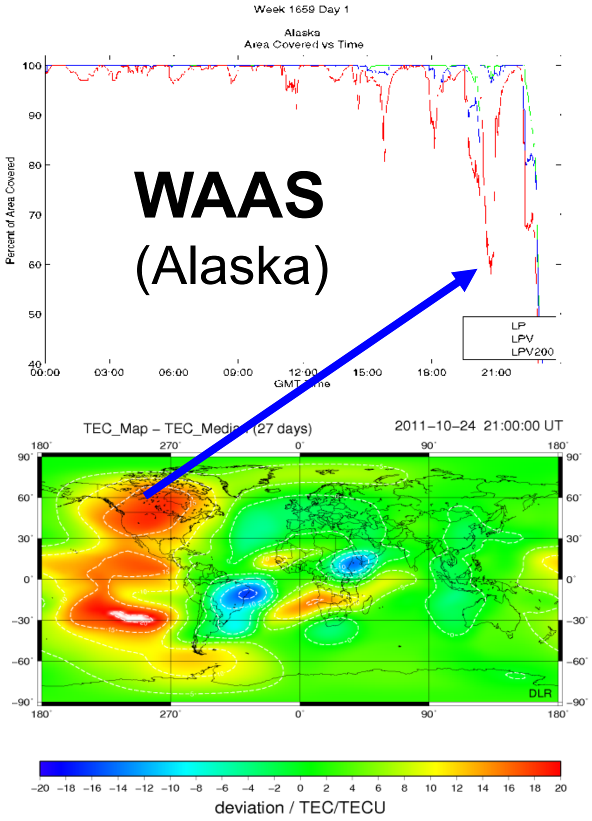
- WAAS (US):Wide Area Augmentation System; since 2003 operational
- EGNOS (Europe): European Geostationary Overlay System; since 2009 operational
- MSAS (Japan): Multi-functional Satellite Augmentation System; since 2007 operational
- GAGAN (India): GPS Aided Geo Augmented Navigation
- SDCM (Russia): System of Differential Correction and Monitoring

Source: ESA

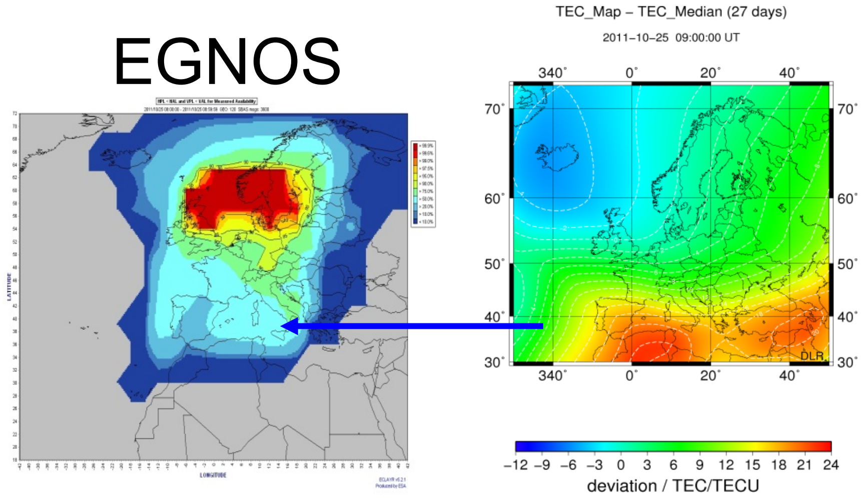
Impact on space based augmentation systems (WAAS/EGNOS)

24/10/2012 - 21:00 UT

25/10/2012 - 09:00UT



EGNOS



Performance of space based augmentation systems such as WAAS und EGNOS may be strongly affected by ionospheric perturbations

Space Weather Application Center Ionosphere

SWACI provides ionospheric information and data primarily deduced from ground and space based GNSS measurements:

e.g.

European and global TEC maps

electron density profiles from radio occultation data

Summary & Conclusions

- Radio wave propagation is strongly affected by space weather effects due to their interaction with the ionospheric plasma.
- Ionospheric plasma causes space weather related refractive delay, diffraction, absorption and scattering of transionospheric GNSS signals.
- Space weather is the largest error source for single-frequency GNSS.
- Severe solar flares may rapidly rise range errors by several meters.
- Ionospheric storms and related effects such as particle precipitation and gradients cause problems in precise and SoL applications.
- Modeling, monitoring and forecasting of ionospheric behavior contributes essentially to mitigate ionospheric impact on GNSS.
- Better understanding of ionospheric processes and their coupling is required for further improving mitigation techniques e.g. forecasts.


Thank you for your attention!
Contact:
Dr. Norbert Jakowski
German Aerospace Center
Kalkhorstweg 53
D-17235 Neustrelitz
Germany
Tel. +49 (0)3981 480 - 151
Fax. +49 (0)3981 480 - 123
Email: Norbert.Jakowski@dlr.de
Web: www.dlr.de/kn http://swaciweb.dlr.de