Space weather impact on radio wave propagation

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Outline

- Introduction
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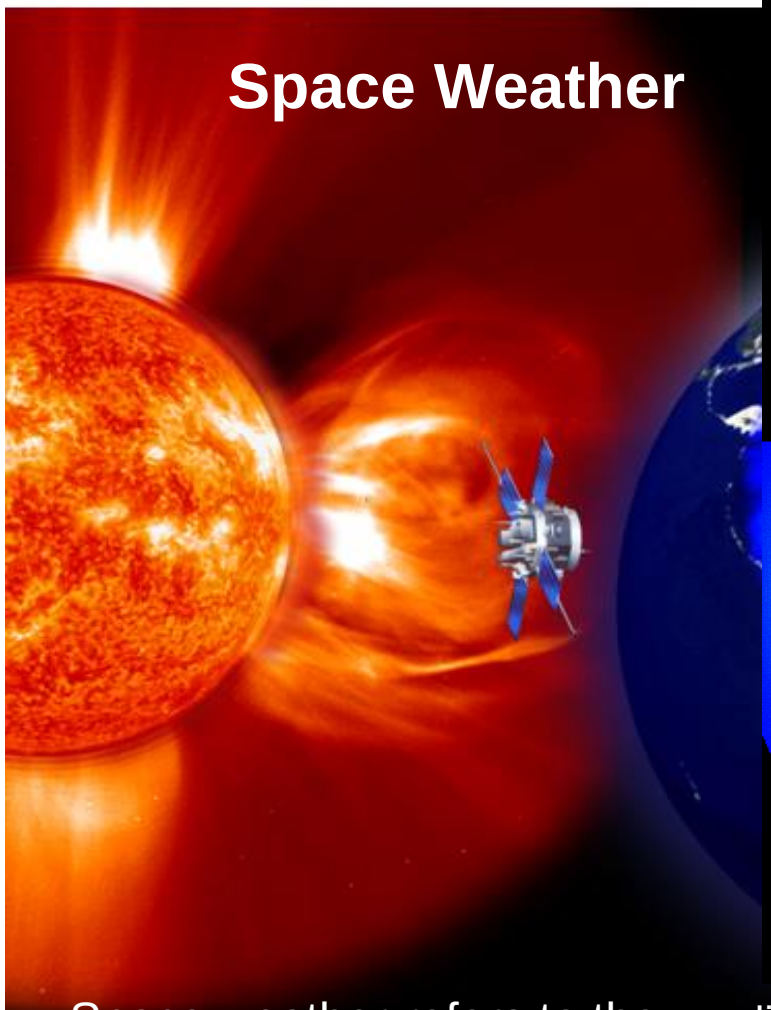
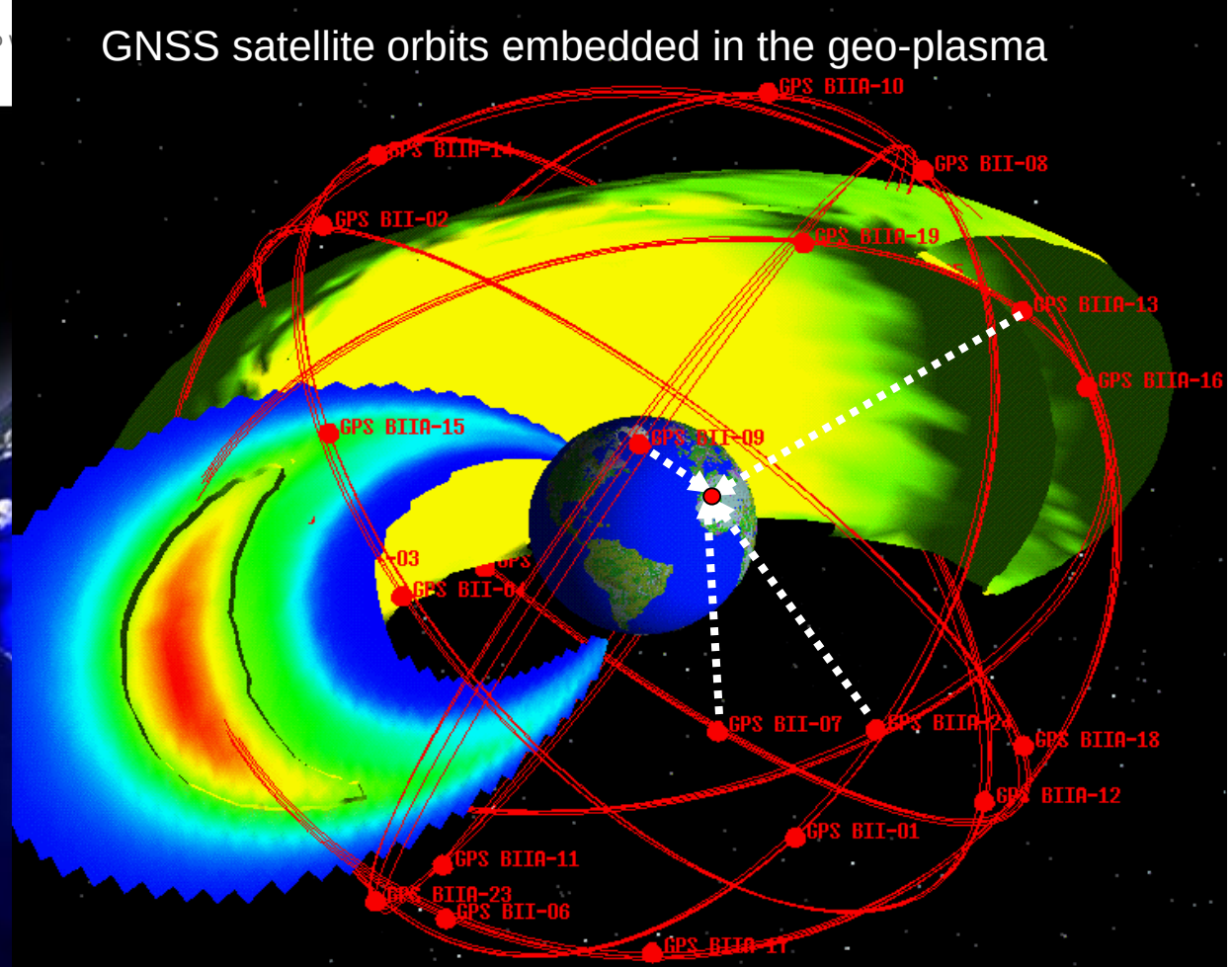
  - Ionosphere
- Radio wave propagation and ionosphere
  - The ionosphere
  - Fundamentals of radio wave propagation
- Ionospheric impact on radio systems
  - Telecommunication
  - Space based navigation
  - Remote sensing
- Summary

Space Weather



GNSS satellite orbits embedded in the geo-plasma



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

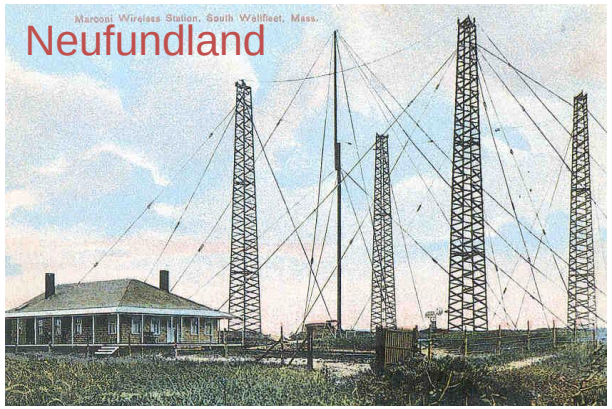
Credit: NASA

Radio waves play a significant role in modern technological systems:

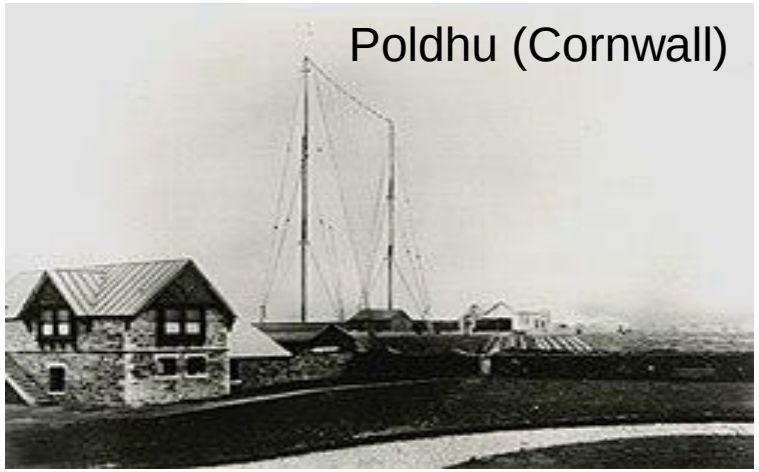
- Terrestrial and space based telecommunication
- Ground and space based navigation systems (e.g. GNSS)
- Remote sensing radars

History of electromagnetism - radio waves

- James Clark Maxwell (1862) Theory of electromagnetism
- Heinrich Rudolf Hertz(1886) Approval of the existence of electromagnetic waves
- Guglielmo Marconi (1901) Transatlantic radio transmission (Nobel prize 1909)
- Oliver Heaviside and Ernest Kenelly (1902) Assumption of an electrically conductive layer in the atmosphere
- Edward. V. Appleton (1927- 32) **Theory of radio wave propagation in plasma** (Nobel prize 1947)



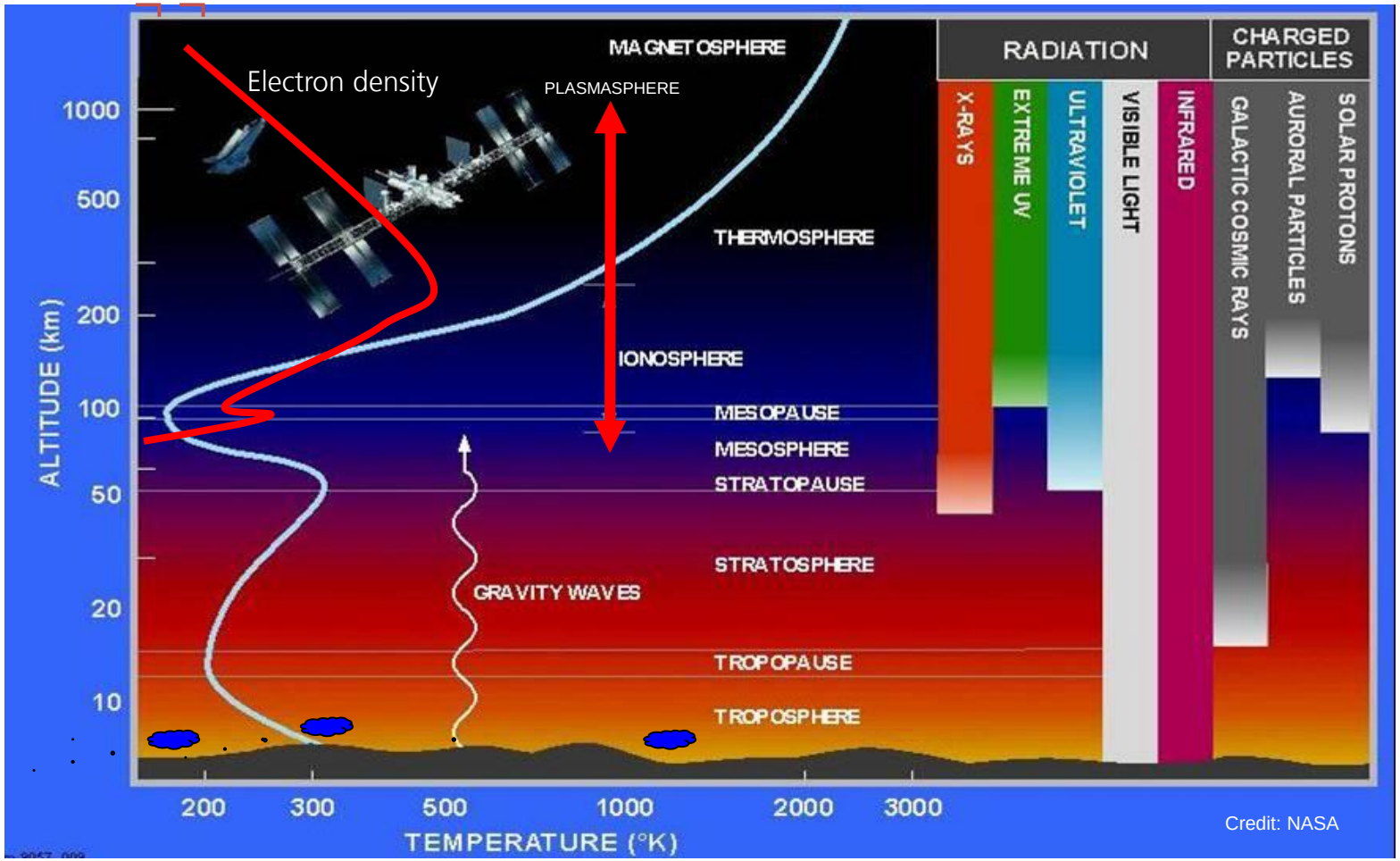
3500 km



Marconi‘s successful experiment demonstrates the close relationship between radio wave propagation and ionosphere - up today.

Ionosphere is a component of space weather.

The Ionosphere/plasmasphere - integral part of the Geo-sphere



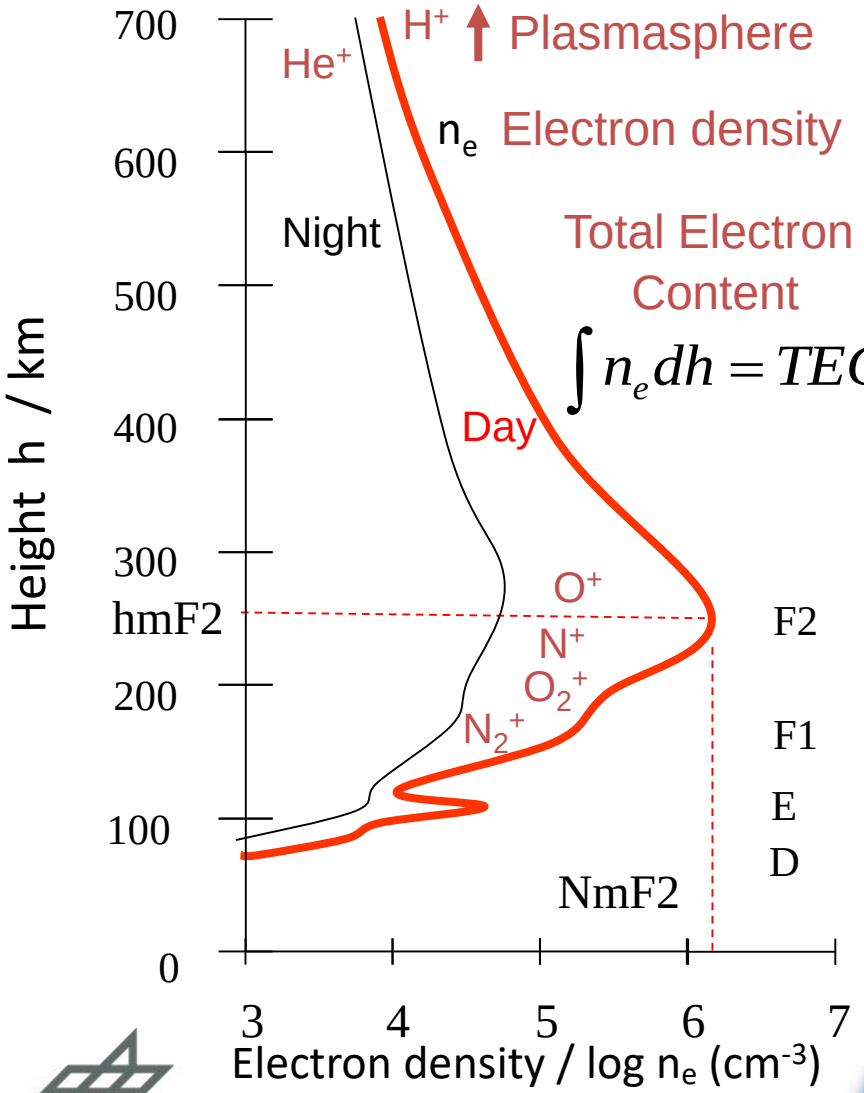
The Ionosphere/plasmasphere is an integral part of the Earth‘s environment and is characterized by strong coupling with other geo-spheres.

All geo-spheres are strongly impacted by the electromagnetic and corpusular radiation of the sun.

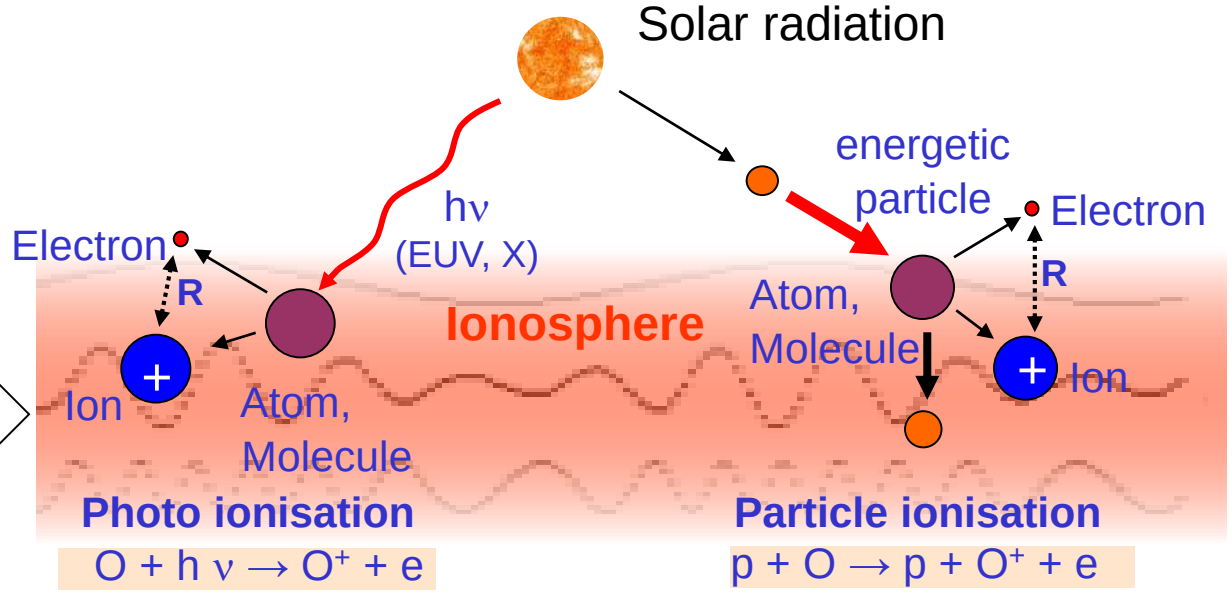
The ionospheric plasma is mainly formed by solar radiation at wavelengths < 130 nm.

Solar storms and associated Coronal Mass Ejections (CMEs) may heavily disturb the ionospheric and plasmaspheric behaviour.

The ionosphere - ionized part of the atmosphere



Radio wave



Ionosphere as the ionized part of the Earth‘s atmosphere

- is generated by electromagnetic and particle radiation from te sun
- is closely coupled with other geospheres such as the upper atmoshere, thermosphere and magnetosphere
- impacts propagation of electromagnetic radio waves,
- measurable changes of wave parameters **amplitude, phase, polarization** due to **absorption, refraction, diffraction, scattering**

Refractive index of the ionospheric plasma

electromagnetic plane wave based on Maxwell's theory:

$$\vec{E} = A(\vec{k}) \cdot \exp\left(i(\omega(\vec{k}) \cdot t - \vec{k} \cdot \vec{r})\right)$$

$v_\varphi = \frac{2\pi \cdot f}{k}$ phase velocity $\vec{k}$ wave vector $k = \frac{\omega}{c} = \frac{2 \cdot \pi}{\lambda}$

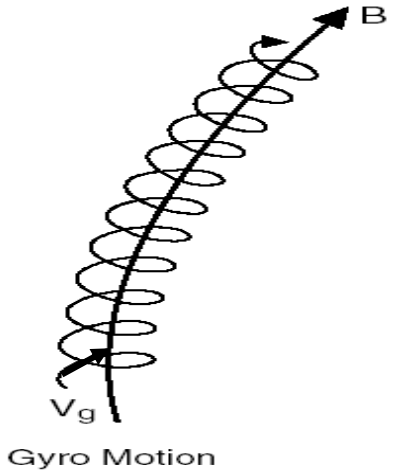
Refractive index for a magnetized plasma (Appleton equation)

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y^2 \sin^2\Theta}{2(1 - X - iZ)} \pm Y\left[\frac{Y^2 \sin^4\Theta}{4(1 - X - iZ)^2} + \cos^2\Theta\right]^{1/2}}$$

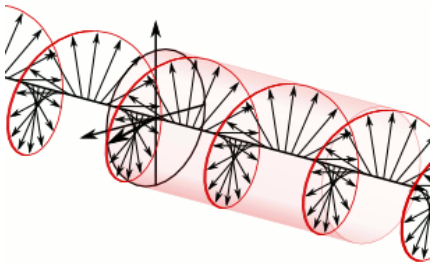
double refraction

$$X = \frac{f_p^2}{f^2} \qquad Y = \frac{f_g}{f} \qquad Z = \frac{\nu}{2\pi \cdot f}$$

f_p : plasma frequency f_g : gyro frequency ν: collision frequency



GPS polarization



Source: Galileo GNSS

Gyro motion of electrons
Electrons gyrate around geomagnetic field lines

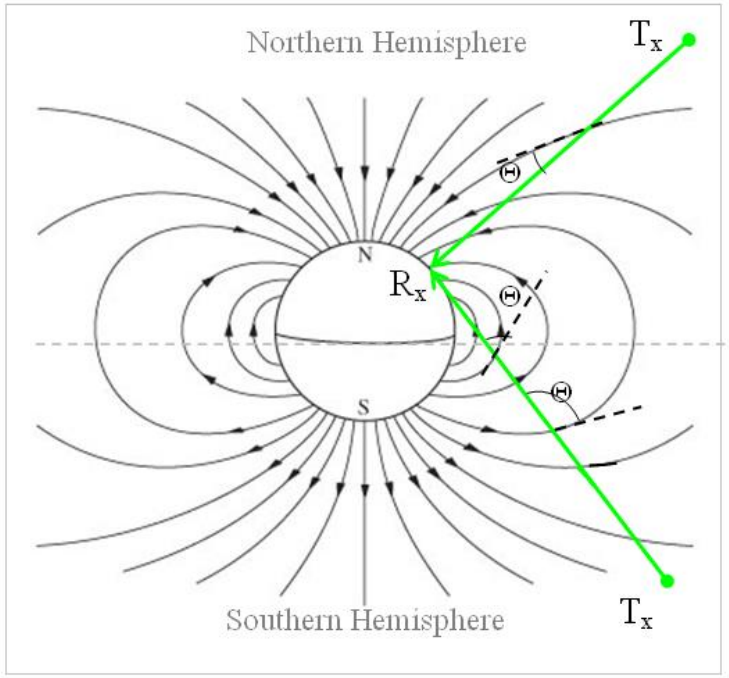
Θ angle between ray path and geomagnetic field

Absorption can be ignored at GNSS frequencies.
Refractive index depends on electron density and magnetic field vector.
Ionosphere is anisotropic due to the presence of the geomagnetic field.

Refractive index of ionospheric plasma (f >> f_p)

$$n \approx 1 \underbrace{-\frac{f_p^{\,2}}{2f^2}}_{\text{First – order}} \underbrace{\pm \frac{f_p^2 f_g \cos\Theta}{2f^3}}_{\text{Second – order}} \underbrace{-\frac{f_p^4}{8f^4}}_{\text{Third – order}} \quad \text{term} \qquad v_{phase} = \frac{c}{n}$$

<100 m L1 | < 20 cm L1 | <1 cm L1



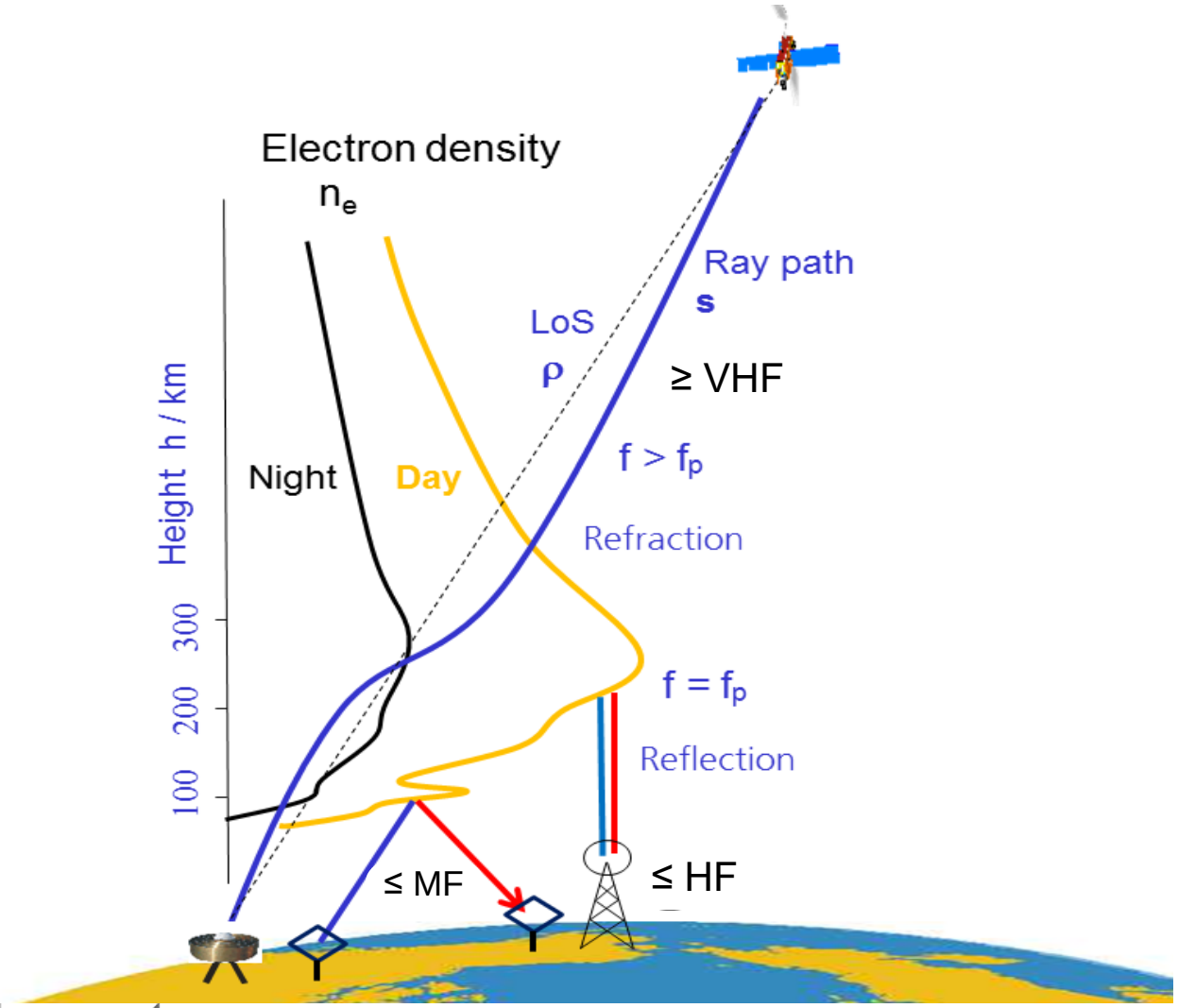
Plasma frequency: $f_p = \sqrt{e^2 n_e / (4\pi^2 m_e \varepsilon_0)}$ < ≈ 20 MHz

Gyro frequency: $f_g = eB / 2\pi \cdot m_e$ < ≈ 1.5 MHz

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

Hoque, M.M.,and N. Jakowski (2006). Higher order Effects in Precise Positioning,
J. of Geodesy, 10.1007/s00190-006-0106-0

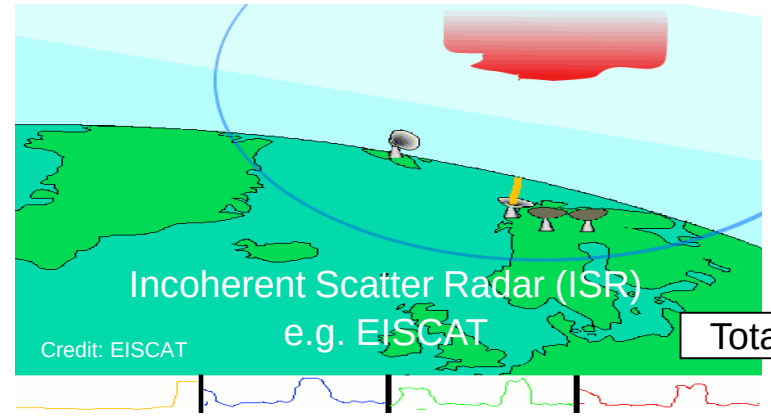
Radio frequency spectrum & propagation

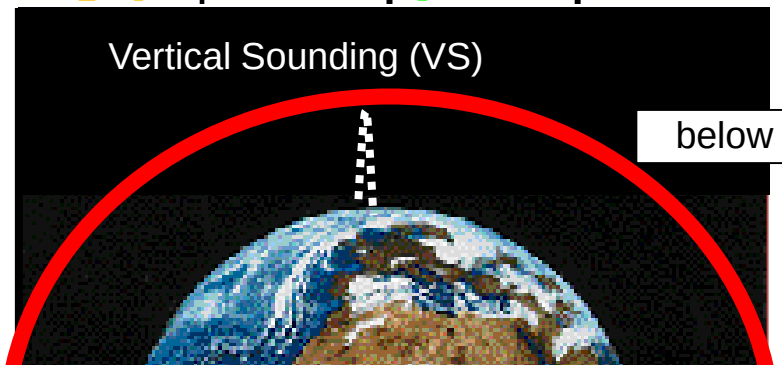


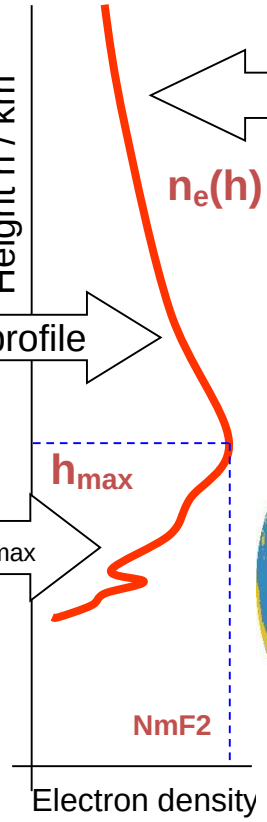
Symbol of frequency band	Frequency range	Wavelength range
ELF Extreme Low Frequency	< 300 Hz	> 1000 km
ULF Ultra Low Frequency	300 Hz - 3 kHz	1000 - 100 km
VLF Very Low Frequency	3 kHz - 30 kHz	100 - 10 km
LF Low Frequency	30 kHz - 300 kHz	10 - 1 km
MF Medium Frequency	300 kHz - 3 MHz	1000 - 100 m
HF High Frequency	3 MHz - 30 MHz	100 - 10 m
VHF Very High Frequency	30 MHz - 300 MHz	10 - 1 m
UHF Ultra High Frequency	300 MHz - 3 GHz	1000 - 100 mm
SHF Super High Frequency	3 GHz - 30 GHz	100 - 10 mm

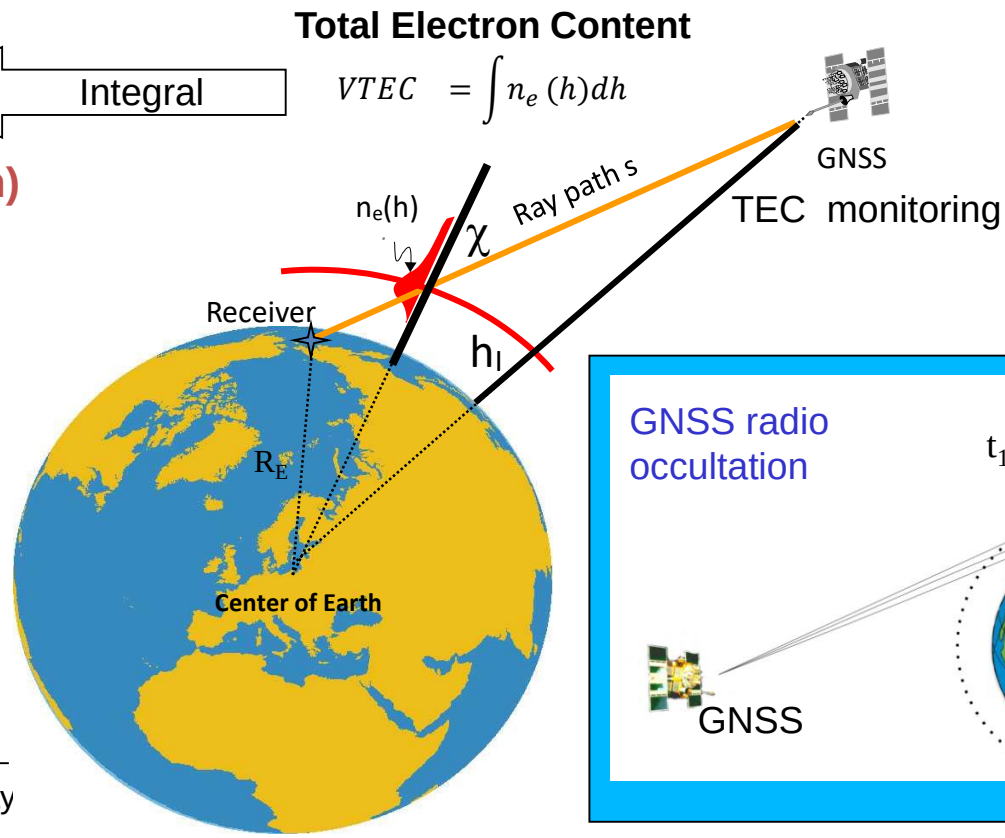
Space weather impact on radio wave propagation is closely related to the state of the geo-plasma, in particular the ionosphere, acting as propagation medium.

Sounding the Ionosphere with radio waves









ISR: Radar utilizes scattering at charged particles in the ionosphere up to 1000 km height.

VS: Radar utilizes reflection of radio waves at the bottomside of the ionosphere

- Our knowledge about the Ionosphere stems mainly from the analysis of ionospheric modifications of propagation parameters of radio waves:
  amplitude, phase, signal delay, polarization
- **On te other hand:** Knowledge of space weather related ionospheric conditions is needed to understand/predict the propagation of radio waves

Terrestrial radio wave propagation (HF)

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

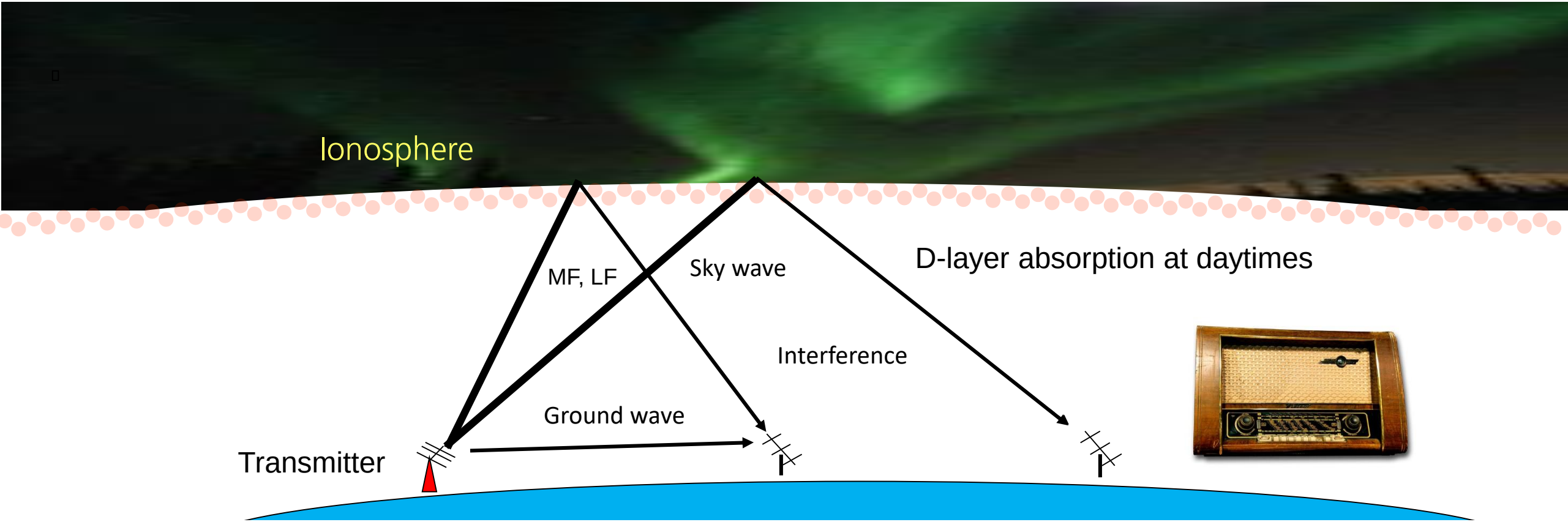
* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

URL: *www.swpc.noaa.gov/NOAAscales*

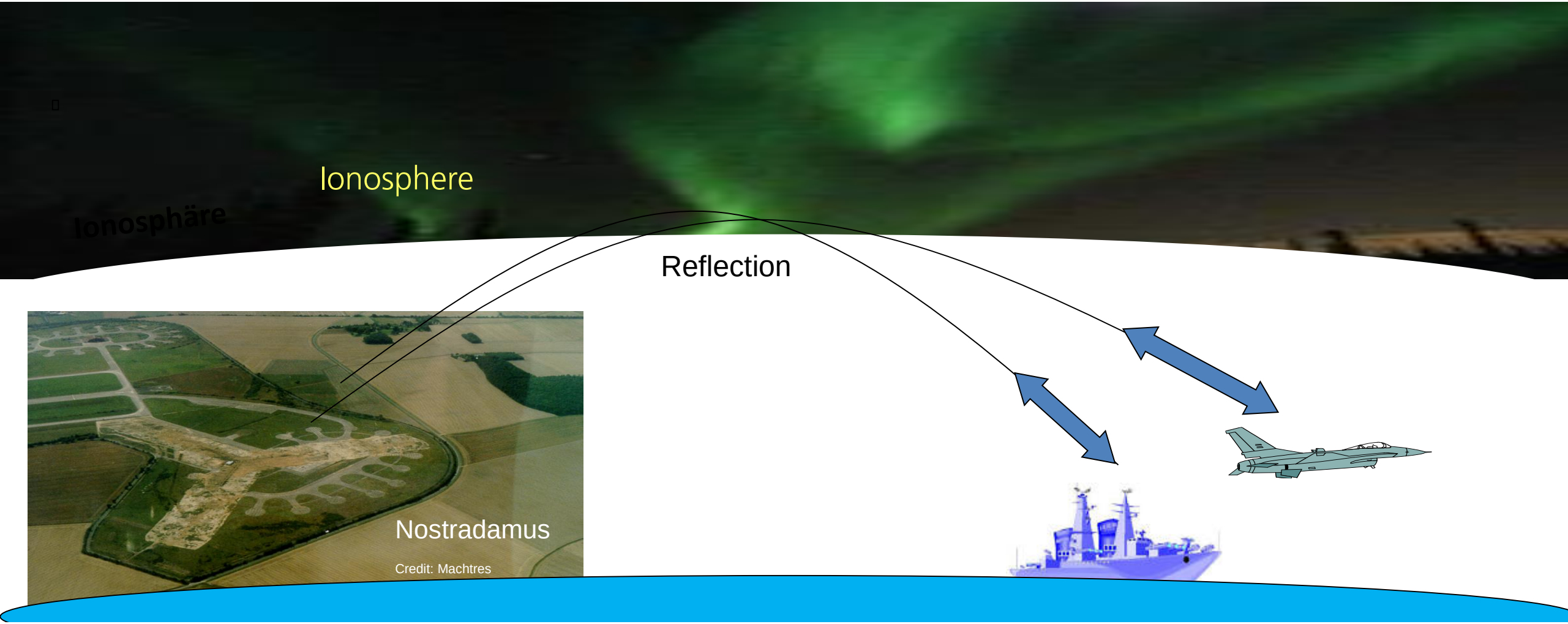
April 7, 2011

Terrestrial radio wave propagation (HF)



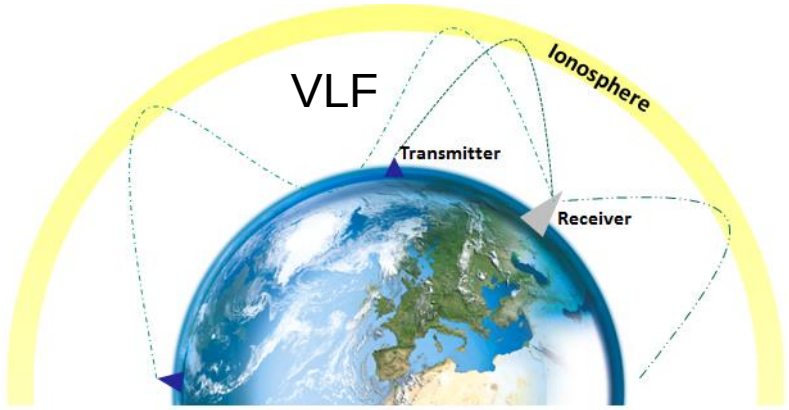
D-layer exists only at daytime created by the energetic spectrum of solar radiation reduces in particular the strength of MF and LF signals, phase shift of radio waves

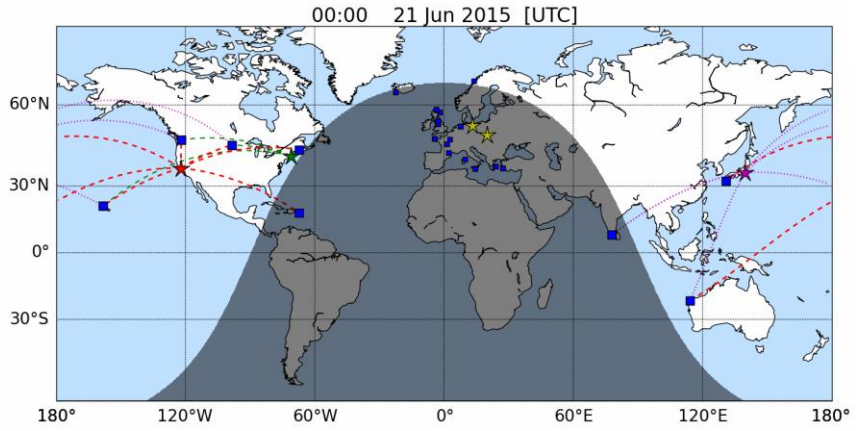
OTH - Radar NOSTRADAMUS near Paris

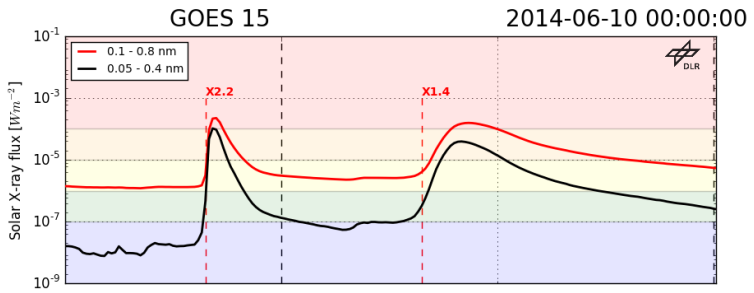


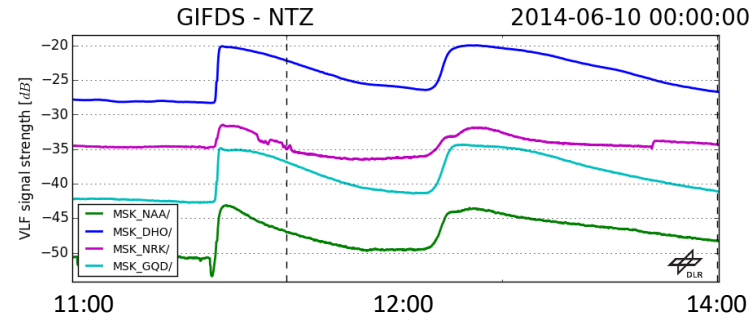
Nostradamus: 300 antennas, Range: 3000 km, f: 6-28 MHz, Detection of airplanes and ships, e.g. North Africa

Solar Flare impact on VLF radio wave propagation (e.g. June 10, 2014)









GIFDS
Global **I**onosphere **F**lare **D**etection **S**ystem

VLF receiver

Severe solar radiation bursts commonly measured as X ray bursts at GOES satellites may considerably enhance the plasma density in the ionosphere.

X rays: impact mainly the bottomside ionosphere, i.e. HF communication is affected.

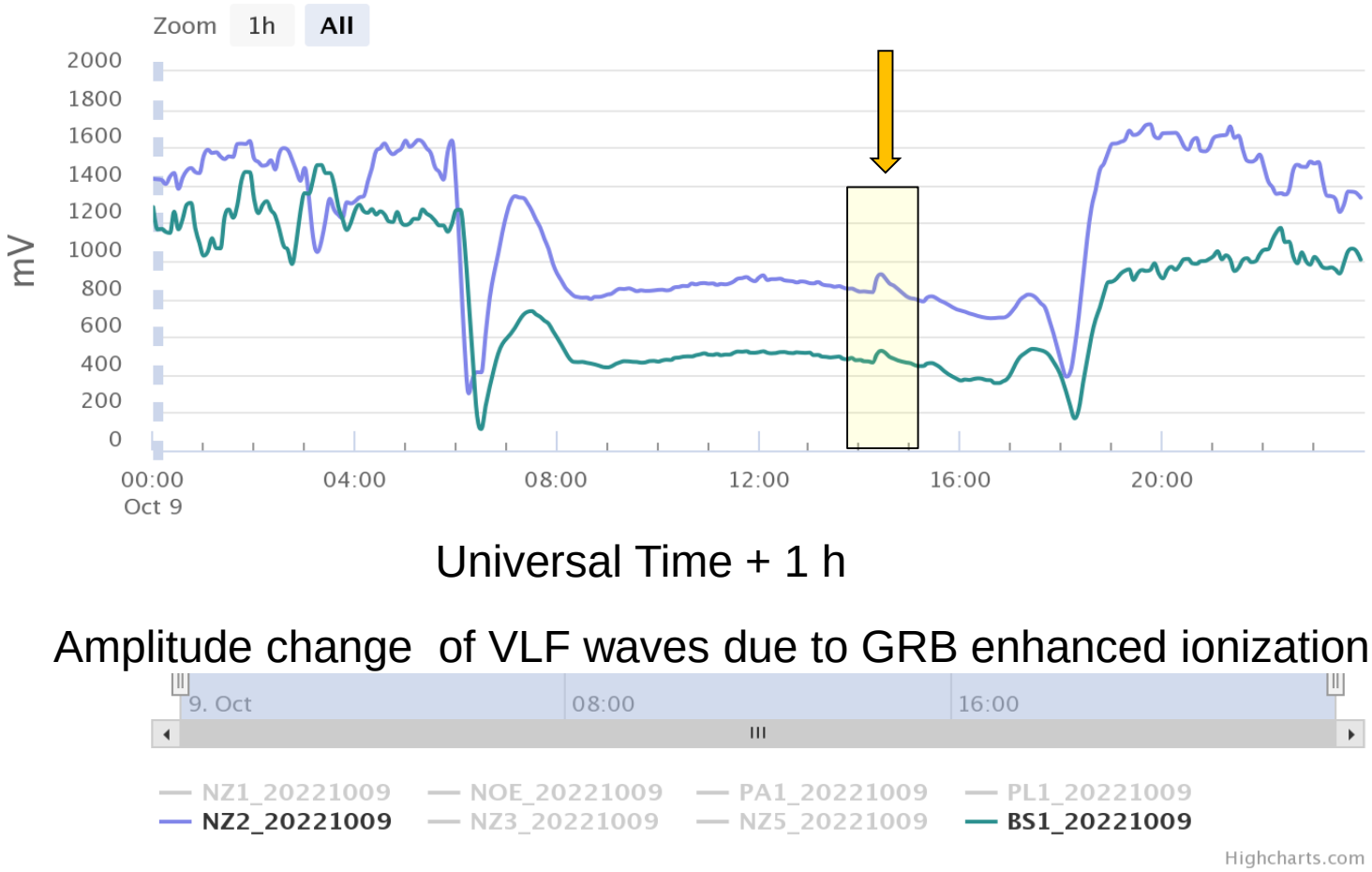
EUV: impacts mainly the F2 layer, trans-ionospheric communication incl. GNSS applications are affected.

Wenzel et al. (2016) Global ionospheric flare detection system (GIFDS), JASTP, vol. 138-139, 233-242, http://dx.doi.org/10.1016/j.jastp.2015.12.011

Detection of a Gamma ray burst on October 9, 2022 by students project SOFIE

SOlar **F**lares by **I**onospheric **E**ffects (SOFIE)

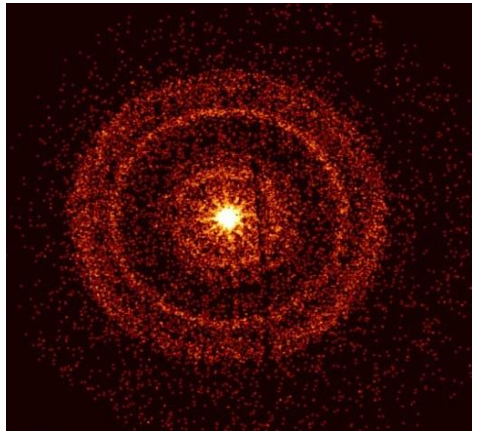
http://www.projectlab-neustrelitz.de/site/de/sofie.html



Universal Time + 1 h

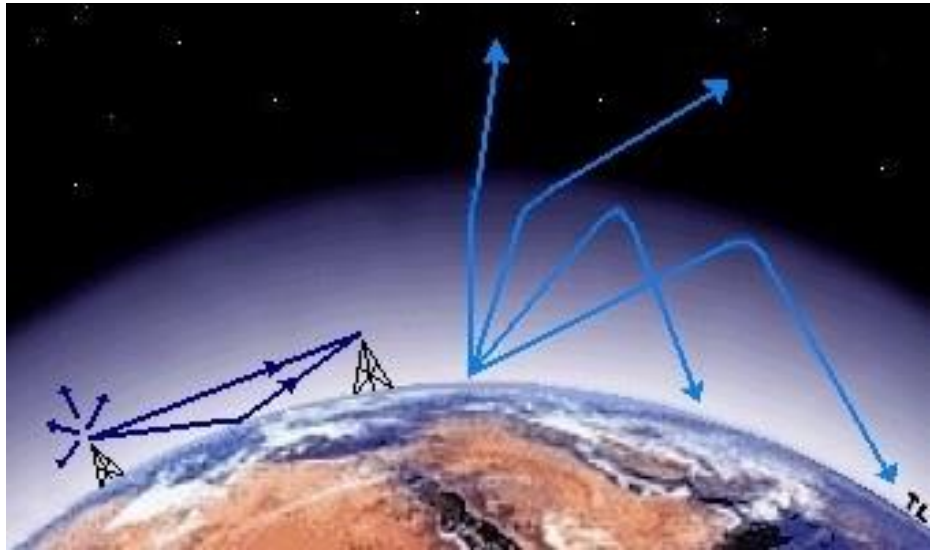
Amplitude change of VLF waves due to GRB enhanced ionization

Long-lasting pulse of high-energy radiation that swept over Earth on Sunday, Oct. 9.
The emission came from a gamma-ray burst (GRB) – the most powerful class of explosions in the universe.

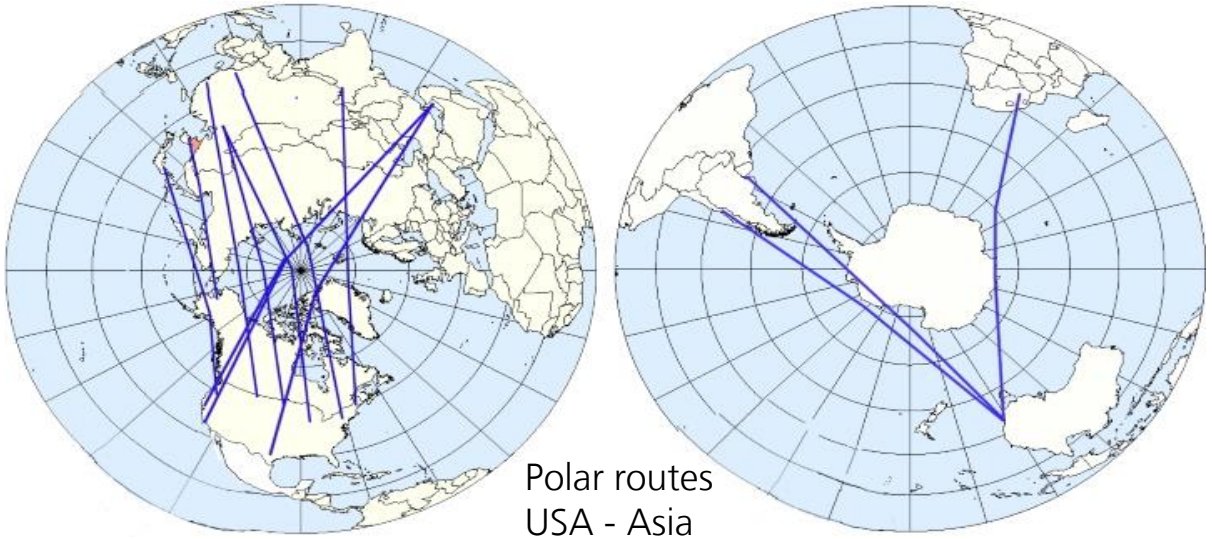


X ray light from GRB scattered by Milky Way dust
Credit: NASA/Swift/A. Beardmore (University of Leicester)

Space weather impact on terrestrial communication



- Radio waves at frequencies below 10 MHz are mostly reflected by the ionosphere
- Long distant propagation of waves possible, Maximum and Lowest usable frequency (MUF/LUF) information provided by HF services
- Solar flares and particle precipitation can prevent the ionosphere from reflecting radio waves (Short wave fadeout)

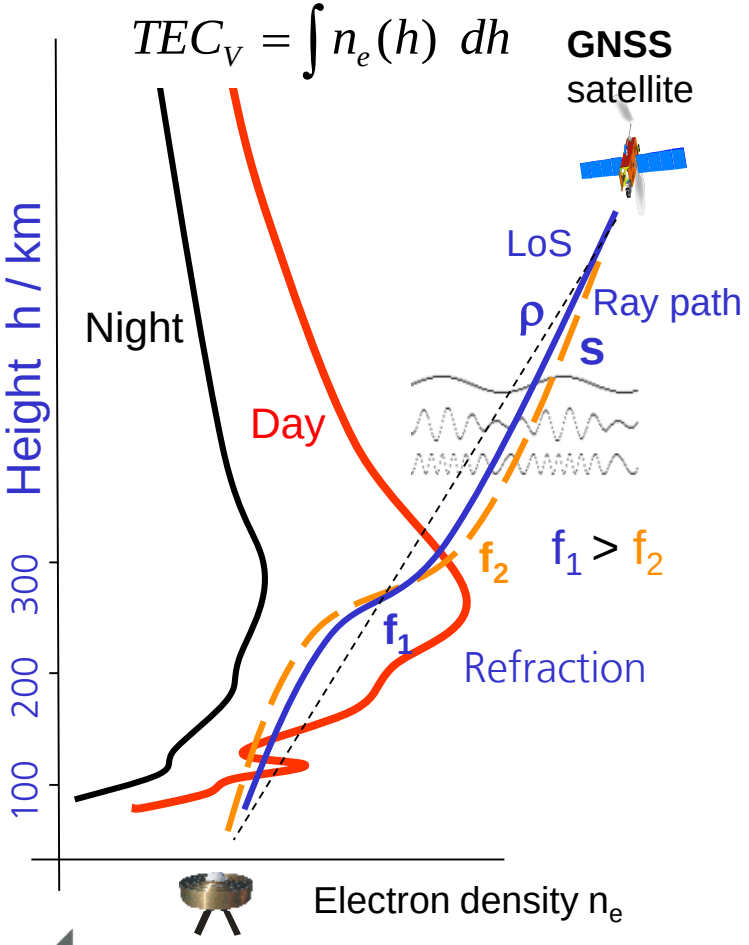


Source: Rolypolyman/Wikimedia Commons

- HF communication with airplanes may heavily be disturbed by ionospheric space weather effects (Fading, Blackout)
- Solar flares impact at day side preferrently at mid- to low latitudes
- Particle precipitation at high latitudes (aurora zone)
- Air traffic control in USA uses predictions concerning HF propagation risks from the Space Weather Prediction Center (SWPC) in Boulder / Colorado (NOAA scale)

Trans-ionospheric propagation of radio waves

Focus on ranging: Space based navigation and remote sensing



Refraction of radio waves transmitted by satellites of Global Navigation Satellite Systems (GNSS):

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

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

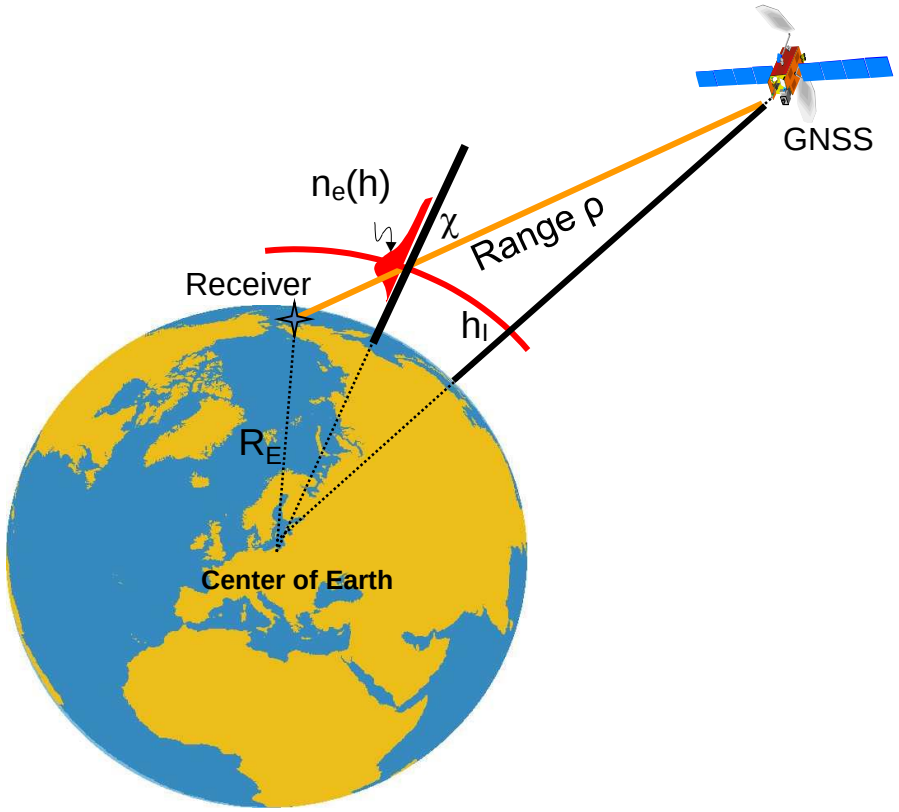
where n is the refractive index and the integral becomes a minimum according to Fermat's principle of fastest arrival.

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.

Observation equations of GNSS measurements



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

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

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

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

$$d_I \approx \frac{K}{f^2} \cdot STEC$$

Ionospheric first order range error depends on the Total Electron Content along the slant ray path (STEC)

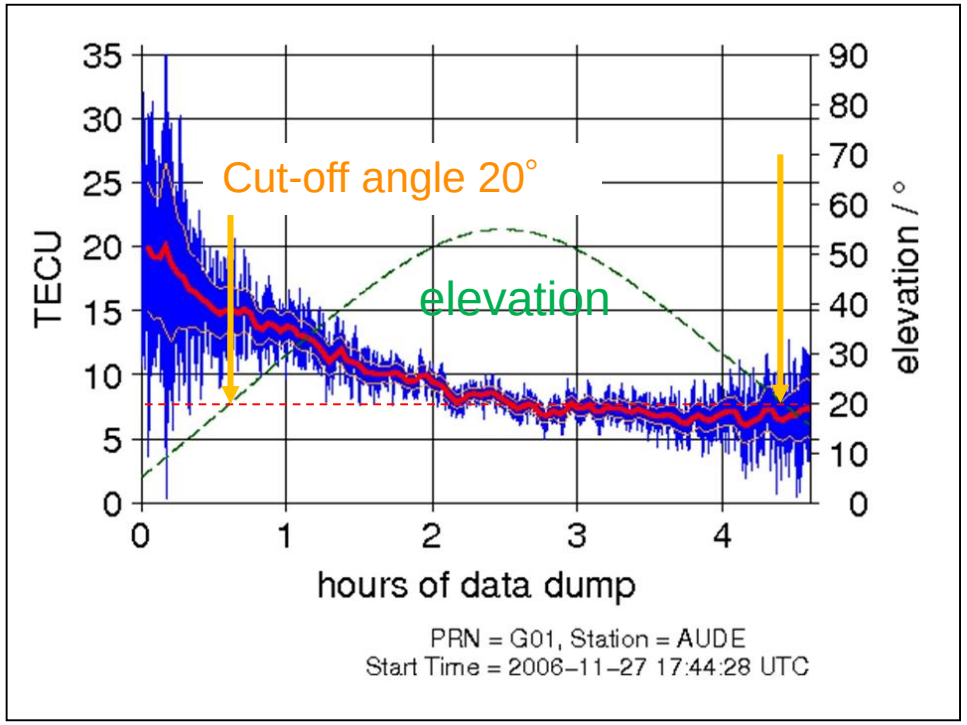
$$K = 40.3\ m^3 s^{-2}$$

d_I up to 100 m

Differential code phase allows correcting d_I

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

Computation of the Total Electron Content (TEC)



$$1\ TECU = 10^{16}\ electrons/m^2 \approx 0.16m\ at\ L_1\ frequency$$

$$P_2 - P_1 = \frac{K(f_1^2 - f_2^2)}{f_1^2 \cdot f_2^2} STEC + \varepsilon_{Poff}$$

$$\Phi_1 - \Phi_2 = \frac{K(f_1^2 - f_2^2)}{f_1^2 \cdot f_2^2} STEC + \varepsilon_{\Phi off}$$

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

GPS L_1=1575.42 MHz
L_2=1227.60 MHz

After levelling relative carrier phase differences into absolute uncalibrated code phase differences, subsequent TEC computation uses only carrier phases.

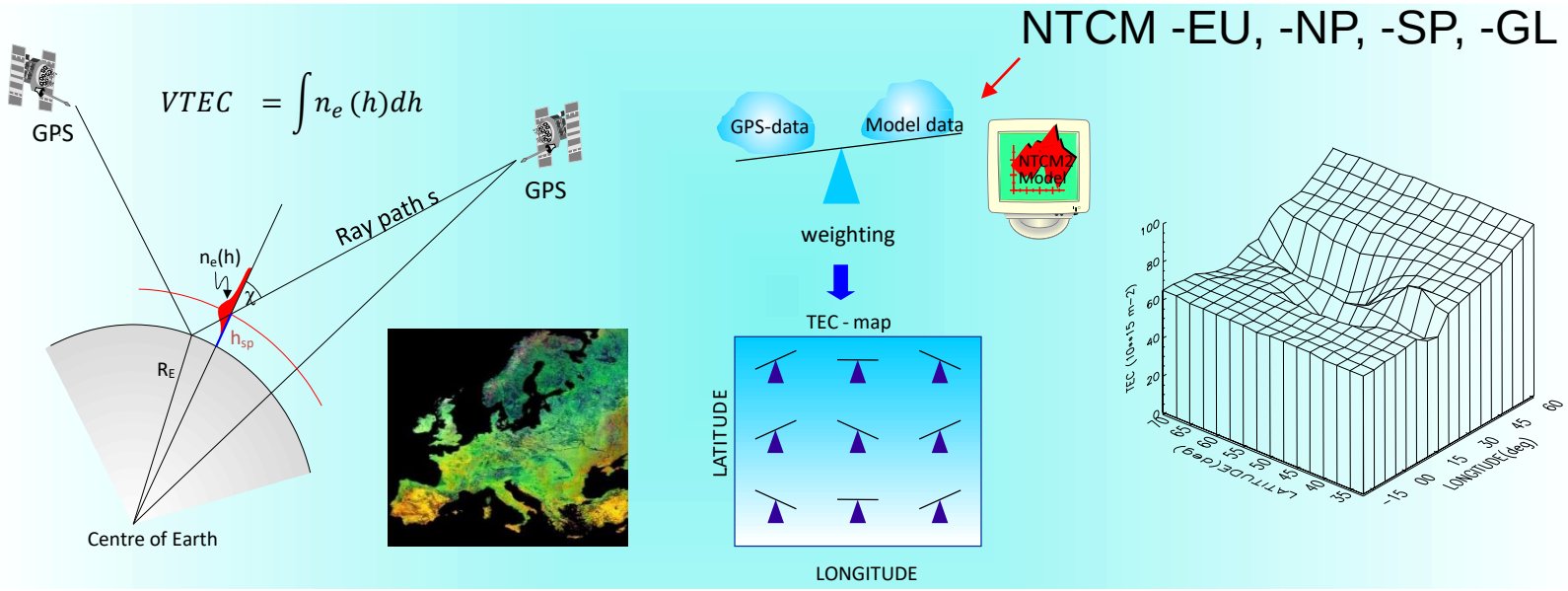
$$STEC = \frac{f_1^2 \cdot f_2^2}{K(f_1^2 - f_2^2)}(\Phi_1 - \Phi_2) + B + \varepsilon_N$$

Bias

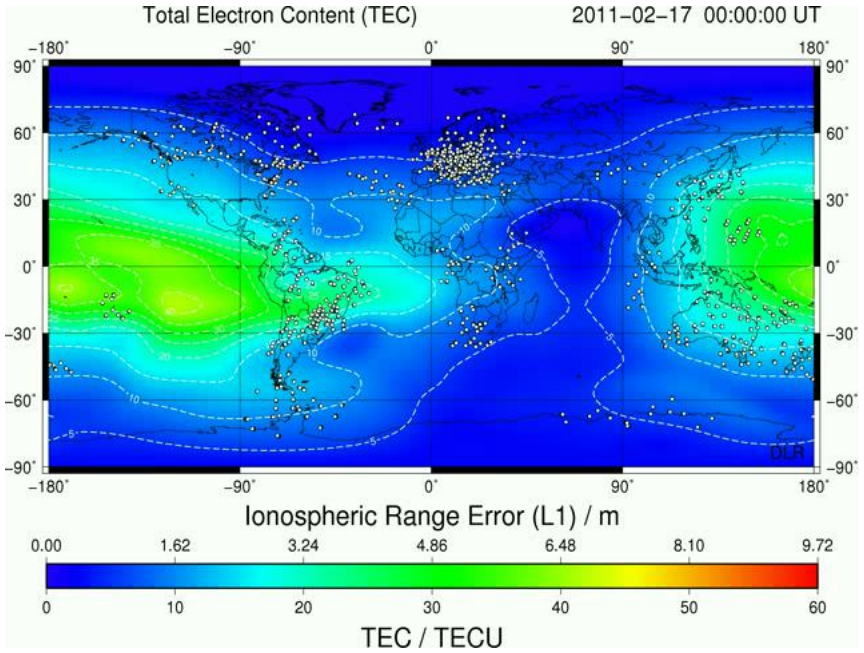
Jakowski, N. (1996). Modern Ionospheric Science, (Eds. H.Kohl, R. Rüster, K. Schlegel), EGS, Katlenburg-Lindau, ProduServ GmbH Verlagsservice, Berlin, pp 371-390

Jakowski, N. (2017). Ionosphere monitoring. In: Springer Handbook of Global Navigation Satellite Systems, Springer Verlag, 1139-1162. ISBN 978-3-319-4292926-7.

TEC monitoring for range error mitigation



Global TEC map



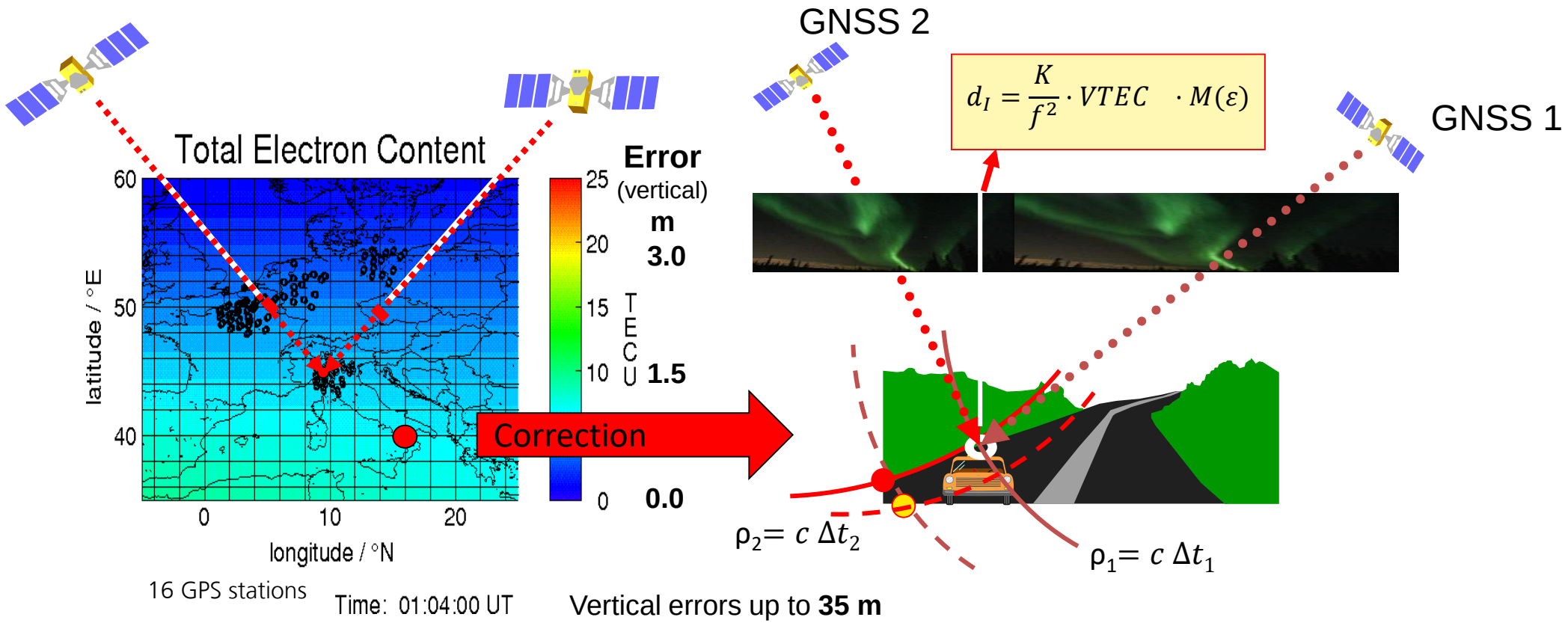
Measurement, Calibration	Conversion to vertical	Data assimilation into a regional/global TEC model	TEC- Map

Background model:
Neustrelitz **TEC** **M**odel (NTCM)

Jakowski, N., Modern Ionospheric Science, (Eds. H.Kohl, R. Rüster, K. Schlegel), EGS, Katlenburg-Lindau, ProduServ GmbH Verlagsservice, Berlin, pp 371-390,1996

Jakowski et al. (2011) A new global TEC model for estimating transionospheric radio wave propagation errors, Journal of Geodesy, 10.1007/s00190-011-0455-1

Ionospheric range error correction for single frequency GNSS by n.r.t. service



Vertical errors up to **35 m**

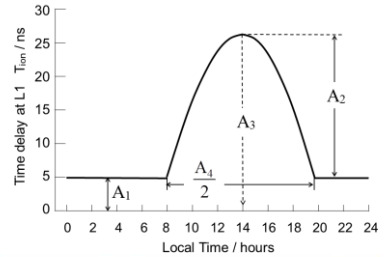
Near real time TEC monitoring data can be used for correcting single frequency GNSS measurements.
Data base provided by geodetic networks such as the International GNSS Service (IGS) and national networks.

Ionospheric error mitigation in single frequency applications by ionospheric models

GPS: **Klobuchar model** (ICA)

Klobuchar J. (1987) Ionospheric time-delay algorithm for single frequency GPS users. IEEE Trans Aerosp Electron Syst 23: 325–332.

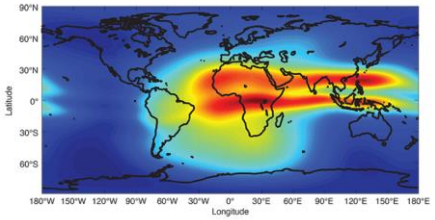
8 coefficients determine cosine type delay model of LT dependence
Coefficients updated every day.



Galileo: **NeQuick**

Nava B, Coisson P, Radicella SM (2008) A new version of the NeQuick ionosphere electron density model. J Atmos Terr Phys 70(15):1856–1862. https://doi.org/10.1016/j.jastp.2008.01.015

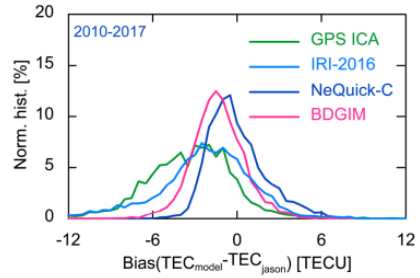
NeQuick 3D model of electron density, time consuming integration of electron density along ray paths.
Virtual solar activity from updated Az



Beidou: **BeiDou Global Ionospheric delay correction Model (BDGIM)**

Wang, N., Li, Z., Yuan, Y., Huo, X. (2021) Bei Dou Global Ionospheric delay correction Model (BDGIM), performance analysis during different levels of solar conditions GPS Solutions, 25:97, https://doi.org/10.1007/s10291-021-01125-y

BeiDou Spherical Harmonics model of TEC, 9 model parameters are routinely updated using ionospheric observation and transmitted to single-frequency GNSS.

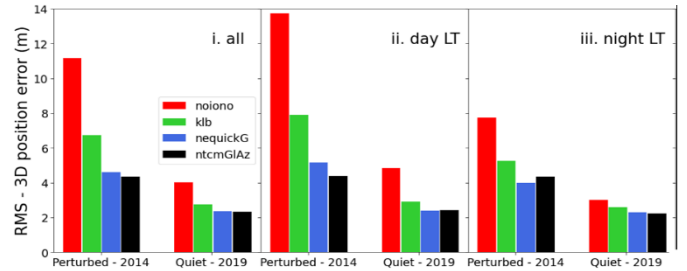


Galileo alternative:
Neustrelitz **TEC** **M**odel-**G**lobal (**NTCM-G**) recommended by European GNSS Service Center

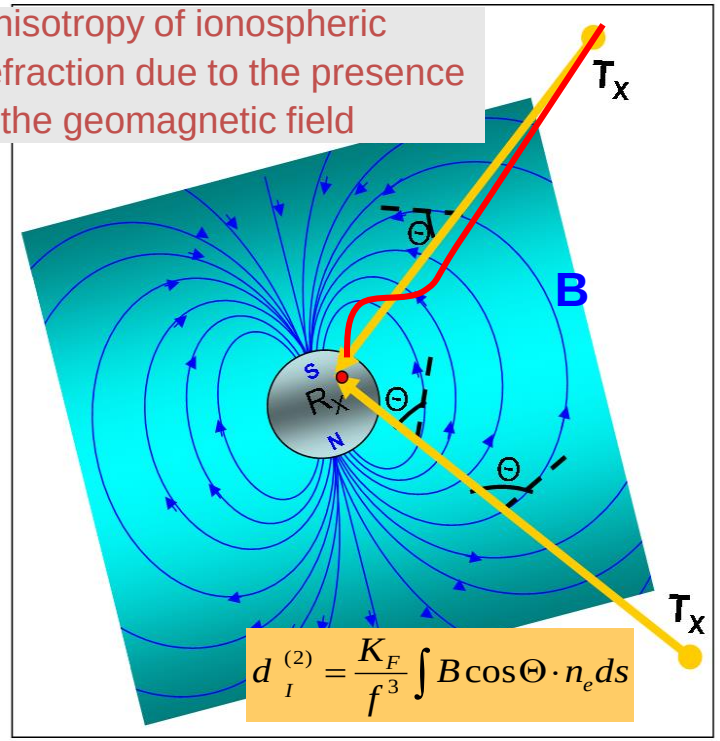
Hoque, M.M., Jakowski, N., Orús-Pérez, R. (2019) Fast ionospheric correction using Galileo Az coefficients and the NTCM model, GPS Solutions, 23:41, https://doi.org/10.1007/s10291-019-0833-3

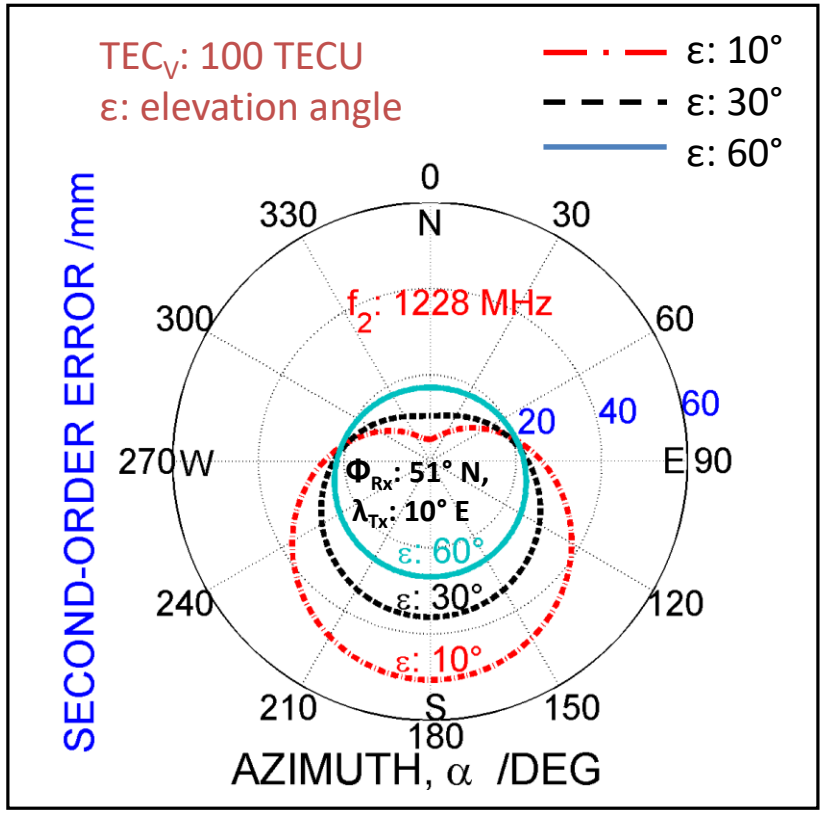
12 coefficients derived from NeQuick dedicated Az parameters.
Compared with NeQuick very fast TEC or delay estimates

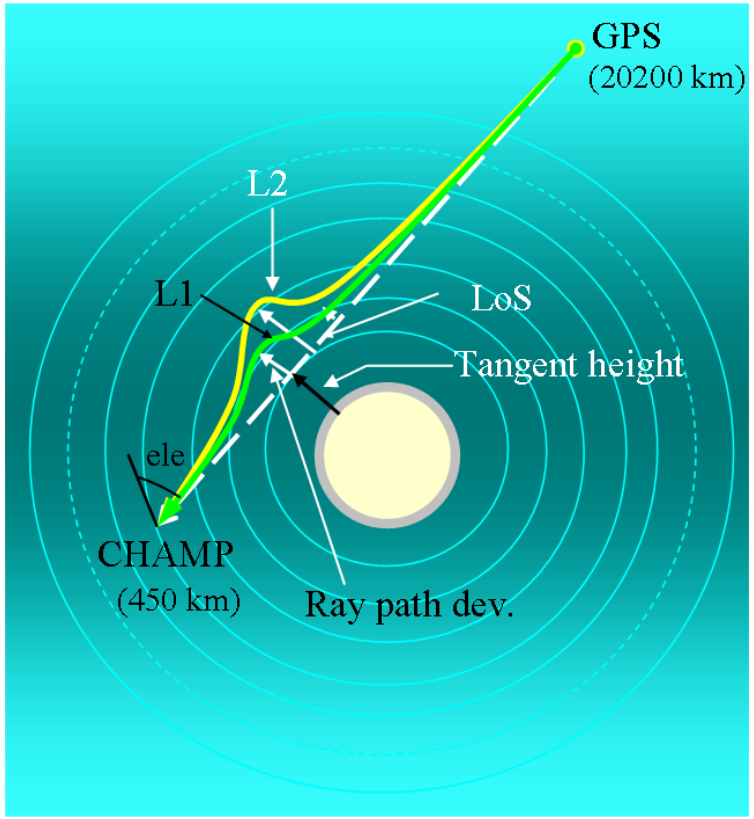
Accuracy of models < 80%



Higher order refraction effects







- **Second order refraction error (< 20 cm**) mostly ignored
- **Correction:** possible via semiempirical formulas taking into acount the regional link geometry

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

Ray path bending effect leads to an excess path length and error in tangential height estimation
(up to 1 km between L1 and L2 ray paths)

Ionosphere-free dual frequency linear combination

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

$$d_I \approx \frac{K}{f^2} \cdot STEC$$

$$\frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2 = \rho + \varepsilon_P$$

d_I mitigated but higher order errors not

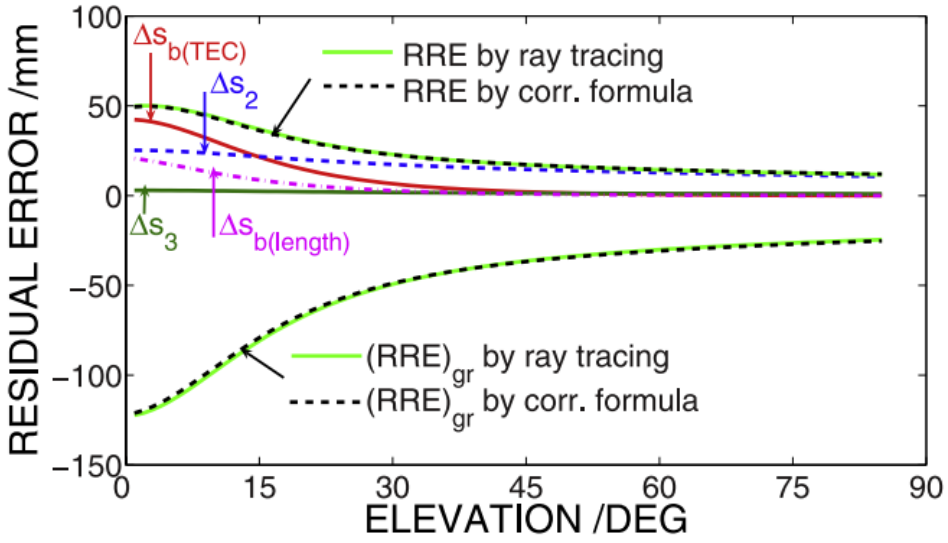
„Ionosphere-free“ linear combination of L1 and L2 frequencies

This linear combination of two frequencies is able to mitigate the ionospheric range error by more than 99%.

Highest accuracy is achieved in Differential GNSS networks utilzing carrier phases.

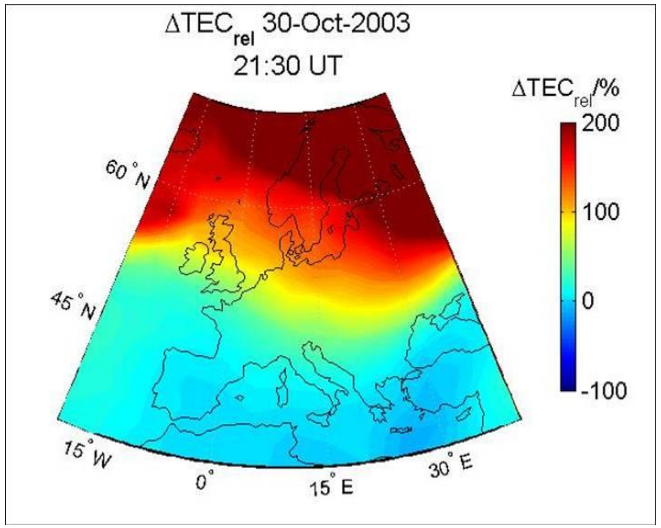
Dual frequency suffer in particular from ionospheric perturbations during ionospheric storms and from small scale plasma irregularities generating scintillations of amplitude and phase of radio waves.

Ionospheric residual range errors for GPS measurements.

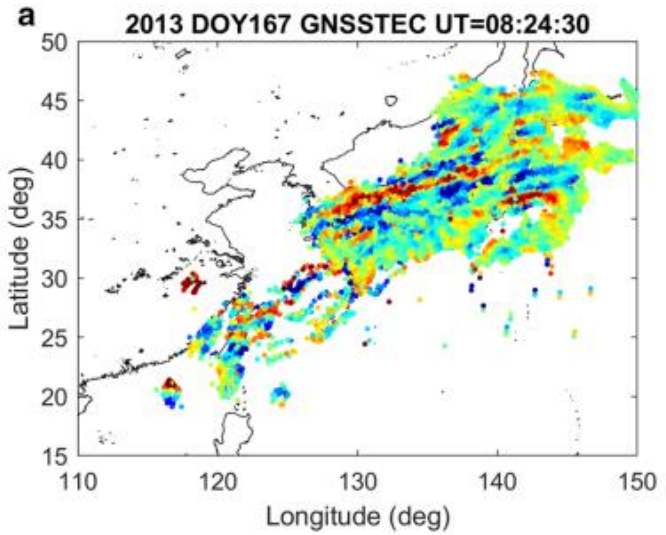


Hoque M. M. and N. Jakowski (2008), Estimate of higher order ionospheric errors in GNSS positioning, Radio Sci., 43, RS5008, doi: 10.1029/2007RS003817.

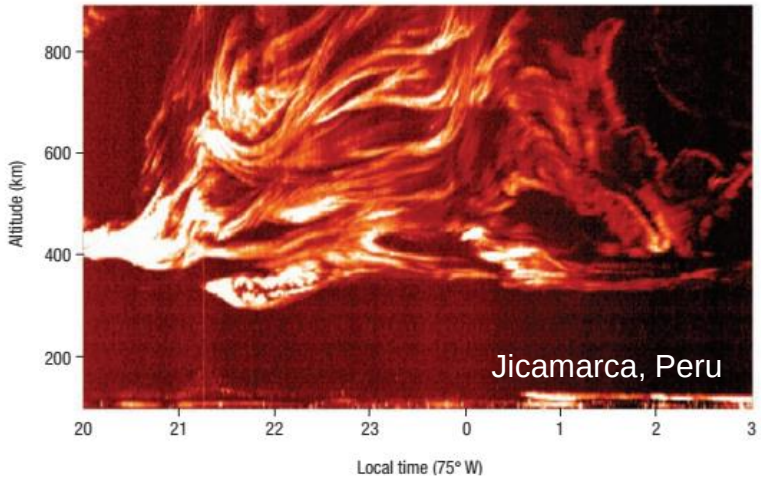
Ionospheric perturbation types impacting ionospheric radio wave propagation



N. Jakowski et al. (2012): J. Space Weather and Space Clim., 2, A22.



Cheng et al. Earth, Planets and Space (2021) 73:105 https://doi.org/10.1186/s40623-021-01432-1



M. Kelley (2008) nature geoscience | VOL 1 | FEBRUARY 2008 | www.nature.com/naturegeoscience

Large scale

Spatial/temp.scale: ≈1000 km/ hours
Amp.: up to 250 TECU, Velocity: ≈ 600 m/s
Moving ionization fronts, patches (LSTIDs)

Mid-scale

Spatial/temp. scale: ≈ 100-400km/min.
Amp.: < ≈ 1 TECU, Velocity: ≈100-250 m/s
Wavelike plasma motion (MSTIDs)

Small scale

Spatial/temp. scale: ≤ 10 km / seconds
signal fading 20dB, Velocity: ≈ 100-200 m/s
Plasma turbulences, instabilities

How to characterize ionospheric perturbations?
In analogy to characterizing solar and geomagnetic activity (e.g. by F10 or Kp) ionospheric perturbations may be characterized also by indices that describe effects of ionospheric perturbations statistically.

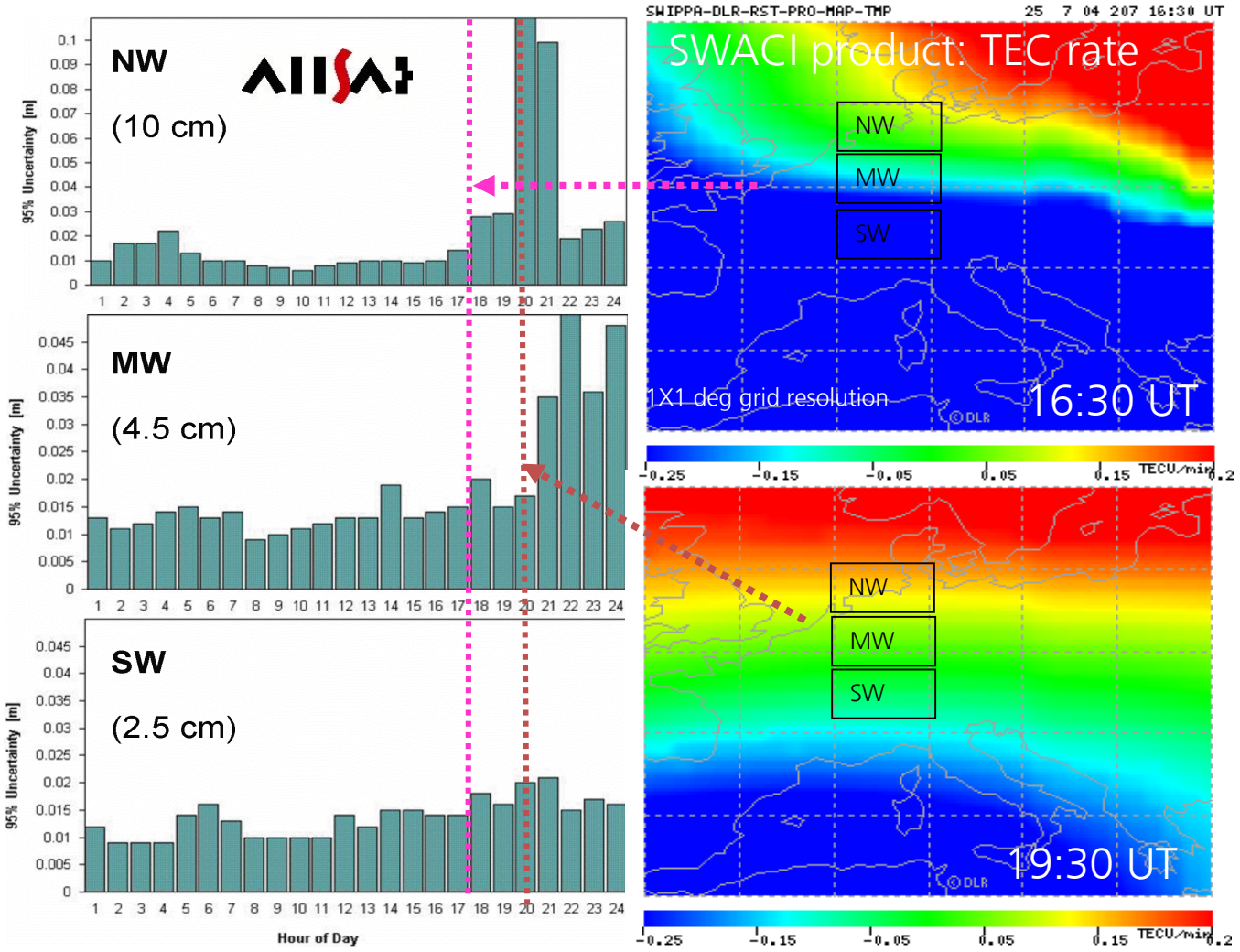
e.g.
S4, σ_ϕ , *ROT*, *ROTI*, *ΔTEC*, *GIX*, *SIDX*

Performance degradation of ascos GPS reference network (25 July 2004)

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

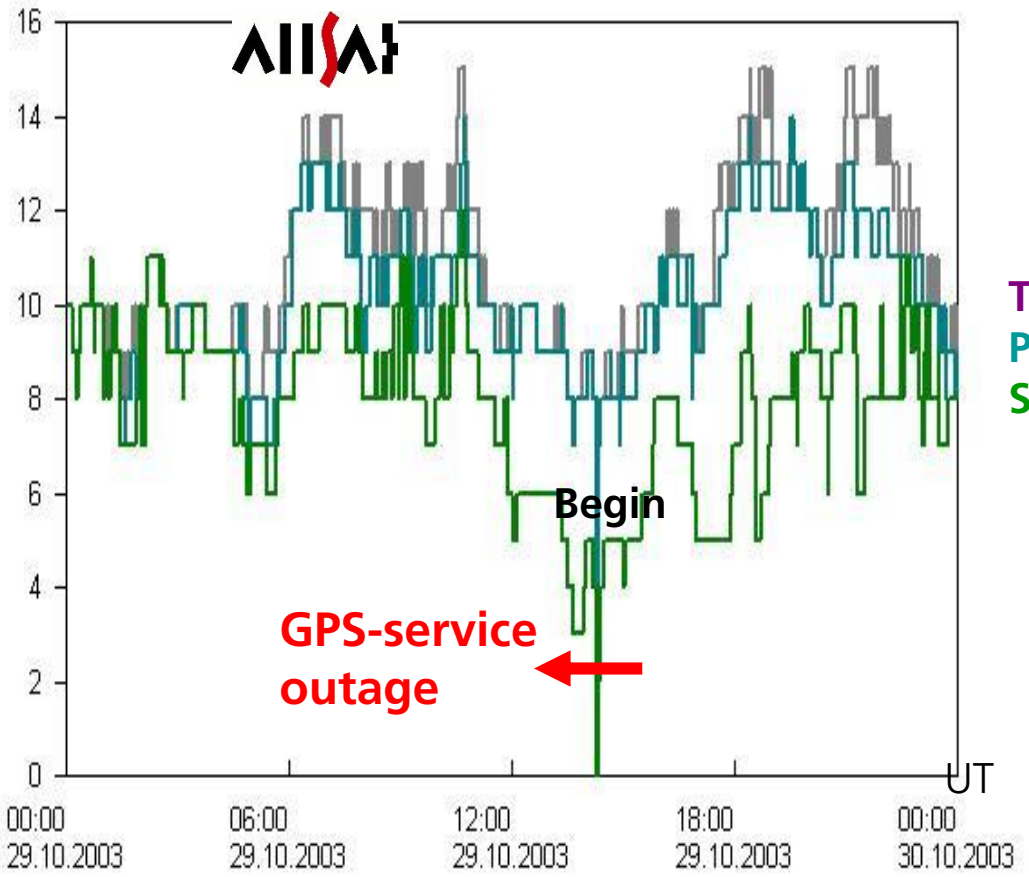
Different effects in different network areas over Germany

- 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



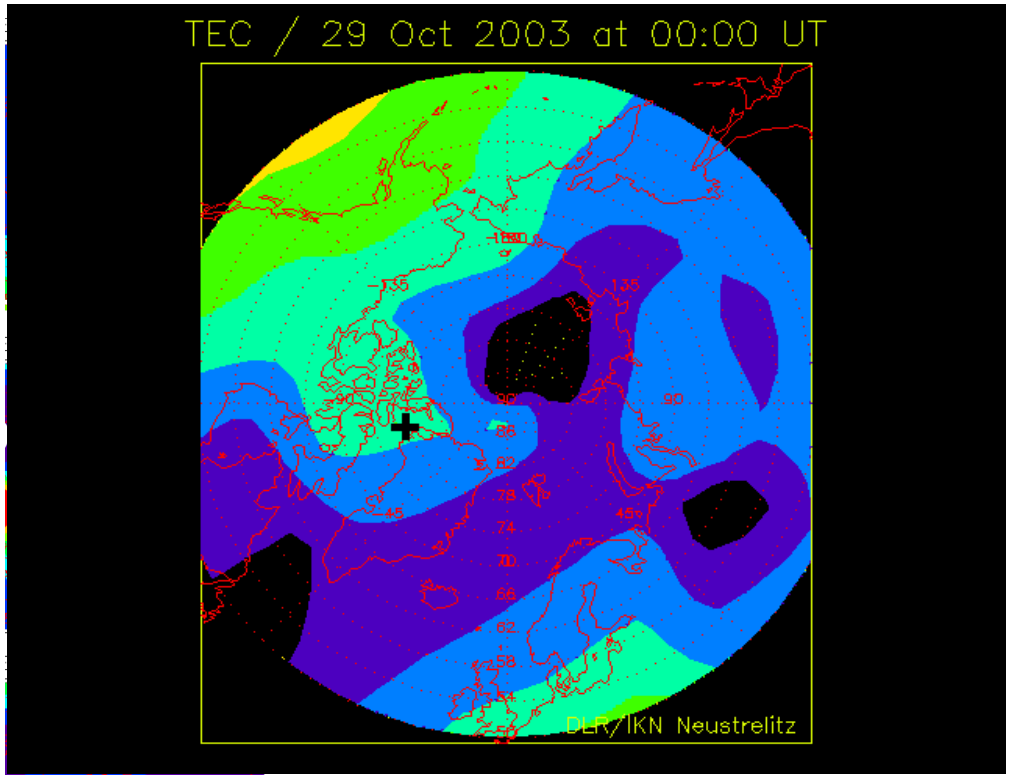
Geomagnetic / ionospheric storm on October 29, 2003

Performance of the ascos reference network

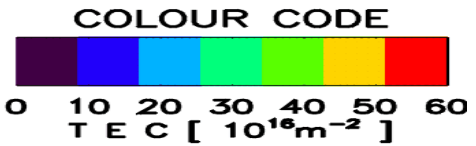


Tracked
Processed
Solved

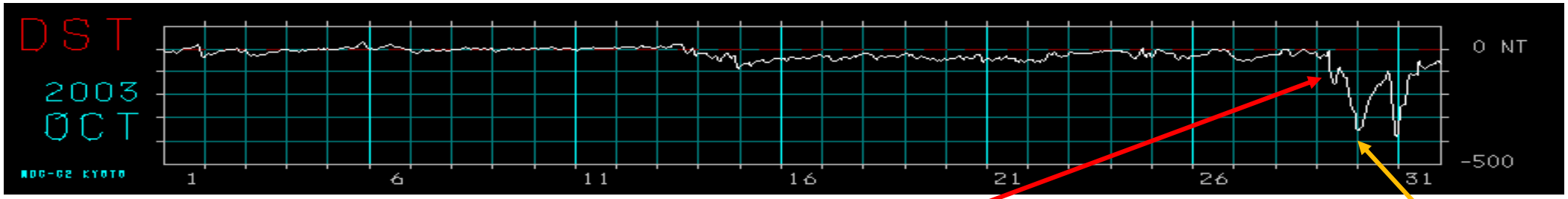
Polar TEC map

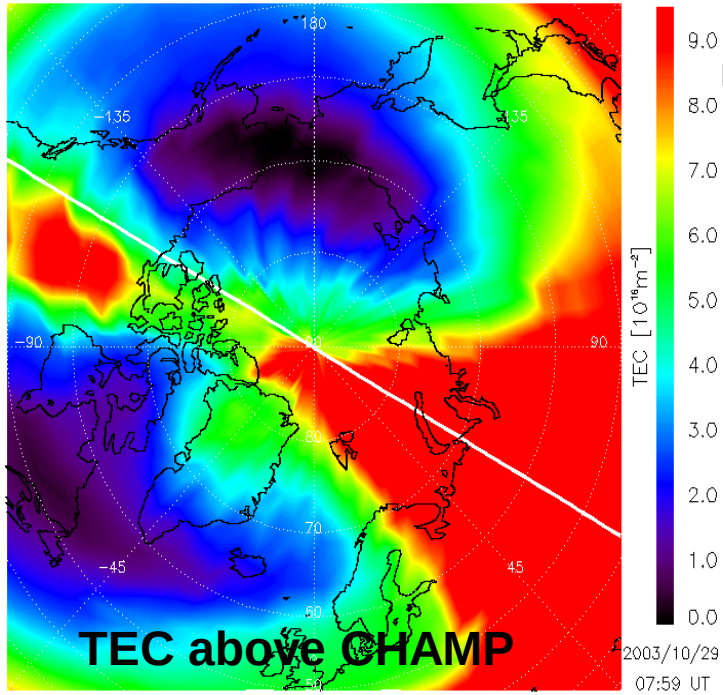


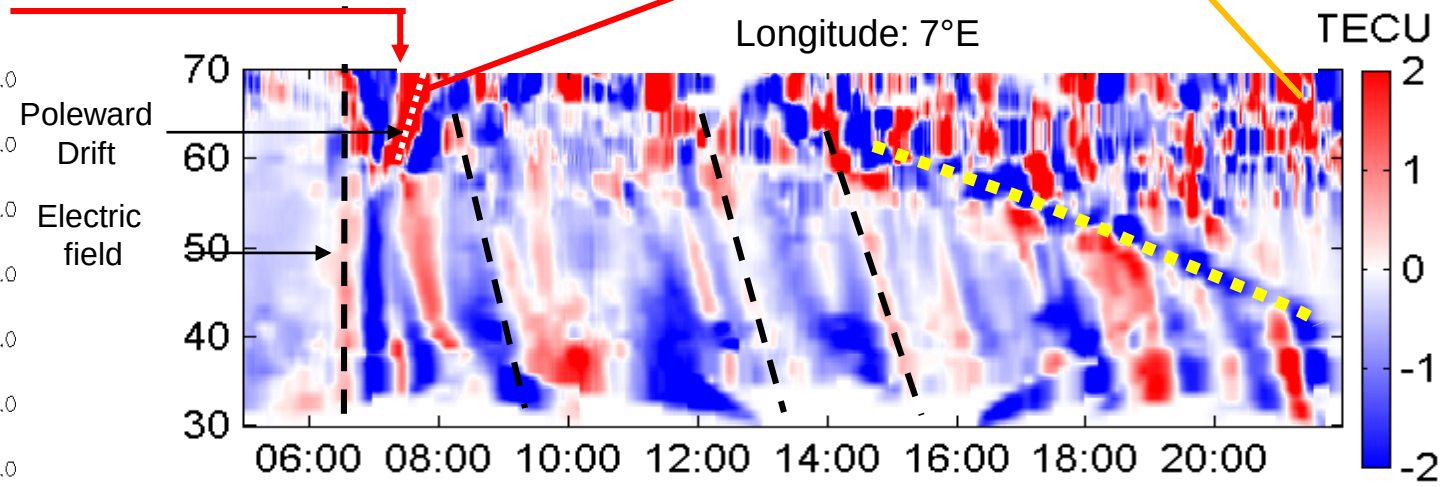
ΔTEC=10min



Ionospheric storm generation and propagation



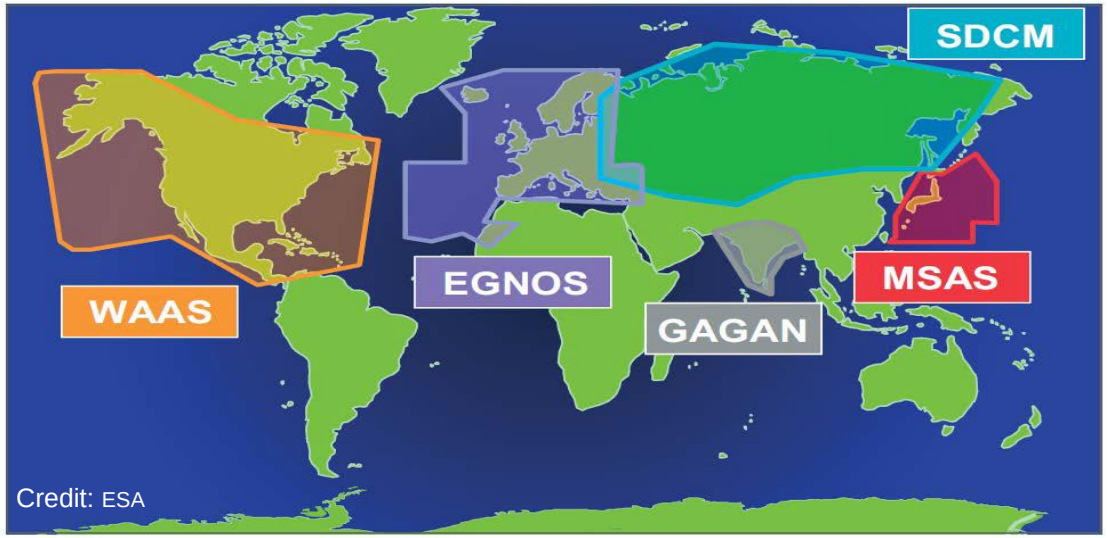




- Immediate response at all latitudes at storm onset
- Tongue of ionization across the Pole
- Wavelike propagation of disturbances during the main phase
- High latitude disturbance zone (northward of the trough) moves equatorward

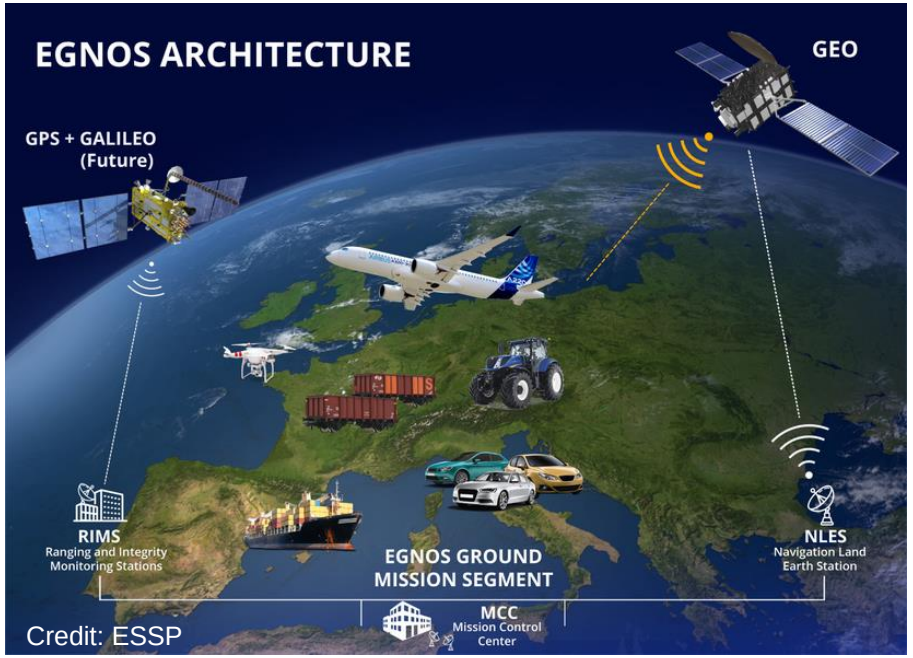
Jakowski, et al. (2012). Monitoring, tracking and forecasting ionospheric perturbations using GNSS techniques, J. Space Weather Space Clim. 2 (2012) A22, DOI:10.1051/swsc/2012022

Space Based Augmentation Systems (SBAS) in aviation



ESSP
WE COMMIT TO SAFE AND CONNECTED WORLDS

European Satellite Services Provider



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

Ground and space based augmentation systems (GBAS/SBAS) are needed to provide ionospheric range error corrections to airplanes.

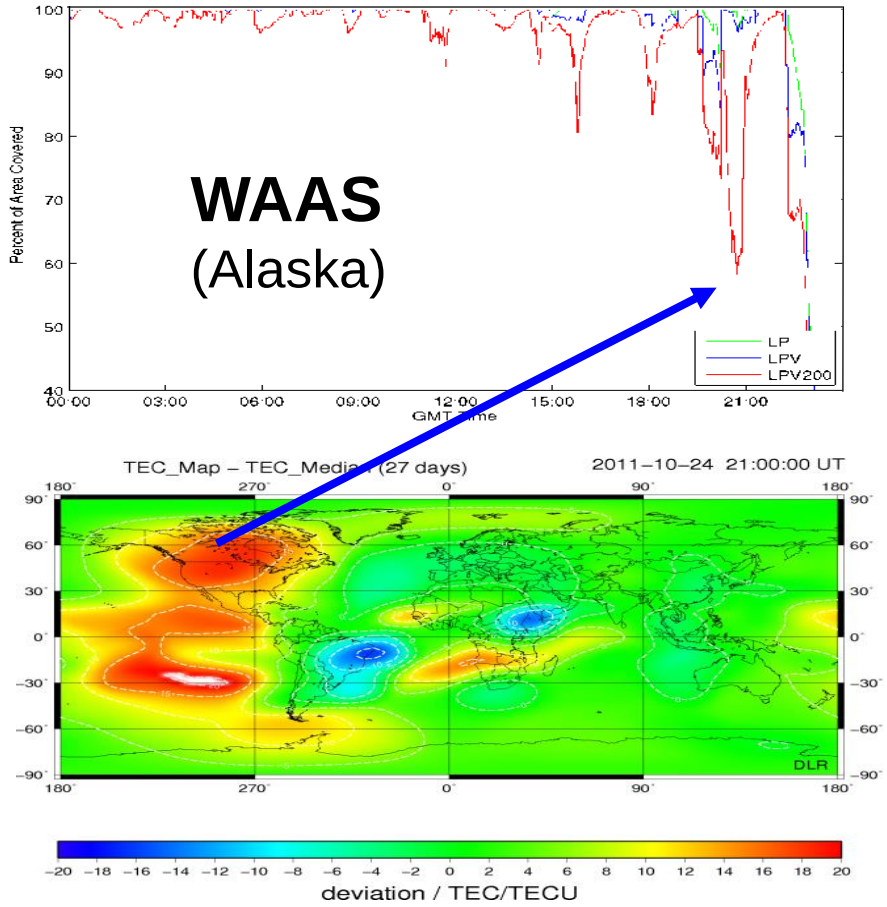
Airplane navigation systems are allowed to use only the certified L1 GPS frequency.

Implemented correction models are not reliable.

DLR

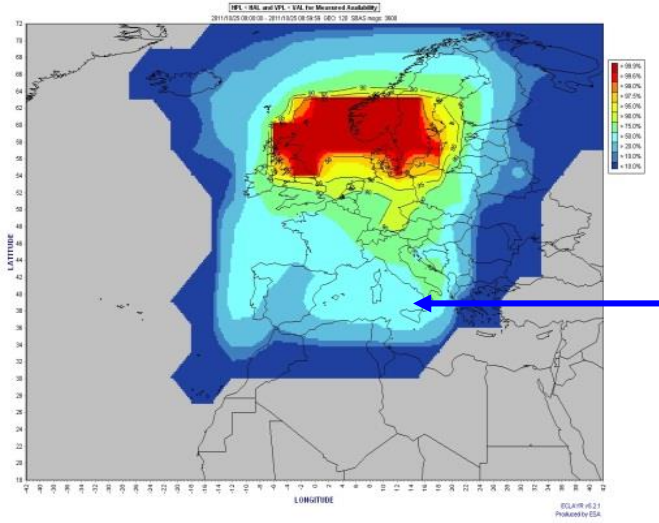
Ionospheric impact on SBAS (WAAS/EGNOS) on 24/25 October 2011

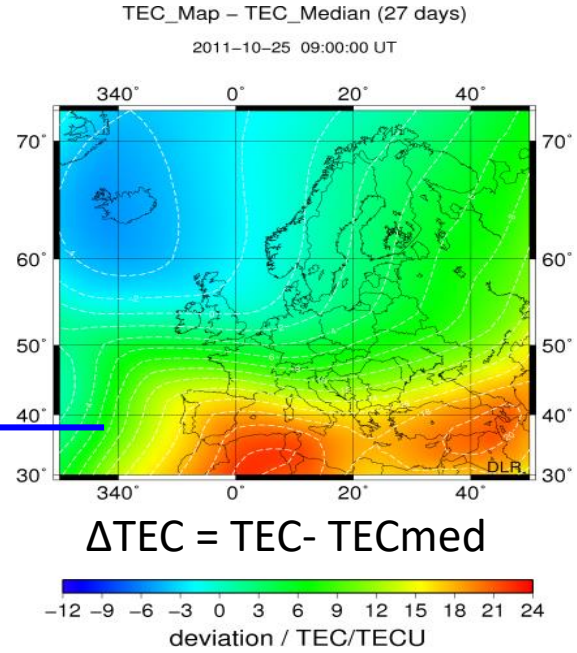
24/10/2011 - 21:00 UT



25/10/2011 - 09:00UT

EGNOS



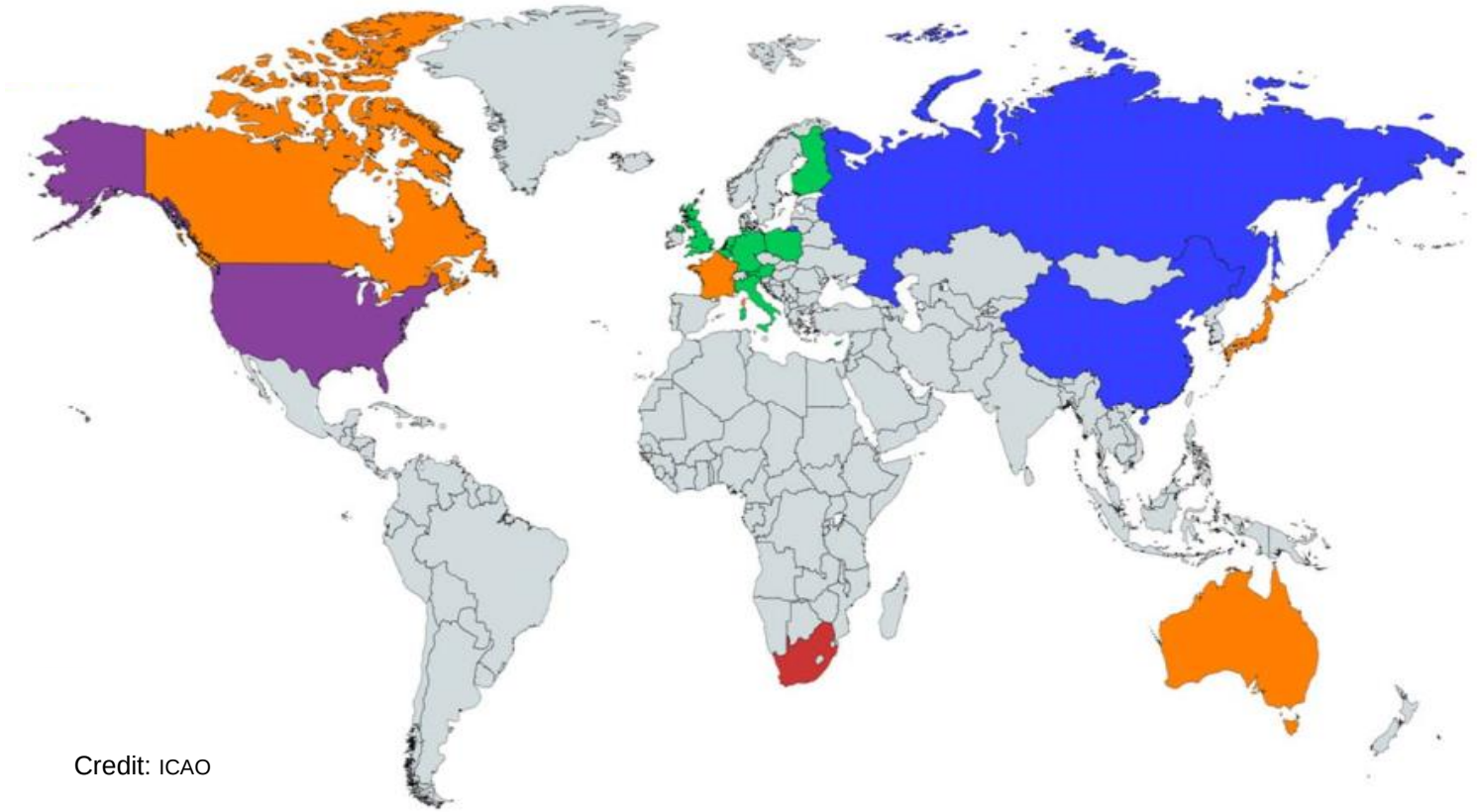


ΔTEC = TEC- TECmed

Ionospheric storm on October 25, 2011 causes strong deviations of TEC from average values (27 medians)

Performance of space based augmentation systems such as WAAS und EGNOS is strongly affected by ionospheric perturbations during the ionospheric storm.

Designated ICAO Space Weather Centers



Credit: ICAO

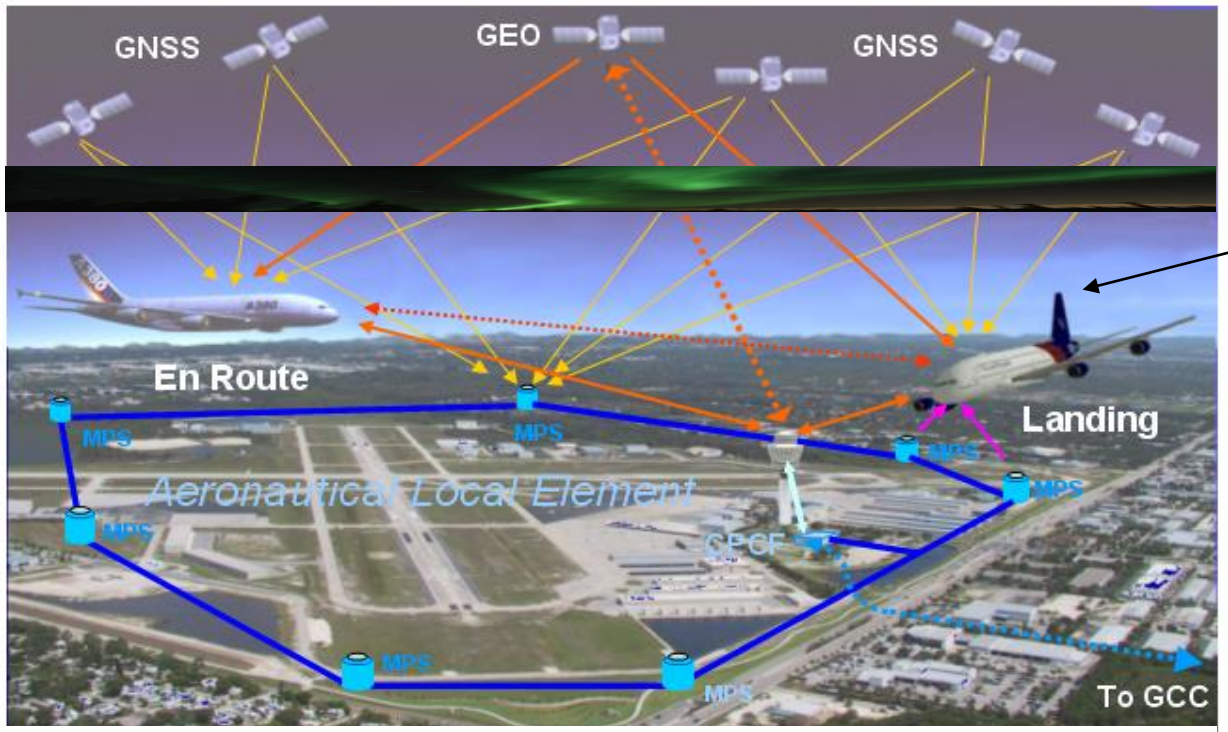
- PECASUS (European consortium)
- ACFJ (Australia, Canada, France, Japan)
- NOAA SWPC (United States)
- China/Russia Consortium

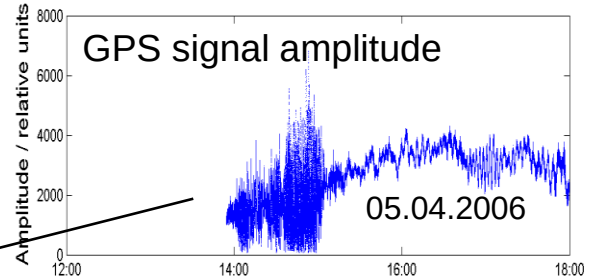
Regional - South Africa

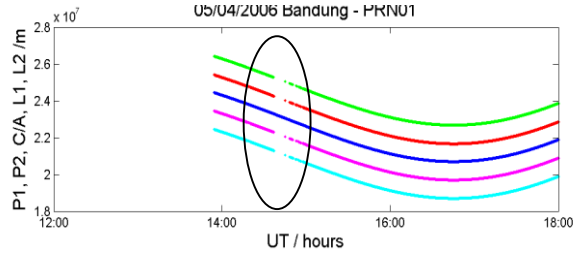
Tasks:
Development of specific space weather services relevant to aviation
Nowcasting and forecasting capabilities

SW impact on
- HF communication
- GNSS navigation
- Radiation exposition at flights

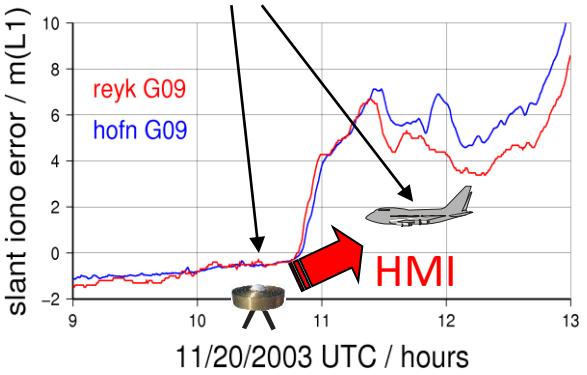
Ionospheric impact on GBAS - Safety of Life (SoL) application







GPS- signal loss



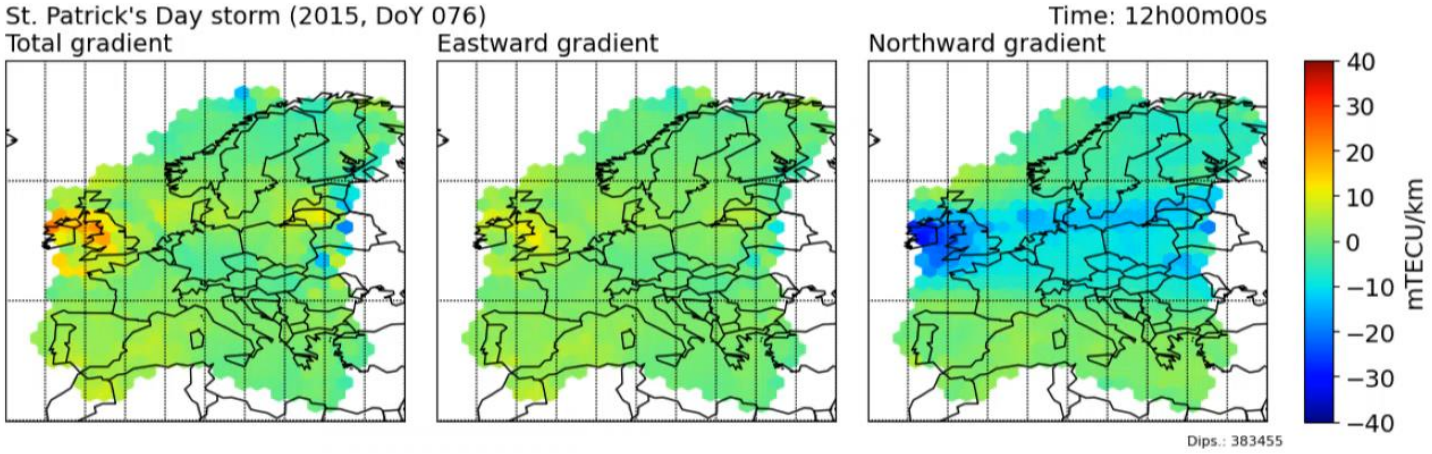
HMI:
Hazardous
Misleading
Information

- Degradation of accuracy, integrity, availability and continuity of signals due to space weather events
- HF Communication disturbed or interrupted

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

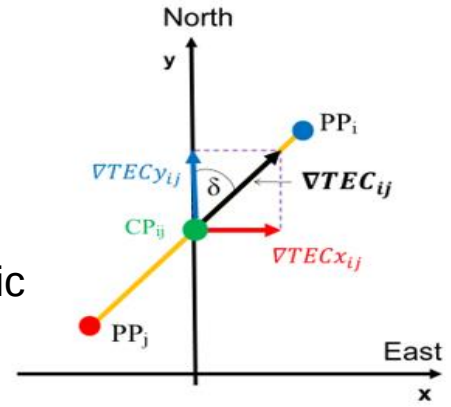
Mayer, C. et al. (2009) Ionosphere Threat Space Model Assessment for GBAS. ION GNSS 2009, 22.-25. Sep. 2009, Savannah, GA, USA.

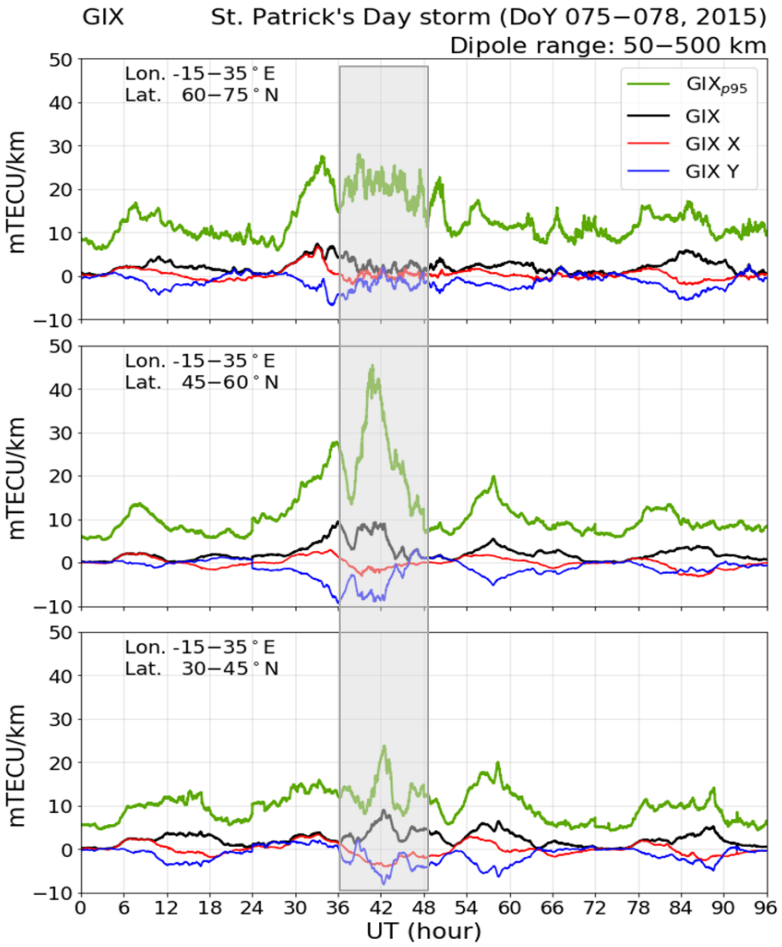
TEC gradients (GIX) over Europe during the St. Patrick's Day storm March 2015



- Spatial gradients calculated with a sample of 831 GNSS stations
- Time resolution of 30 s
- Dipole length ranges between 50 and 1000 km

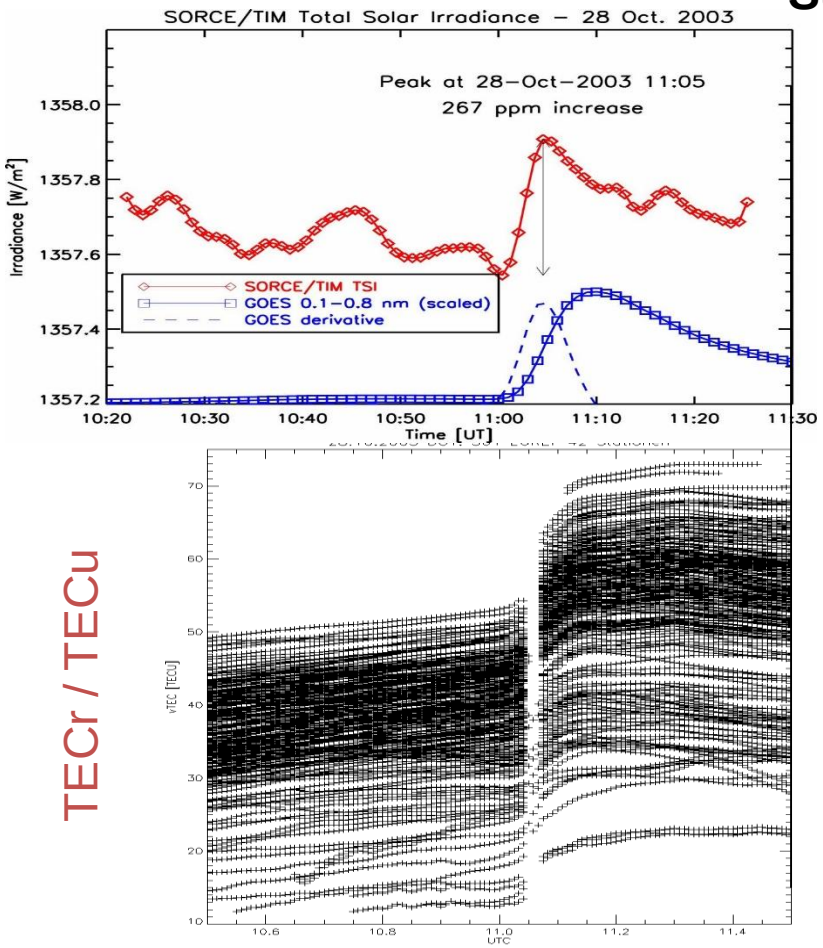
- TEC gradient between ionospheric piercing points PP_i and PP_j
- Averaging over all PPs at each epoch possible, i.e., instantaneous characterisation of ionospheric perturbation degree possible.





Cahuasqui et al. (2022). Regional characterization of ionospheric perturbations degree with GIX and SIDX, 44th COSPAR Scientific Assembly, 16-24 Jul 2022, Athens, Greece.

Space Weather Impact on GNSS – Solar Flare (SIDX)



Sudden **I**onospheric **D**isturbance inde**X** (SIDX)

- SIDX – Basic approach:
  Average rate of TEC of all PP
  in a selected area
- SIDX response to solar flares may differ from X ray classification due to spectral dependence of ionization

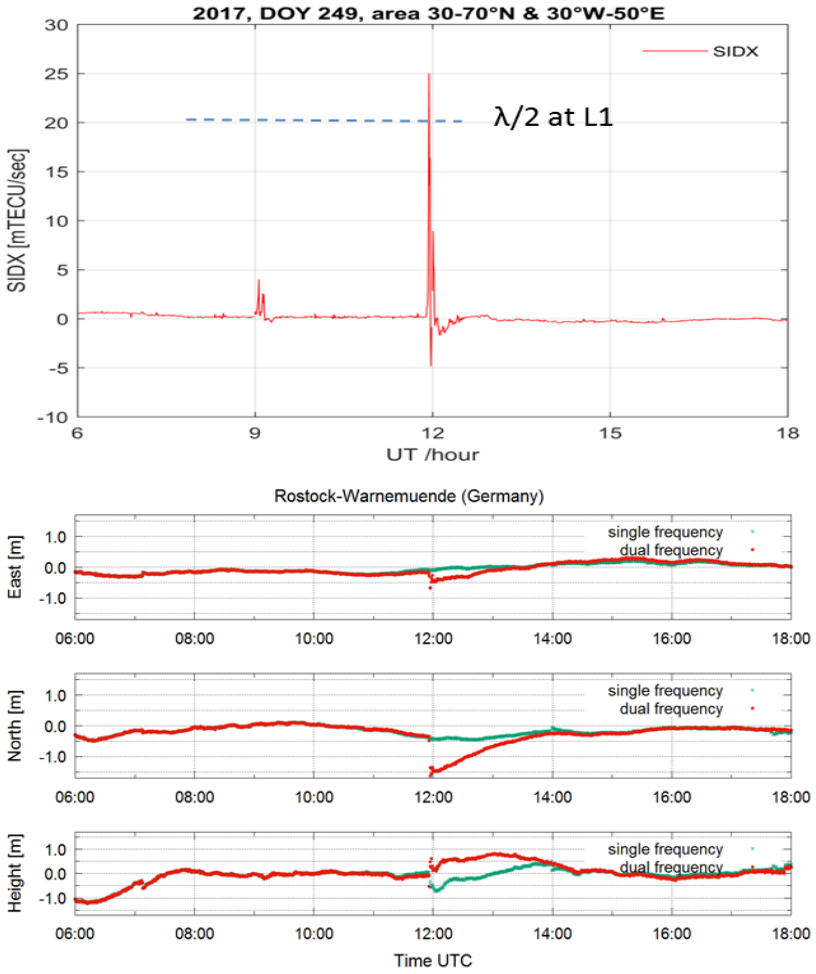
$$\frac{\partial TEC}{\partial t} = \frac{\Delta STEC}{M\,\Delta t} - \frac{\partial TEC}{\partial u} v$$

$$\langle \frac{\partial TEC}{\partial t} \rangle \approx \frac{1}{N} \sum_{i=1}^{N} \left(\frac{\Delta STEC}{M\,\Delta t} \right)_i$$

$$\boldsymbol{SIDX} = \langle \frac{\boldsymbol{\partial TEC}}{\boldsymbol{\partial t}} \rangle$$

$$\boldsymbol{SIDXS} = \sqrt[2]{(\langle \frac{\boldsymbol{\partial TEC^2}}{\boldsymbol{\partial t}} \rangle - \left\langle \frac{\boldsymbol{\partial TEC}}{\boldsymbol{\partial t}} \right\rangle^{\boldsymbol{2}})}$$

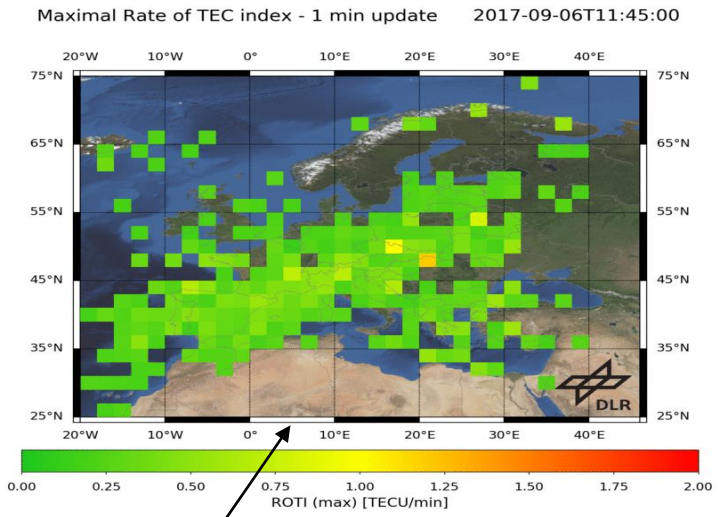
SIDX

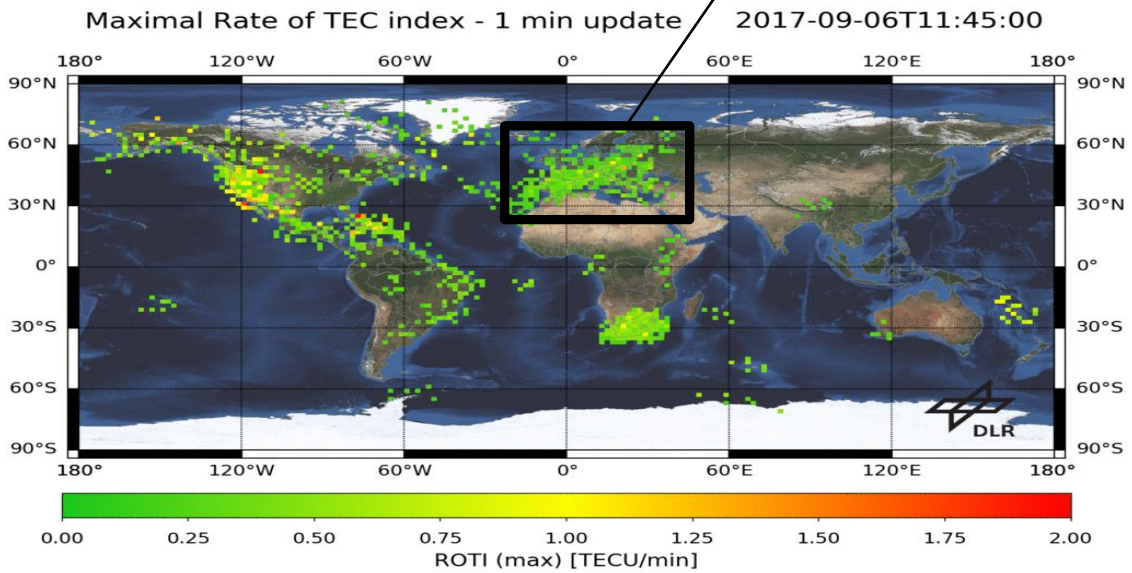


Space Weather Impact on GNSS – Solar Flare (ROTI)

Solar Flare X9.3
on September 6, 2017
at 11:53 UT

Real time ROTI at
impc.dlr.de





Rate **O**f **T**EC **I**ndex (ROTI)

ROTI and many other indices are currently used to describe ionospheric perturbations for comparative studies e.g. with geomagnetic indices or positioning results.

The NOAA space weather scales G, S, R do not include a scale that addresses explicitely **trans-ionospheric radio wave propagation**.

Considering the broad utilization of space based radio systems like GNSS, an internationally well accepted space weather scale is urgenty needed.

The International Space Weather Action Team (ISWAT) initiated by COSPAR addresses many space weather topics.

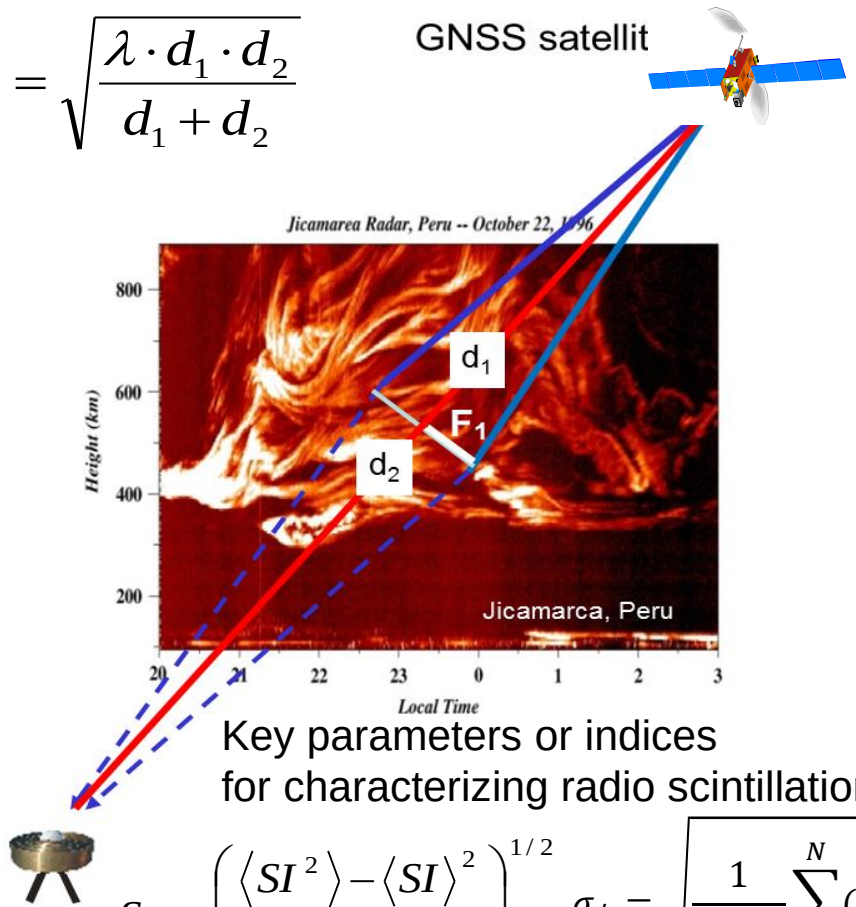
In **ISWAT G2B-04** we address the topic:
„Ionospheric perturbation indices and scales“
(https://iswat-cospar.org/G2B-04)

New team members supporting this action are welcome!

Diffraction effects due to small scale electron density irregularities

1st Fresnel zone

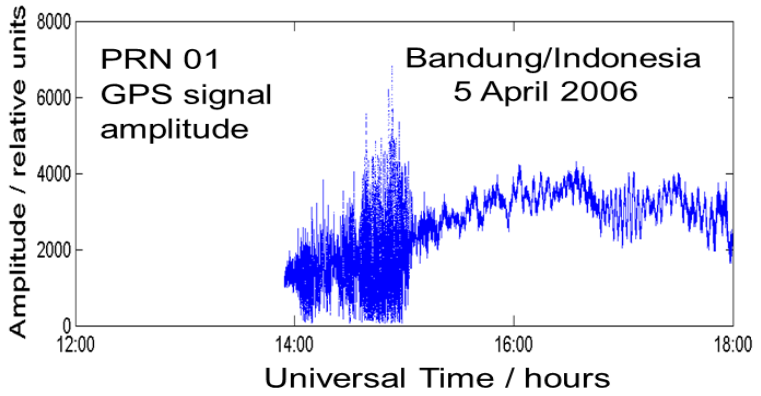
$$F_1 = \sqrt{\frac{\lambda \cdot d_1 \cdot d_2}{d_1 + d_2}}$$

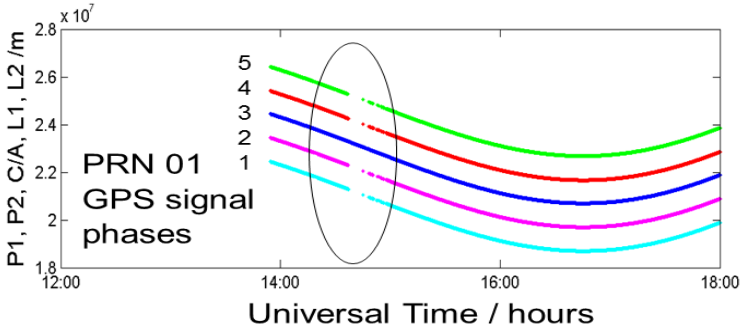


Key parameters or indices
for characterizing radio scintillations

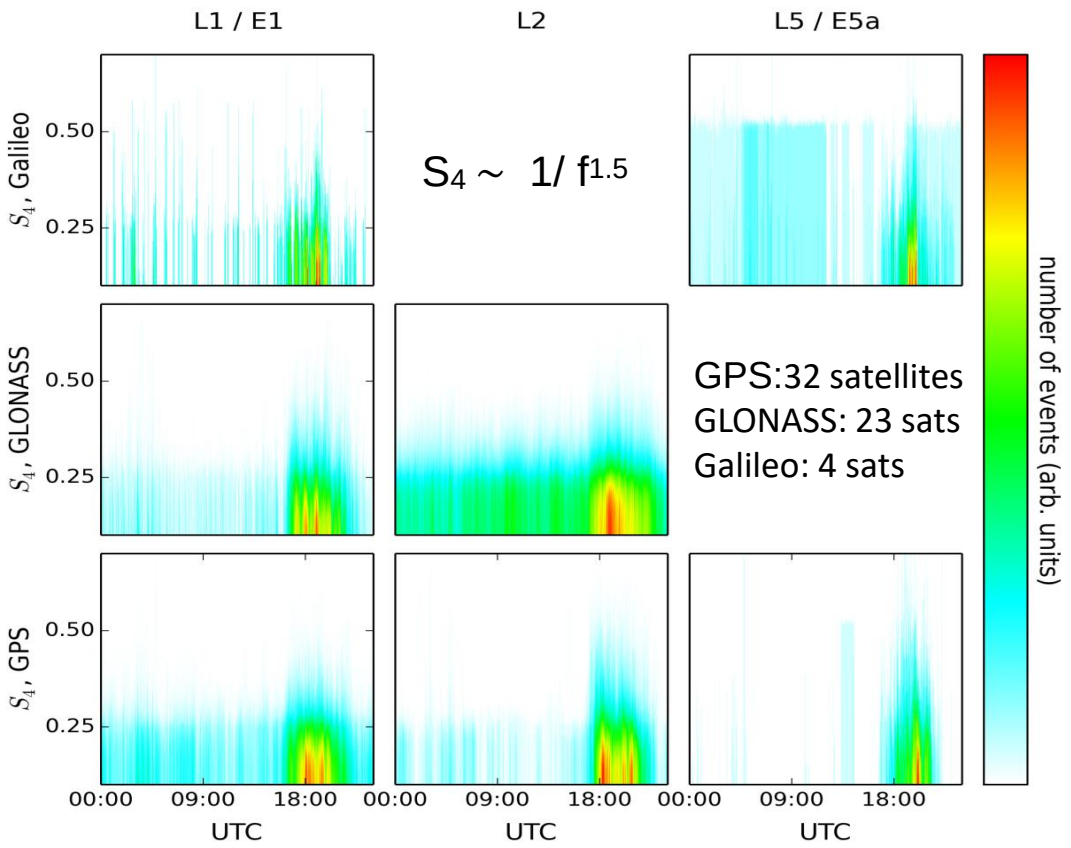
$$S_4 = \left(\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2} \right)^{1/2} \qquad \sigma_\phi = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (\phi_i - \langle \phi \rangle)^2}$$

- Diffraction and forward scattering of radio waves at small scale ionosperic irregularities may cause strong amplitude and phase fluctuations at ground receivers called: **radio scintillations**



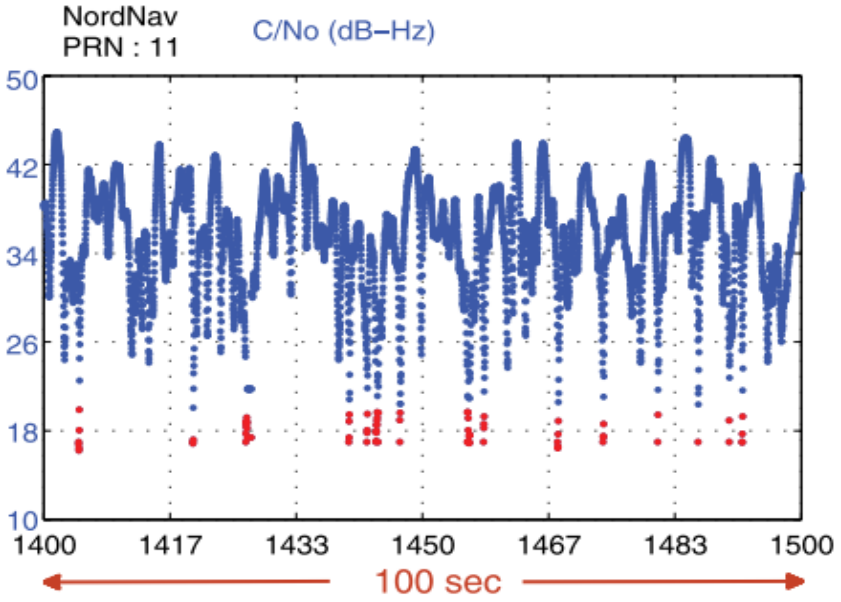


Impact of radio scintillations on GNSS



All GNSS are affected but in different way.

Hlubek, N. et al. (2014). Scintillations of the GPS, GLONASS, and Galileo signals at equatorial latitude. Journal of Space Weather and Space Climate, 4, A22. https://doi.org/10.1051/swsc/2014020

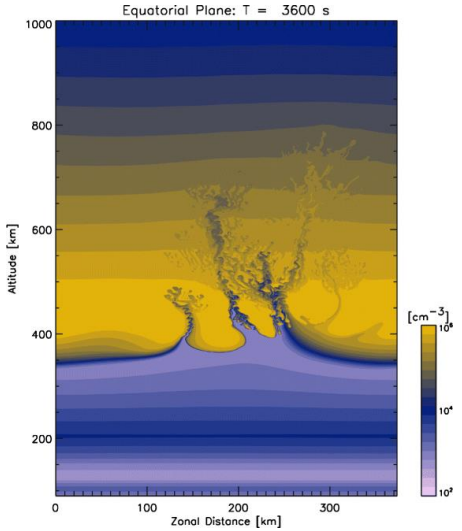


Example of deep signal fades. < 20 dB red

- enhanced noise level
- cycle slips
- loss of lock

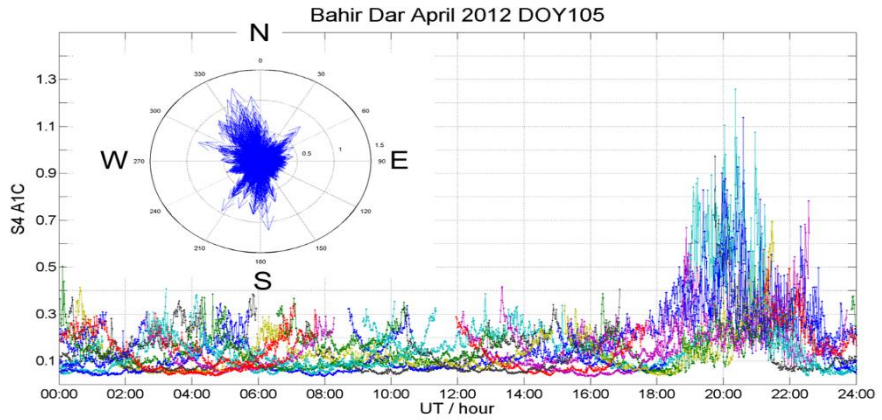
Seo, J. et al. (2009), Characteristics of deep GPS signal fading due to ionospheric scintillation for aviation receiver design, Radio Sci., 44, RS0A16, doi:10.1029/2008RS004077.

Scintillation effects – geophysical relationships



HIRB model

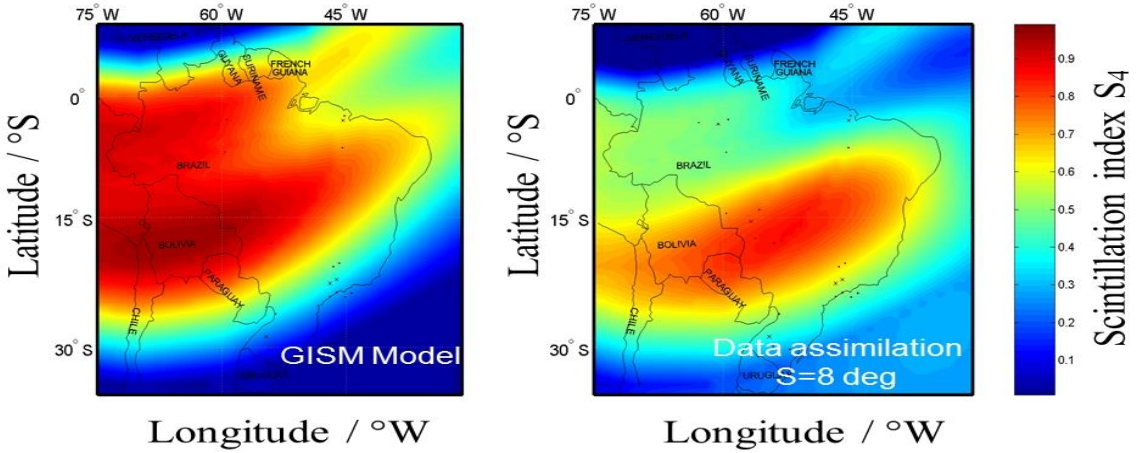
Yokoyama (2017) A review on the numerical simulation of equatorial plasma bubbles toward scintillation evaluation and forecasting, Progress in Earth and Planetary Science (2017) 4:37
DOI 10.1186/s40645-017-0153-6



Mersha et al. (2021). On the Relationship between Low Latitude Scintillation Onset and Sunset Terminator over Africa. Remote Sens, 13, 2087. https://doi.org/10.3390/rs13112087

Knowledge of physics and occurrence probability as a function of local time and location can help to mitigate scintillation impact on positioning and navigation, e.g. by forecasting.

Scintillation maps over Brazil on January 11, 2002
Left: GISM model right: GISM + S4 measurements



Scintillation maps describing the occurrence of scintillation over the user region allow rejecting measurements with ionospheric PPs located in an area with strong scintillation activity. Selection of other satellites with low scintillation activity for positioning.

However: scintillation receivers are costly and rare.

Jakowski, N. (2017) Ionosphere monitoring. In: Springer Handbook of Global Navigation Satellite Systems, Springer Verlag. Seiten 1139-1162. ISBN 978-3-319-4292926-7.

Relationship between ROTI and scintillation index S4

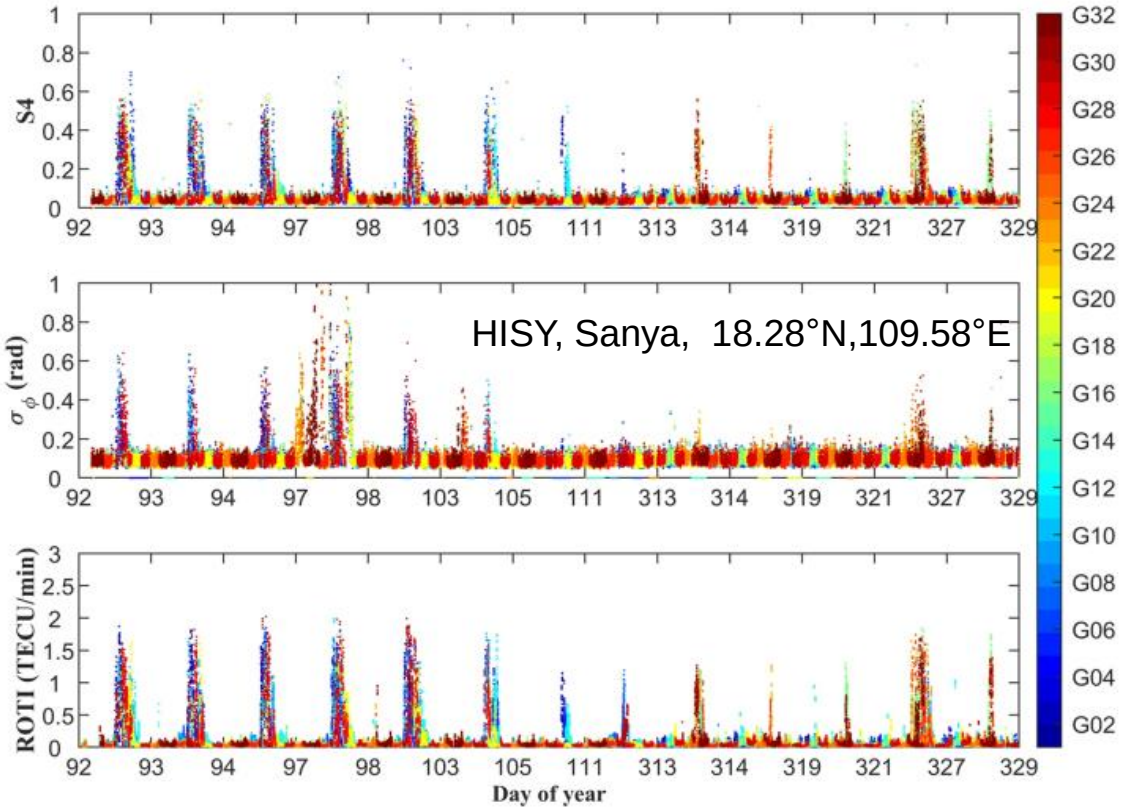


Figure 1. Amplitude scintillation index (top), phase scintillation index (middle) and Rate of change of Total electron content Index (bottom) at HISY station in 2015.

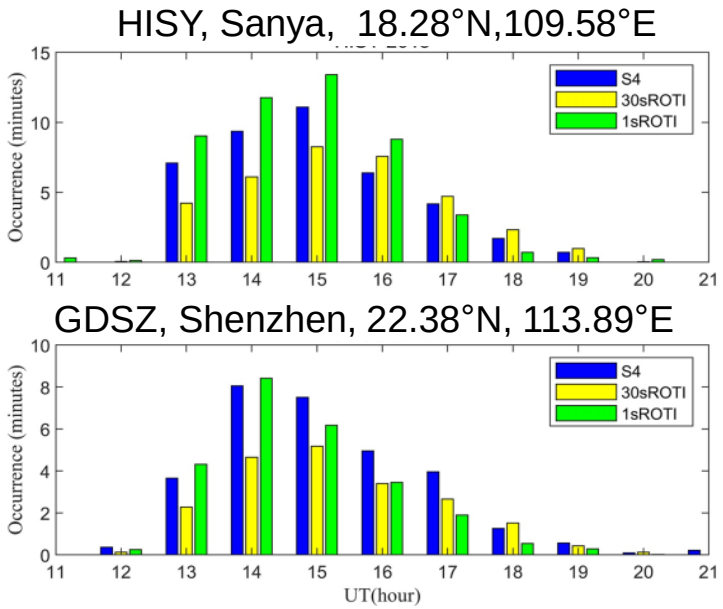


Figure 3. Hourly average duration of scintillation monitored by S_4, 30s-5 min Rate of change of Total electron content Index (ROTI) and 1s-1 min ROTI at HISY (top panel) and GDSZ (bottom panel) in 2015.

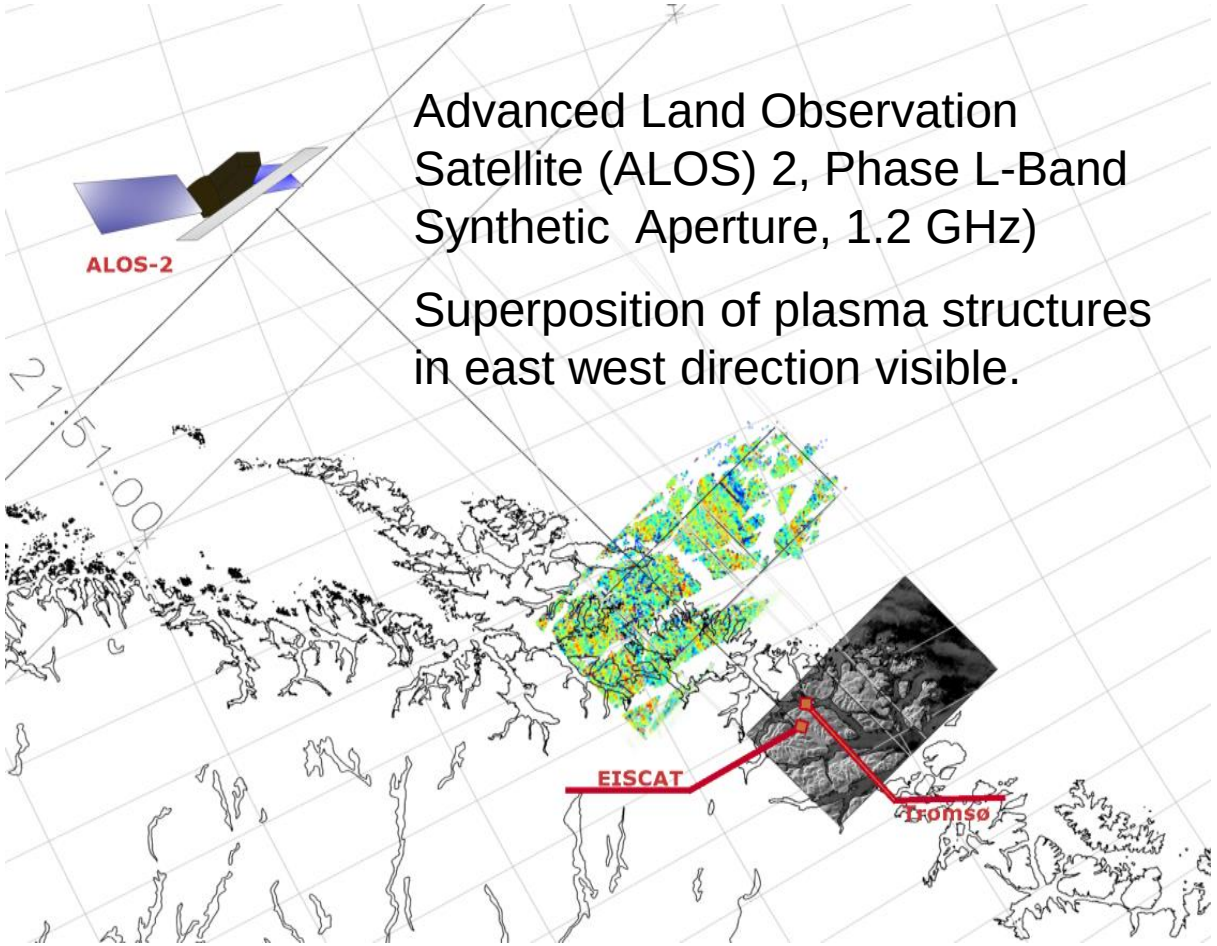
There is a close relationship between ROTI and S4

The reliability of ROTI in indicating the occurrence of scintillation can reach 80% and 88% for 30s ROTI and 1s-ROTI, respectively.

Li, W., Song, S., & Jin, X. (2022). Ionospheric scintillation monitoring with ROTI from geodetic receiver: Limitations and performance evaluation. Radio Science, 57, e2021RS007420. https://doi.org/10.1029/2021RS007420

⇨ **There is a potential for cost-effective monitoring/forecasting of severe radio scintillations causing performance degradation of GNSS and other systems**.

Space weather impact on remote sensing systems



Advanced Land Observation Satellite (ALOS) 2, Phase L-Band Synthetic Aperture, 1.2 GHz)

Superposition of plasma structures in east west direction visible.

Remote sensing radar systems suffer from ionospheric ranging and polarimetric errors.

Remote sensing information is derived from ranging and polarimetric measurements of lineary polarized waves.

Ionosphere impacts

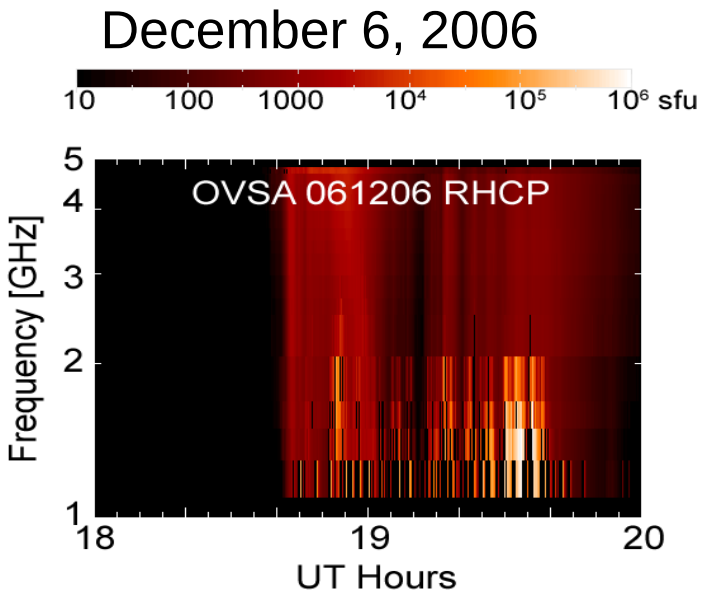
- Ranging: first order effect ~ TEC/f^2
- Polarimetry: second order effect ~ $\overline{B\ cos}\Theta \cdot$ TEC /f^3

Polarization plane of linearly polarized waves changes with TEC and geomagnetic field

GNSS Reflectrometry

Sato et al., (2018), Imaging high-latitude plasma density irregularities resulting from particle precipitation: spaceborne L-band SAR and EISCAT observations, Earth, Planets ,Space, 70(1), 163, doi:10.1186/s40623-018-0934-1.

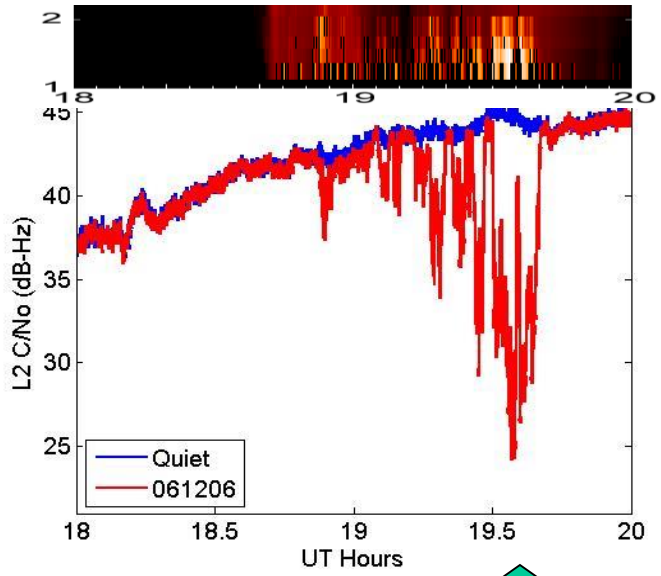
Interference of solar radio flux with GPS signals



Solar radio burst

up to 150,000 sfu

1 sfu = 10^{-22}Wm^{-2}Hz^{-1}

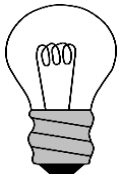


Impact at L2- GPS signal (20 dB loss)

Source: P. Doherty

Satcom (UHF) reception is vulnerable against radio bursts in case receiving antennas are in line with the sun.

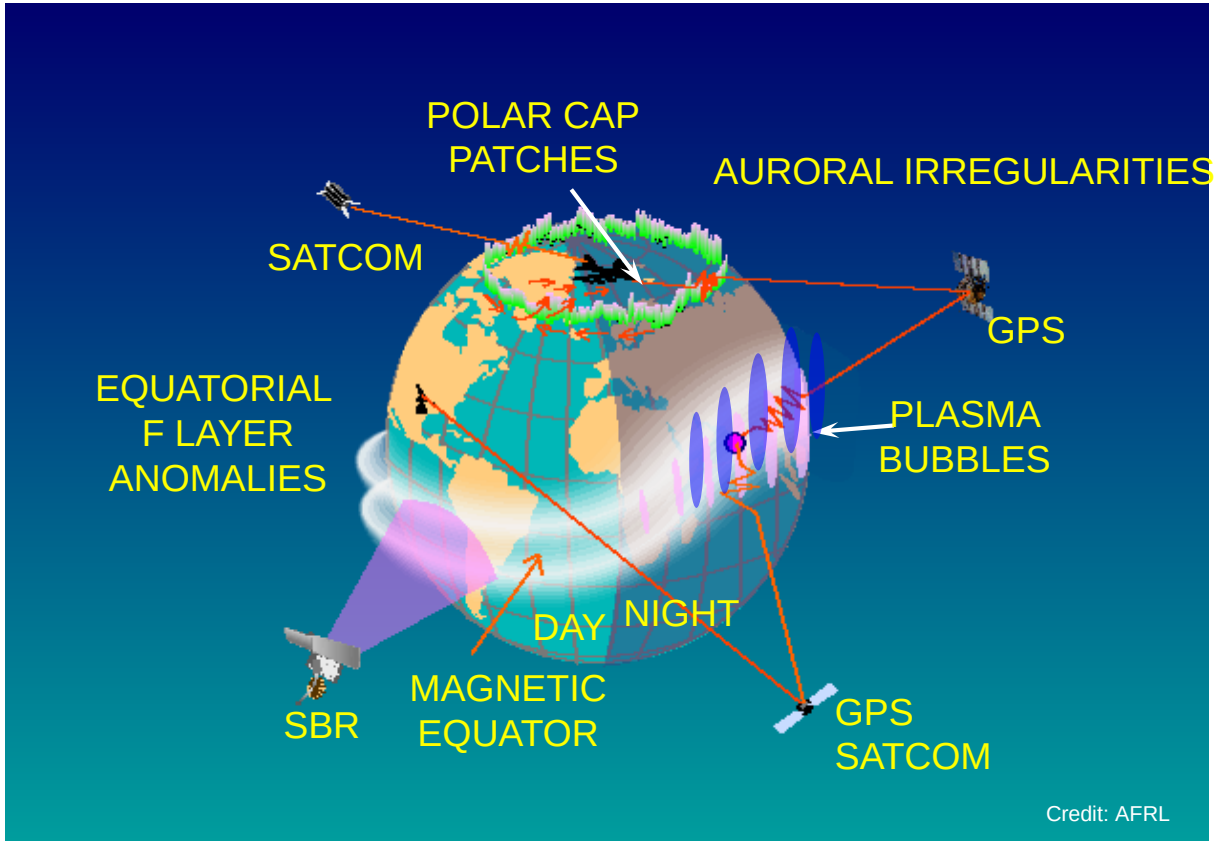
- Intense Solar Radio Bursts (SRBs) at L-band are a source of Radio Frequency Interferences (RFI) for Global Navigation Satellite Systems (GNSS) and space based communication in UHF (Satcom).
- GPS/GLONASS transmitted power is about 20-300 Watt.



- Considering the orbit altitude of 20200 km the received signal is very weak.
- Air traffic control centres in Stockholm and Malmö, Sweden noticed that radar stations of the Swedish Air Navigation Service Provider were not relying on November 4, 2015.
- Solar radio burst interference index dedicated to GNSS single and double frequency users supports GNSS.
- GNSS signals may heavily be disturbed also by man made radio noise in the L-band (Jamming).

Liu et al..(2019). Analysis and Modeling on Interference of Solar Radio Burst on GNSS Signal, China Satellite Navigation Conference (CSNC) Proceedings (pp.196-206), DOI: 10.1007/978-981-13-7759-4

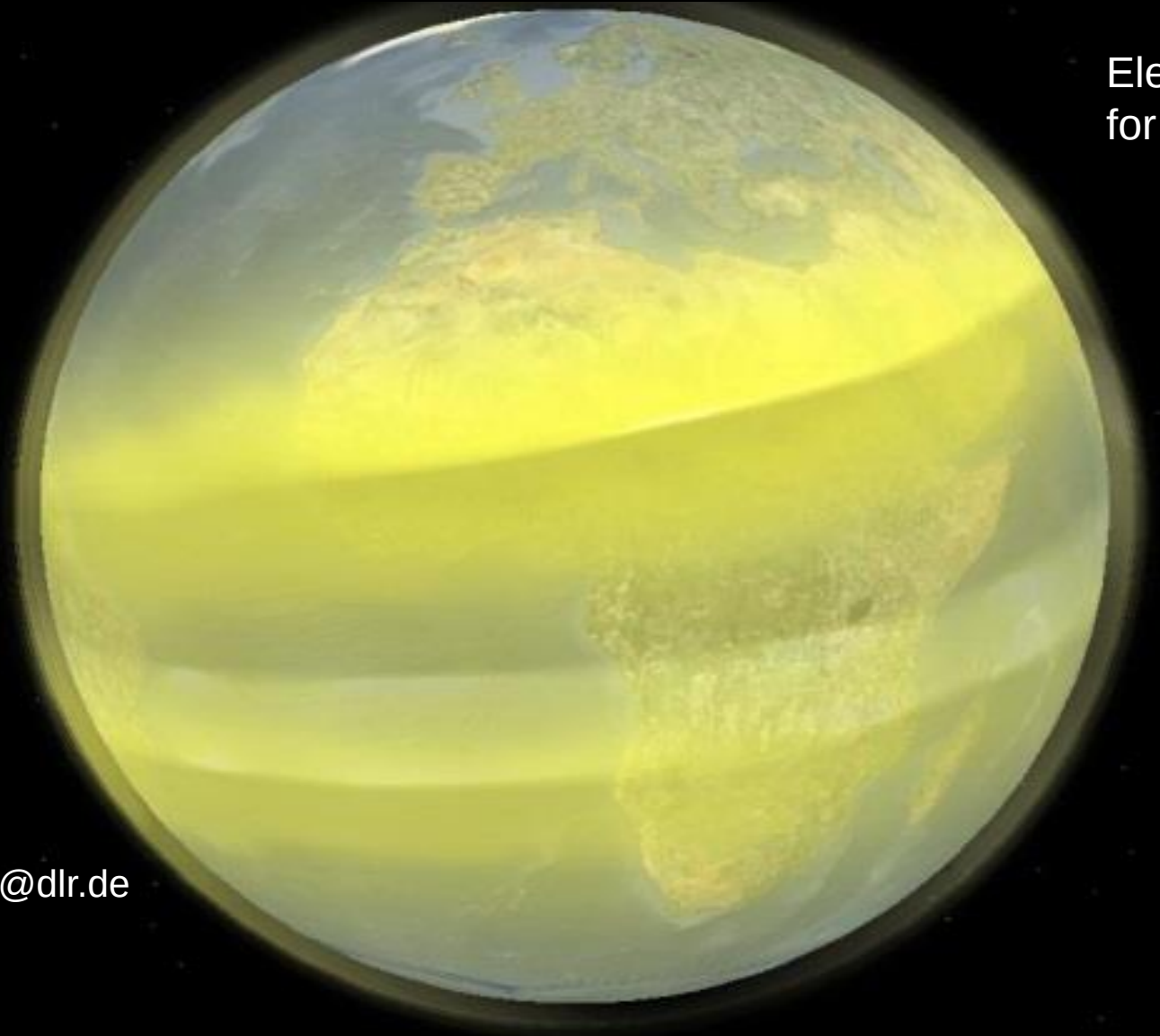
Summary



- Radio signals used in HF communication, space based navigation and radar systems are impacted by the ionospheric plasma due to refraction, absorption, diffraction and scattering.
- Ionospheric delay is the largest error source for single-frequency GNSS and a significant factor for DGNSS.
- Ionospheric storms and small scale irregularities may cause performance degradation in precise / SoL GNSS applications and remote sensing systems.
- Monitoring, modeling and forecasting of ionospheric behavior and derived n.r.t. products like proper indices will further support mitigating ionospheric impact on radio signals as used in telecommunication, space based navigation and remote sensing.

⇒ Challenge of future work

Ionosphere from space



Electron density reconstruction for July 23, 2011, 14:00 UT

Thank you for your attention!

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D-17235 Neustrelitz
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DLR