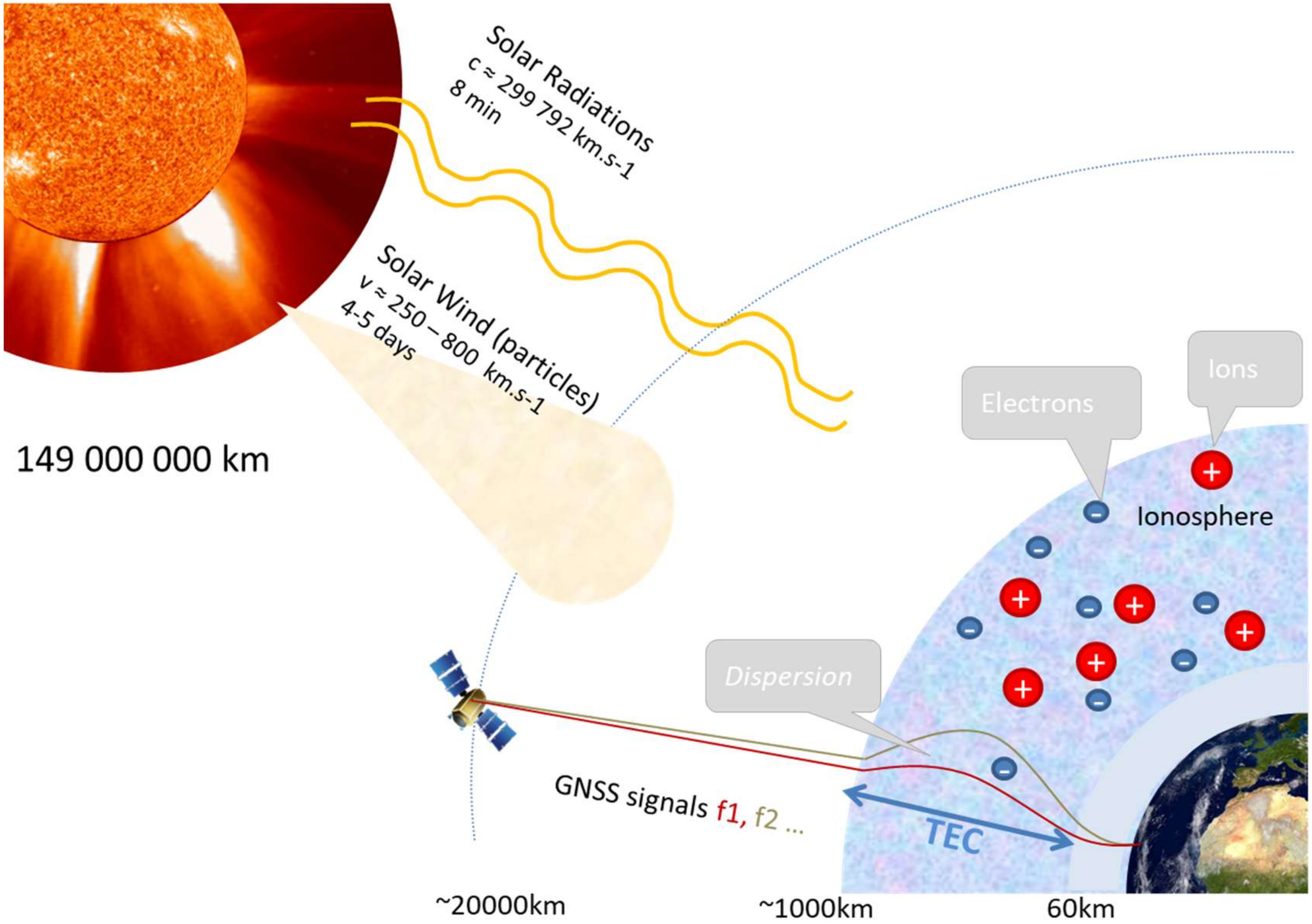
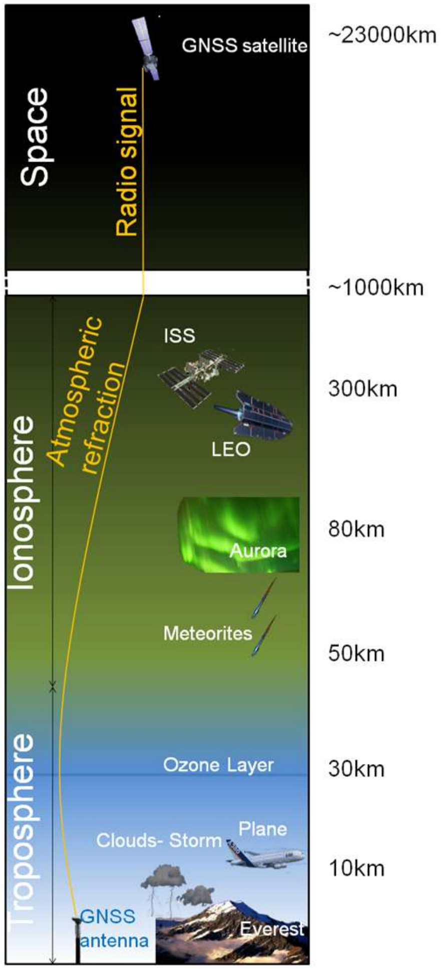
Monitoring the Ionosphere and Solar Radio Bursts based on GNSS

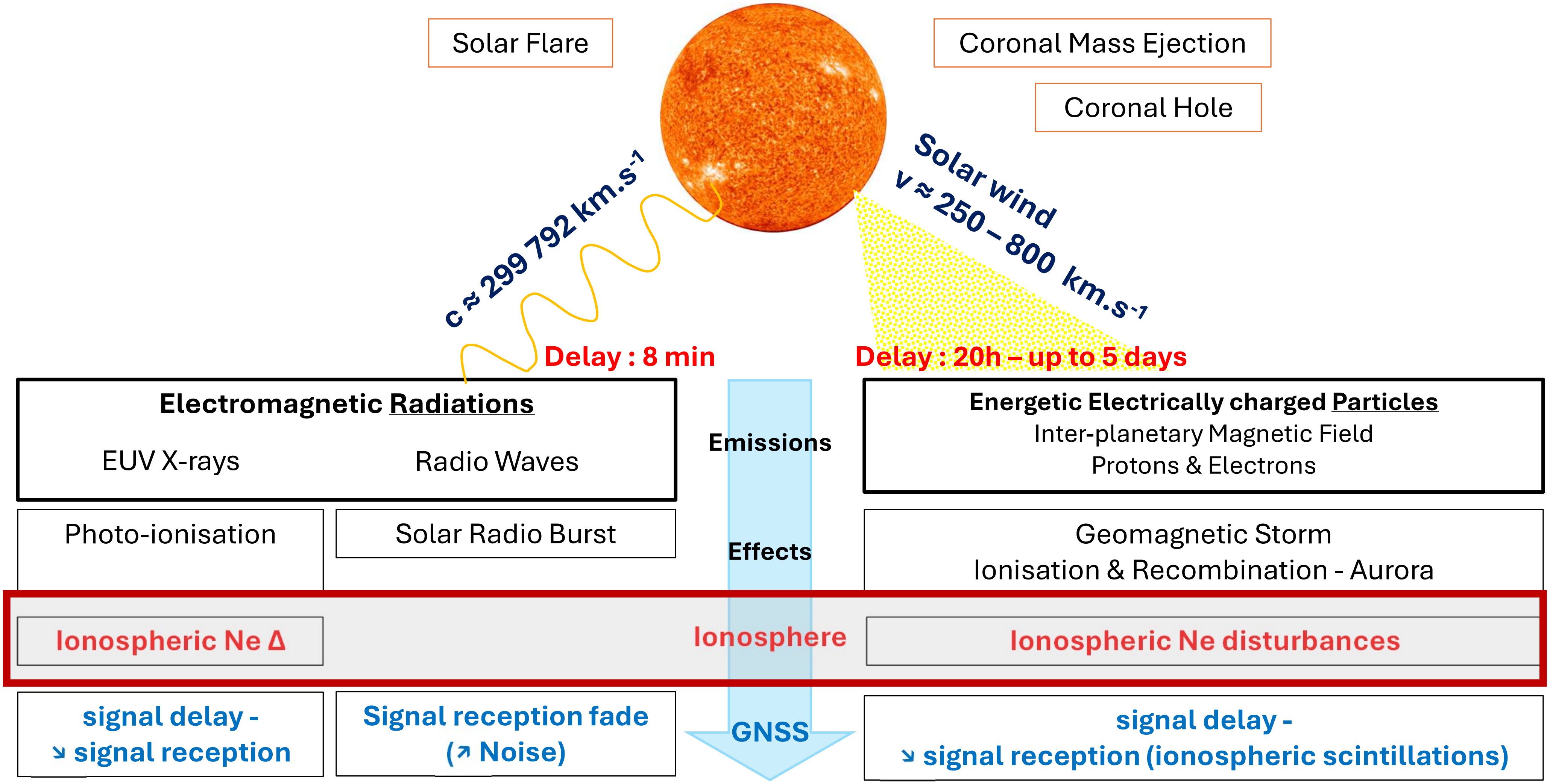
Jean-Marie Chevalier, Nicolas Bergeot and Joshua Dreyer
Royal Observatory of Belgium

Space Weather Introductory Course, 30/01/2025


Solar Radiations
c ≈ 299 792 km.s-1
8 min
Solar Wind (particles)
v ≈ 250 – 800 km.s-1
4-5 days
149 000 000 km
Electrons
Ions
Ionosphere
Dispersion
GNSS signals f1, f2 ...
TEC
~20000km
~1000km
60km


Space
Radio signal
GNSS satellite
~23000km
~1000km
Ionosphere
Atmospheric refraction
ISS
LEO
300km
Aurora
80km
Meteorites
50km
Troposphere
Ozone Layer
30km
Plane
Clouds- Storm
10km
GNSS antenna
Everest

The Sun, Source of Space Weather impacting GNSS



Solar Flare

Coronal Mass Ejection

Coronal Hole

$c \approx 299\,792$ km.s^{-1}

Solar wind

$v \approx 250 – 800$ km.s^{-1}

Delay : 8 min

Delay : 20h – up to 5 days

Emissions

Electromagnetic Radiations

EUV X-rays

Radio Waves

Energetic Electrically charged Particles

Inter-planetary Magnetic Field

Protons & Electrons

Effects

Photo-ionisation

Solar Radio Burst

Geomagnetic Storm

Ionisation & Recombination - Aurora

Ionosphere

Ionospheric Ne Δ

Ionospheric Ne disturbances

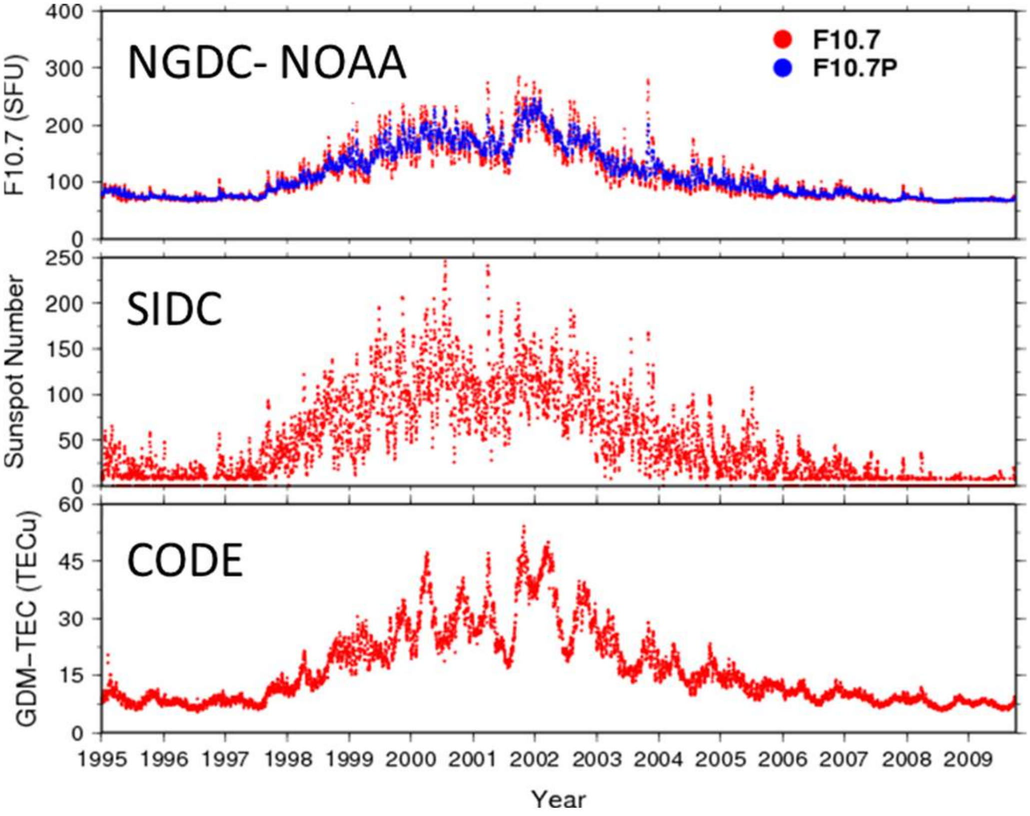
GNSS

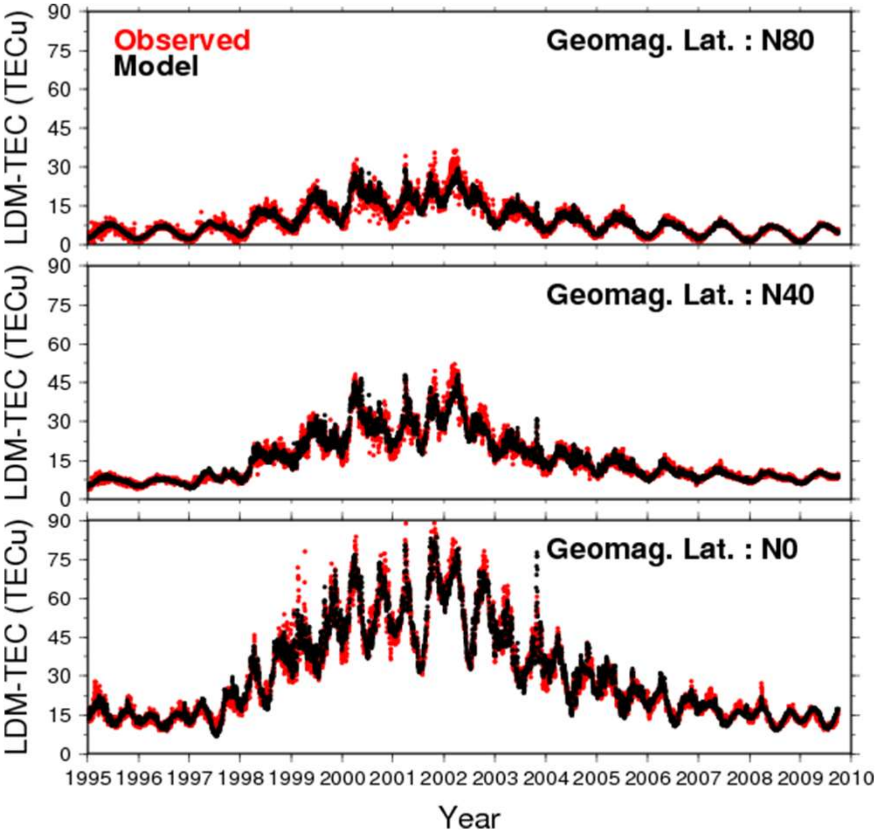
signal delay -
↘ signal reception

Signal reception fade
(↗ Noise)

signal delay -
↘ signal reception (ionospheric scintillations)

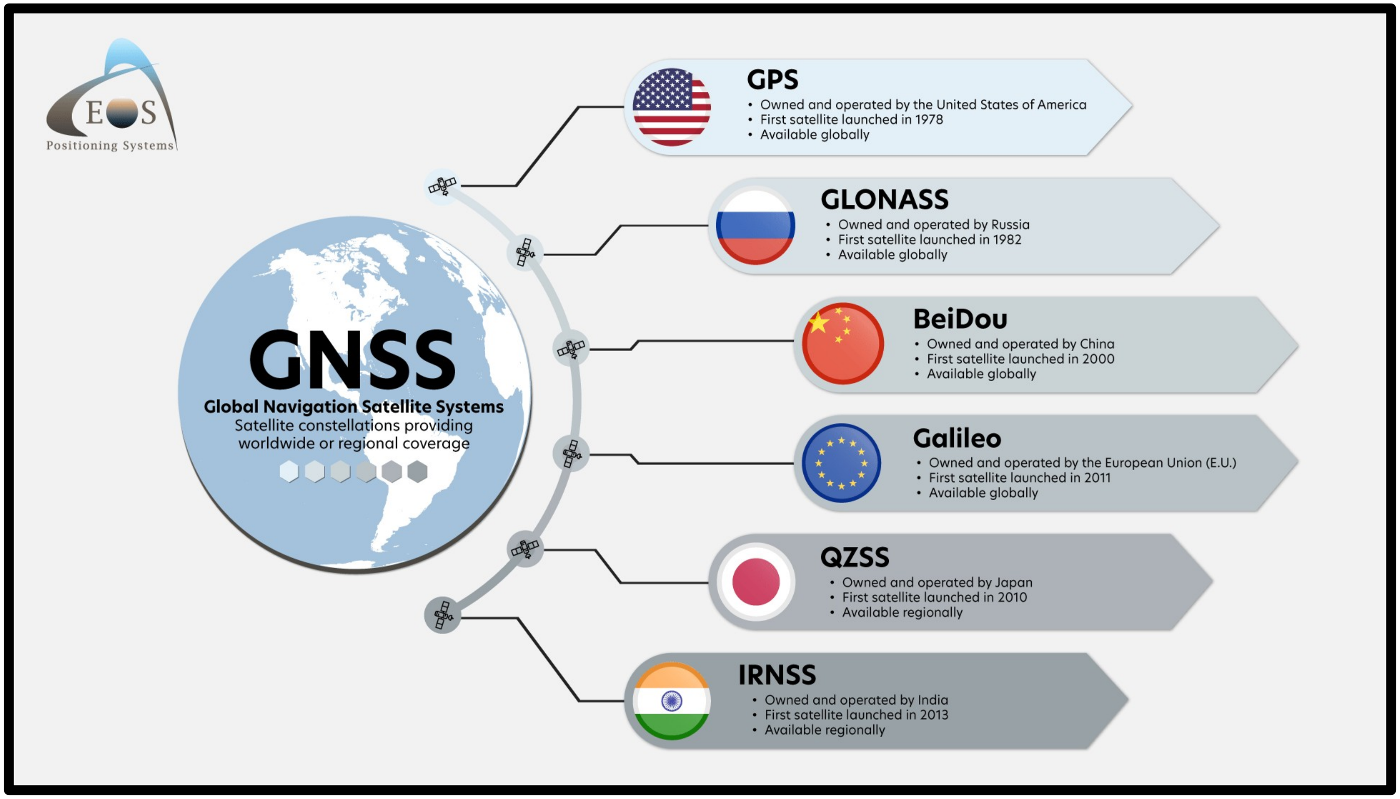
Climatology of the ionosphere





Bergeot, 2013

GLOBAL NAVIGATION SATELLITE SYSTEM



GNSS

Global Navigation Satellite Systems

Satellite constellations providing worldwide or regional coverage

GPS
- Owned and operated by the United States of America
- First satellite launched in 1978
- Available globally

GLONASS
- Owned and operated by Russia
- First satellite launched in 1982
- Available globally

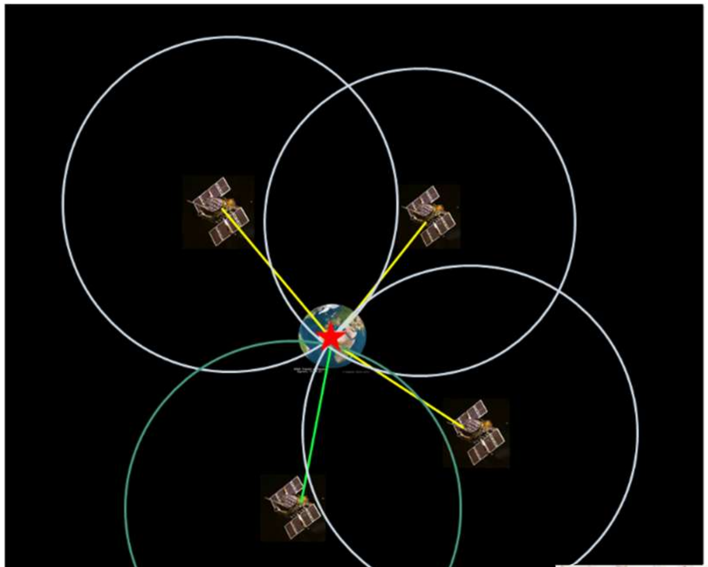
BeiDou
- Owned and operated by China
- First satellite launched in 2000
- Available globally

Galileo
- Owned and operated by the European Union (E.U.)
- First satellite launched in 2011
- Available globally

QZSS
- Owned and operated by Japan
- First satellite launched in 2010
- Available regionally

IRNSS
- Owned and operated by India
- First satellite launched in 2013
- Available regionally

Few GNSS basics : To find your position, you first need the right Time



4 unknows :
- position (x, y, z)
- time synchronization (t)

→

≥4 satellites needed
Sat. positions transmitted in nav. message

Estimation of the pseudo-distance satellite-receiver:

$$D = c\,(t_{rec} - t_{sat})$$

A delay of 1 ns (10^{-9} second) → 30 cm error in the pseudo-distance

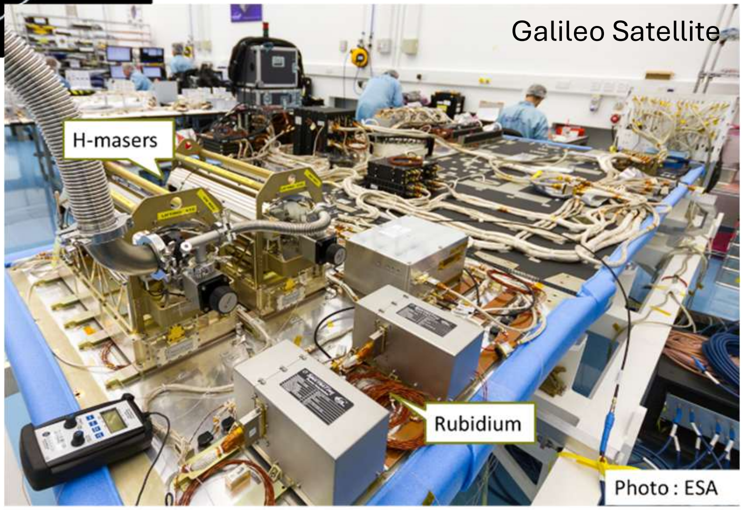
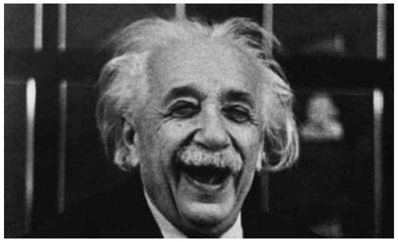


Photo : ESA

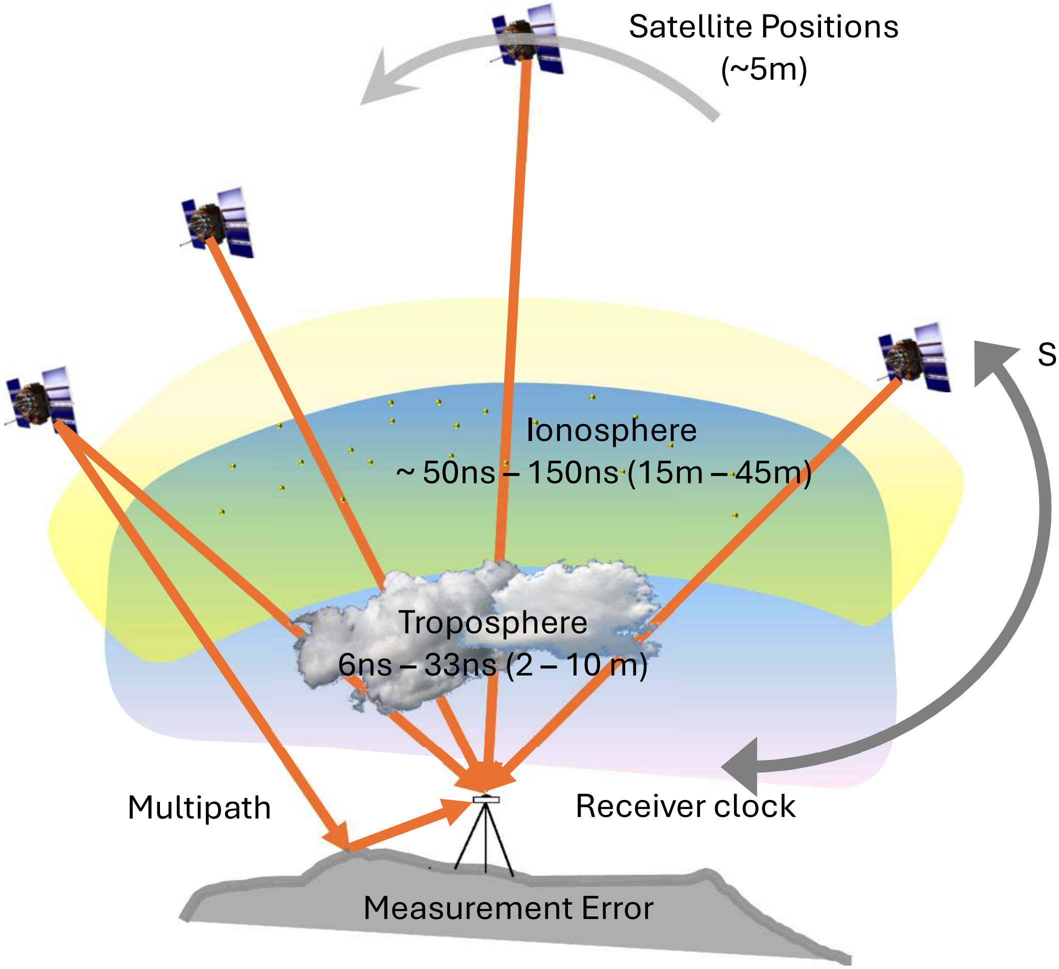
- Atomic clocks generate the signal carrier
- GNSS satellite clocks are kept synchronized in a reference atomic time scale

Race at the ns level, don’t loose time on the way !
Error sources affecting the GNSS positioning quality

Vincent Hie



Relavistic effects are corrected in the navigation message and by the receiver, otherwise the error would increase by ~10km everyday.



Satellite Positions
(~5m)

Satellite Clocks (some ns)

Ionosphere
~ 50ns – 150ns (15m – 45m)

Error of synchronisation between the satellite clocks and the receiver clock

Troposphere
6ns – 33ns (2 – 10 m)

Multipath

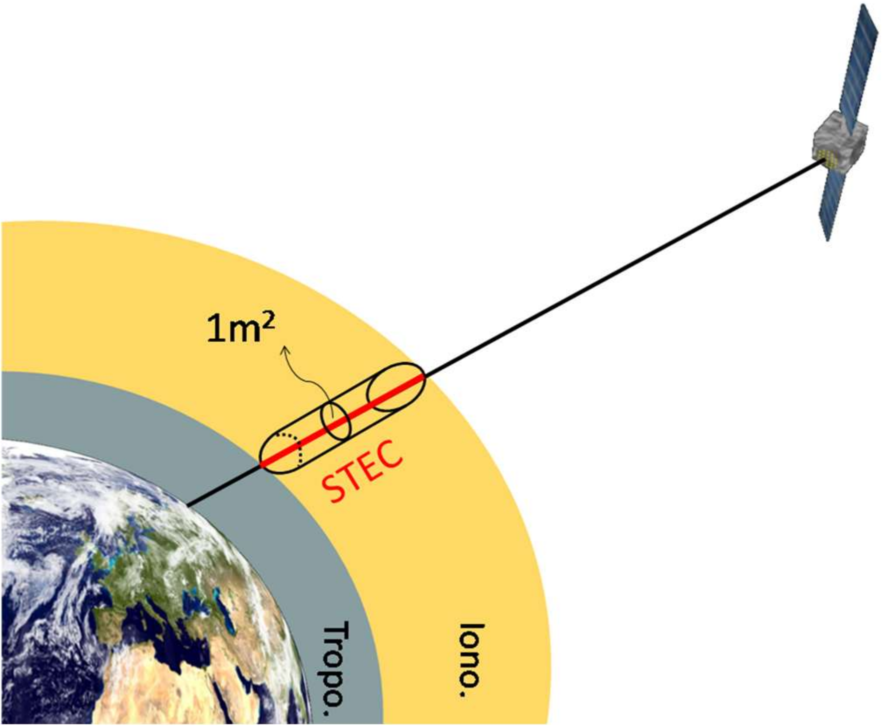
Receiver clock

Measurement Error

GNSS vs Ionosphere

Electrically charged media affect the radio-wave propagation depending on the frequency

⇨ Ionospheric delay depends on the GNSS signal frequency



<u>Using 2 GNSS signals at 2 frequencies:</u>

« ionosphere-free » combination ⇨ removes 99.9% of the ionospheric delay

NO MORE IONOSPHERIC PROBLEM FOR GNSS ?

🤔

Well, still...

Civilian users
⇒ **single-frequency receivers**
(mostly)

- Double-frequency GNSS receivers expensive.
- The ionosphere-free combination relies on the tracking quality of the GNSS signals (hardware and software).
- **GPS 2nd frequency encrypted**, requiring specific cross-corelated tracking technics or M-code key.
- But new civilian signals such as GPS L2C and Galileo E5, protected for **safety-related application**

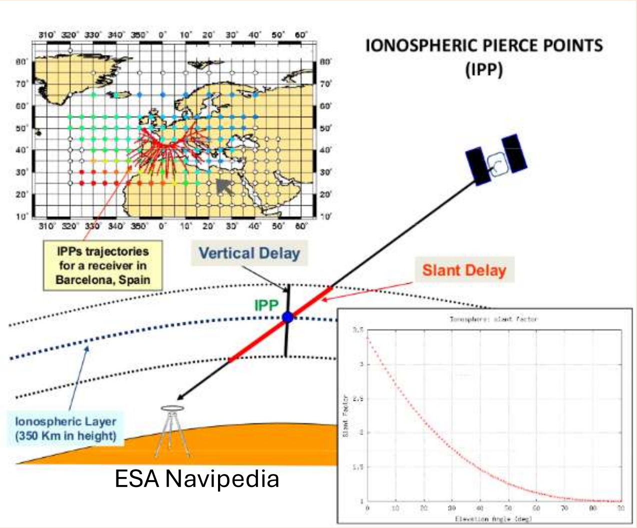
George Karachristo

For **GNSS single frequency users, abnormal ionospheric activity** remains a problem.
Even for double-frequency receivers, space weather events affecting the ionosphere (scintillations) or the radio frequency bands (solar radio bursts) can generate **GNSS signals fading up to the loss of lock**.

GNSS single-frequency users are not left behind for mitigating the ionospheric effect

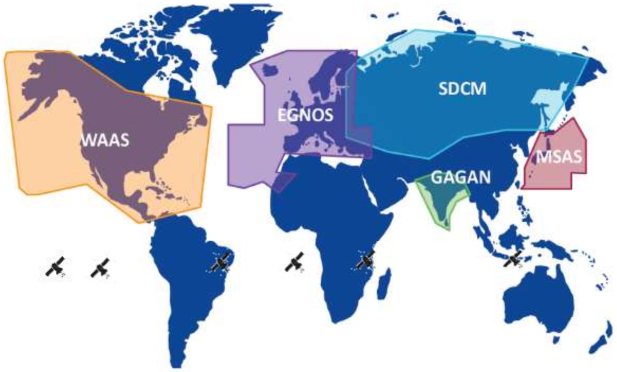
Most common to the public

Broadcasted parameters in the navigation message for the **Klobuchar** and **NeQuick ionospheric models**, correcting **50%** of the **ionospheric range error**.
Do not include space weather.

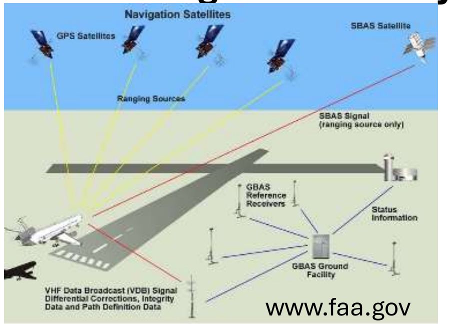


ESA Navipedia

Satellite-based Augmentation Systems



Ground-based Augmentation Systems

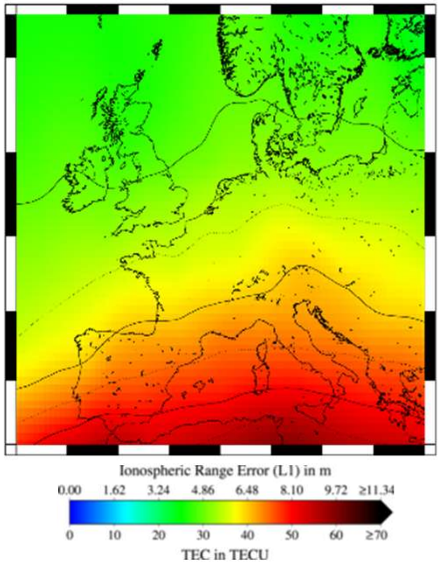


www.faa.gov

Differential GNSS

DGNSS (1-3m)
Real Time Kinematic RTK (3-10cm)
Precise Point Positioning PPP (1-10 cm)

Ionospheric TEC Maps



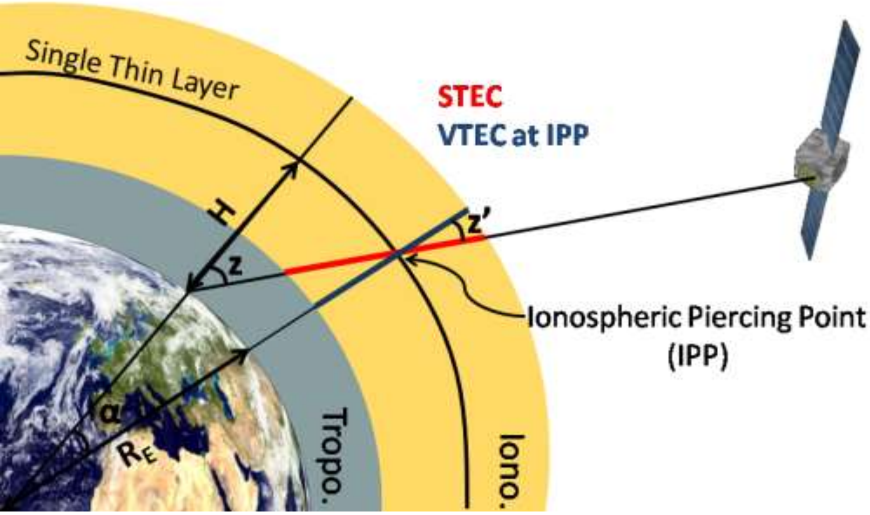
GNSS vs Ionosphere

Electrically charged media affect the radio-wave propagation depending on the frequency

→ Ionospheric delay depends on the GNSS signal frequency

Using 2 GNSS signals at 2 frequencies:

« ionosphere-free » combination → removes 99.9% of the ionospheric delay



« geometry-free » combination → Estimate the ionospheric delay (+hardware delays)

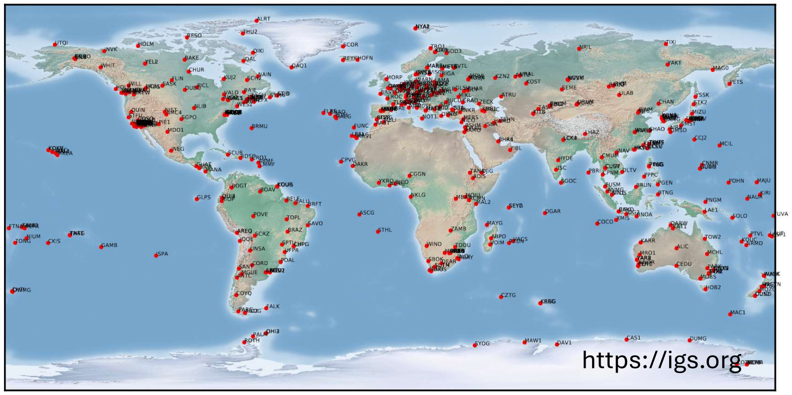
Ionospheric delay

$$I_{1,2} = 40.3\frac{STEC}{f_{1,2}^{2}}$$

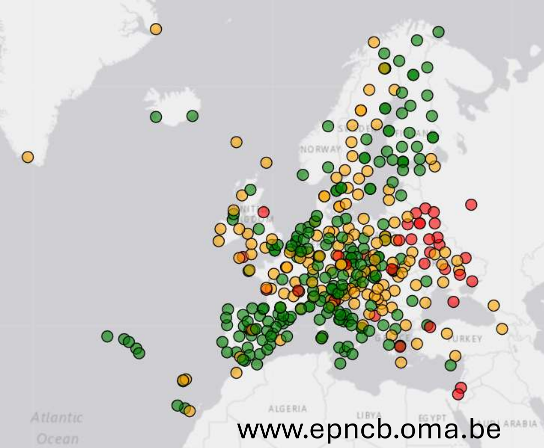
Slant Total Electron Content

$$STEC = \int_{R}^{S} Ne.dl$$

Ionosphere monitoring based on GNSS



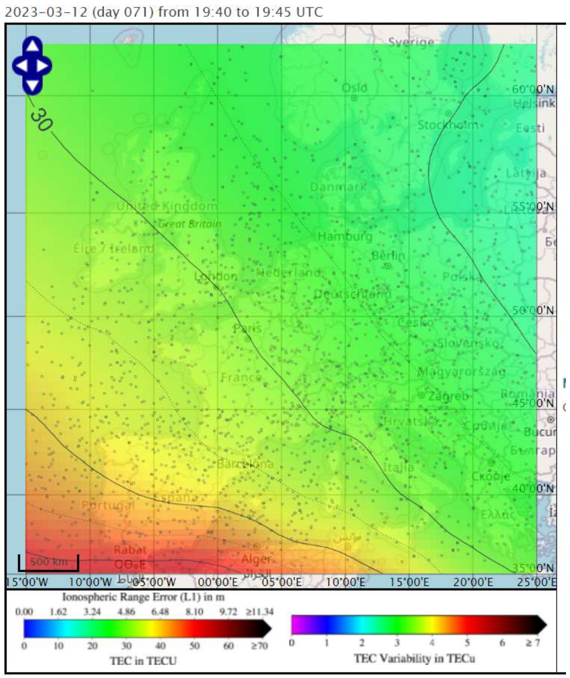
International GNSS Service (IGS)



EUREF Permanent Network

NRT European TEC Maps

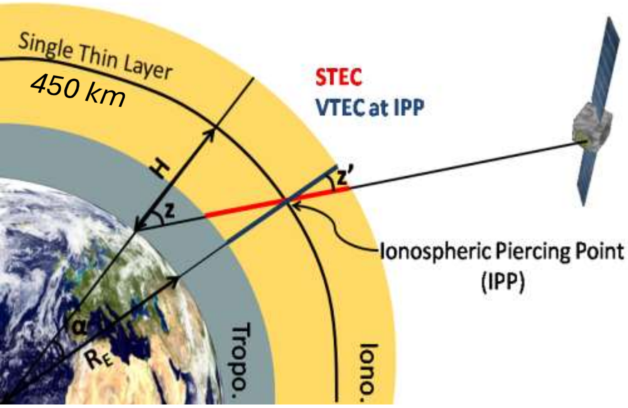
5-min, GPS+GLONASS+GALILEO,
~180 EPN stations

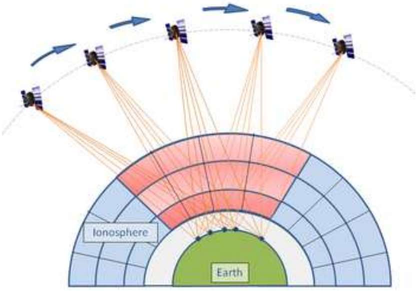


https://www.gnss.be/SpaceWeather/

Source of error becomes source of information

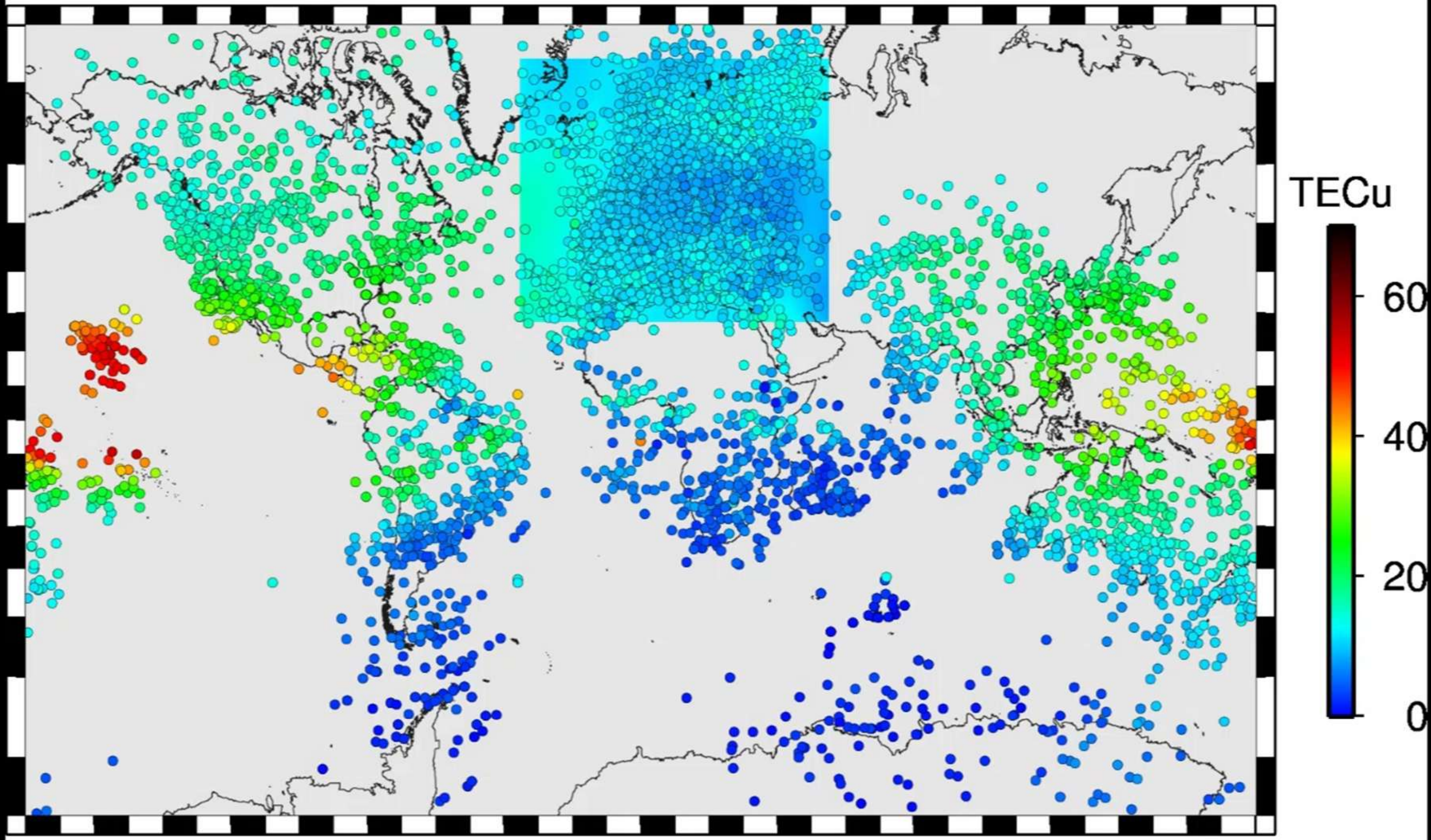
Using large number of GNSS stations, ionospheric total electron content is derived over multitude points





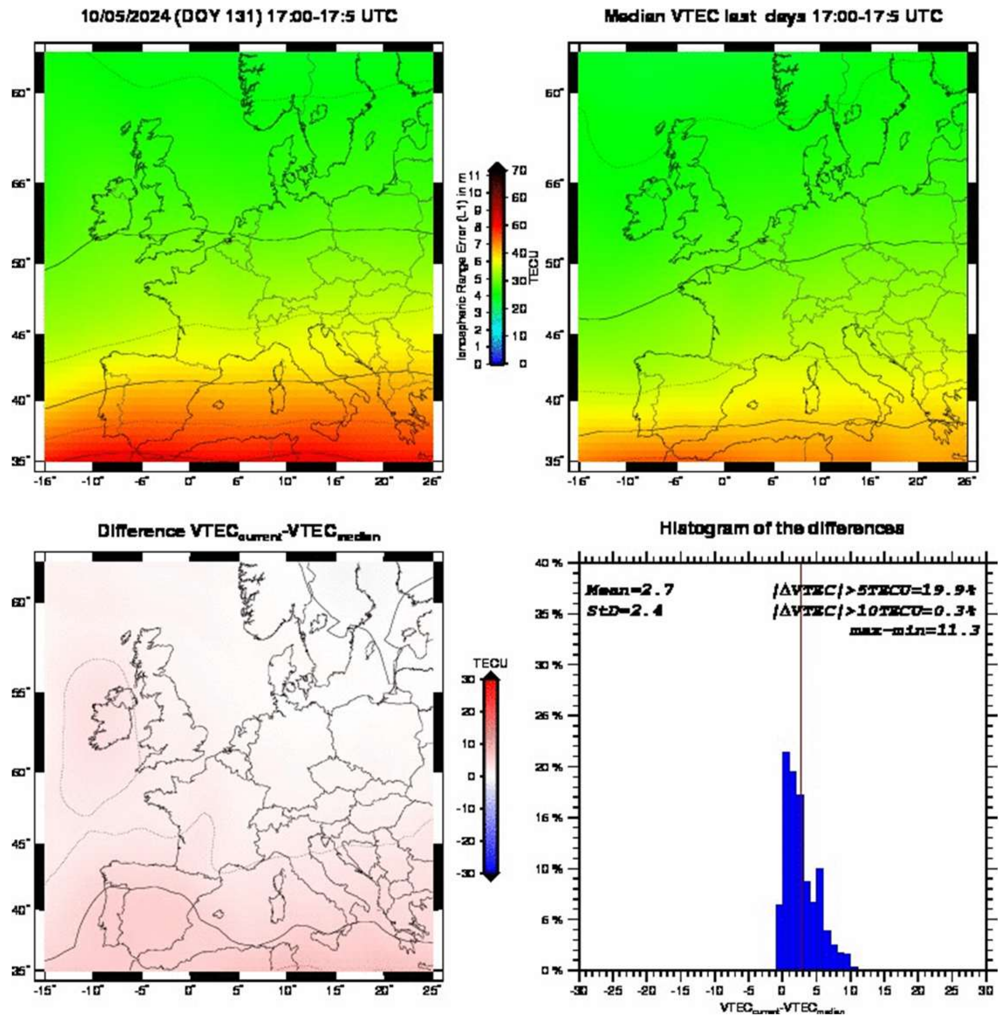
Bergeot, 2014

TEC IPPs



Ipp Total : 9172 Ipp Interp : 5781

Monitoring the ionospheric activity

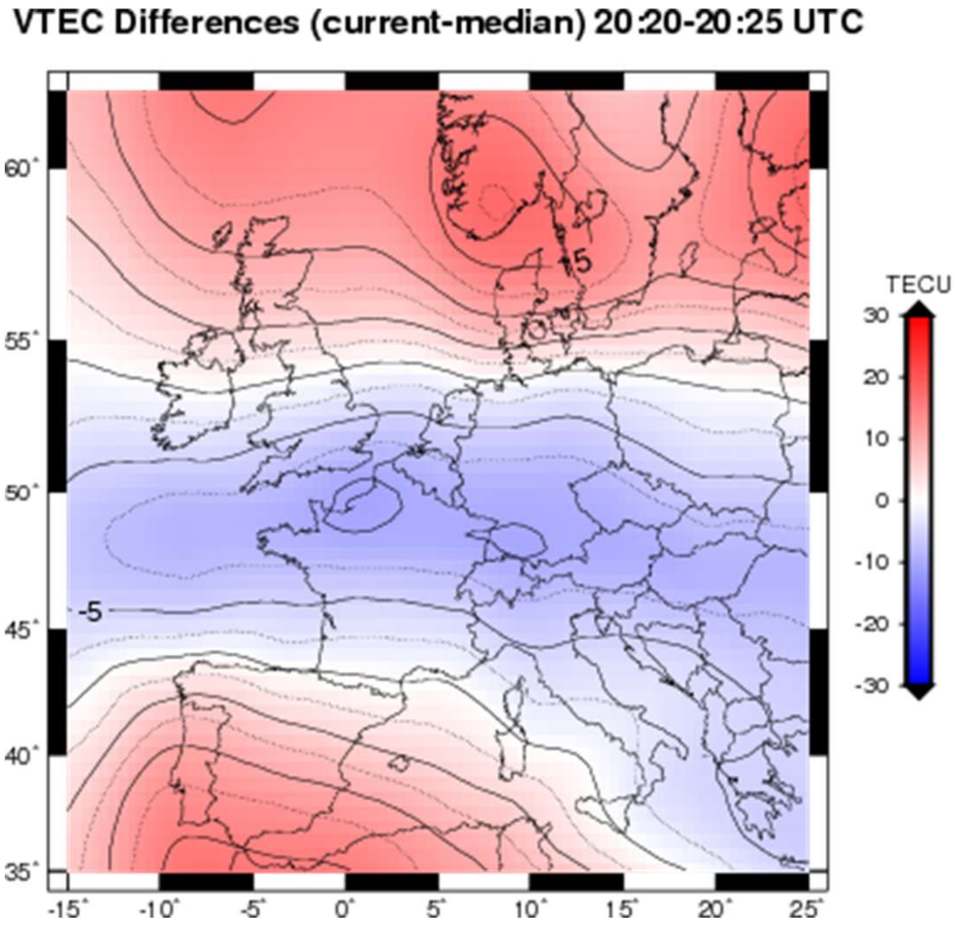


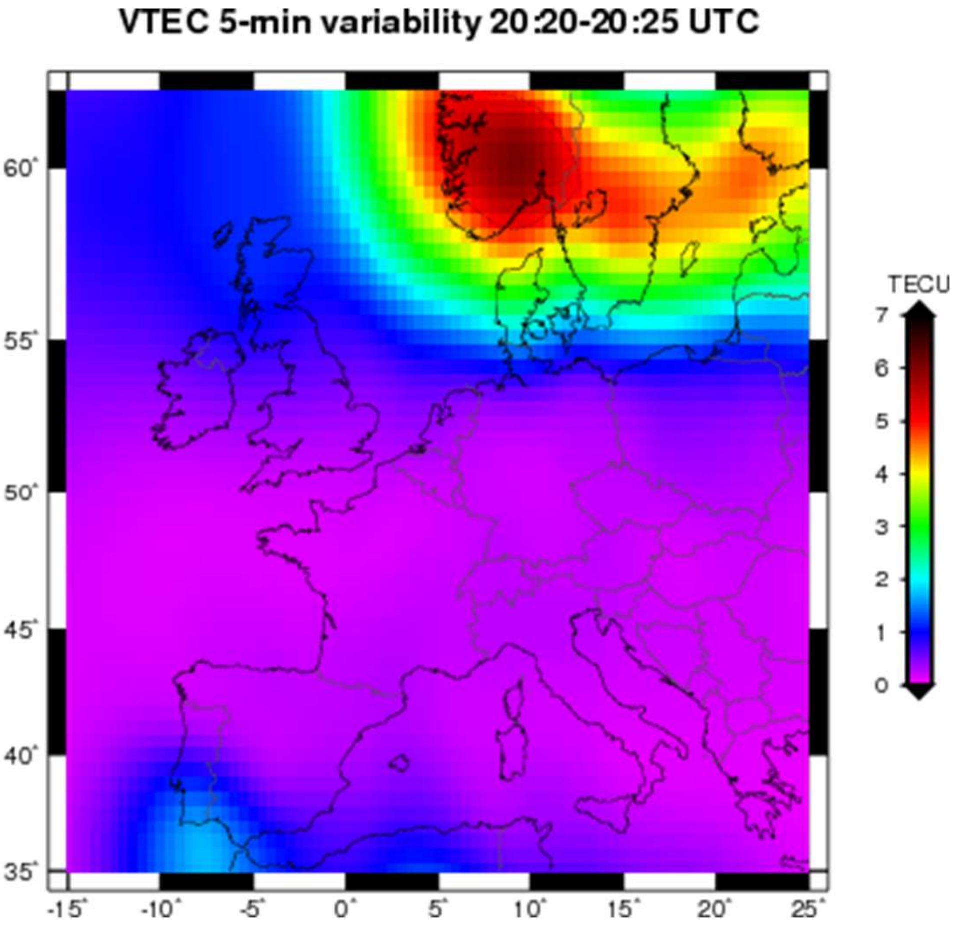
https://www.gnss.be/SpaceWeather/

10-11 MAY MOTHER'S DAY STORM

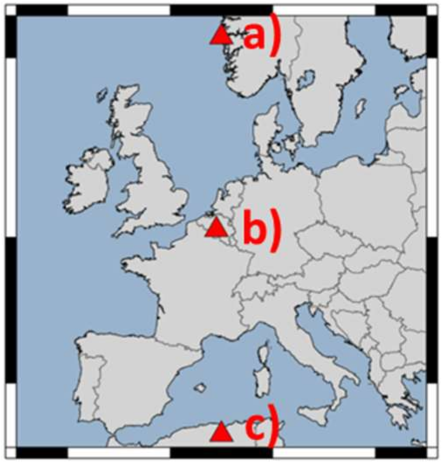
NRT European TEC Maps
5-min, GPS+GLONASS+GALILEO,
~180 EPN stations

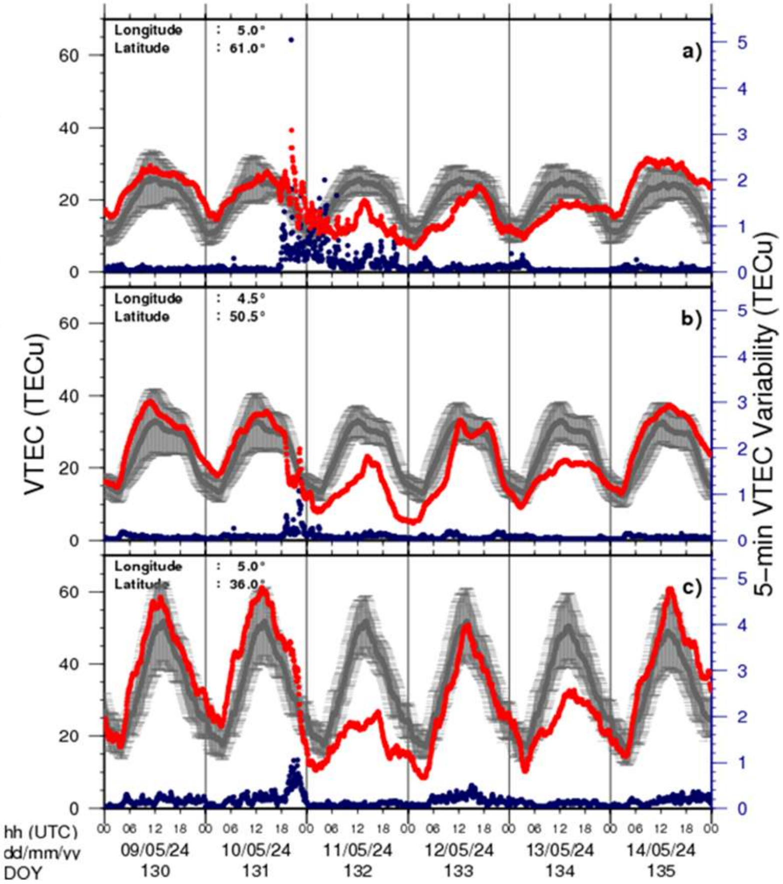
Monitoring the ionospheric activity

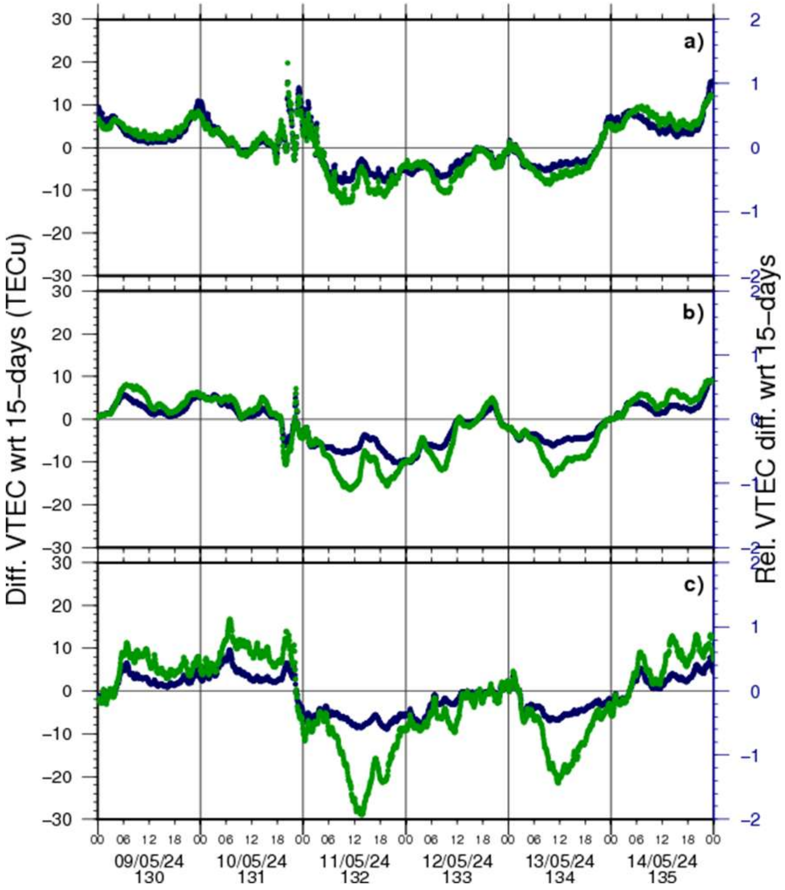




Monitoring the ionospheric activity







- Left plot:

TEC current

15-days median TEC

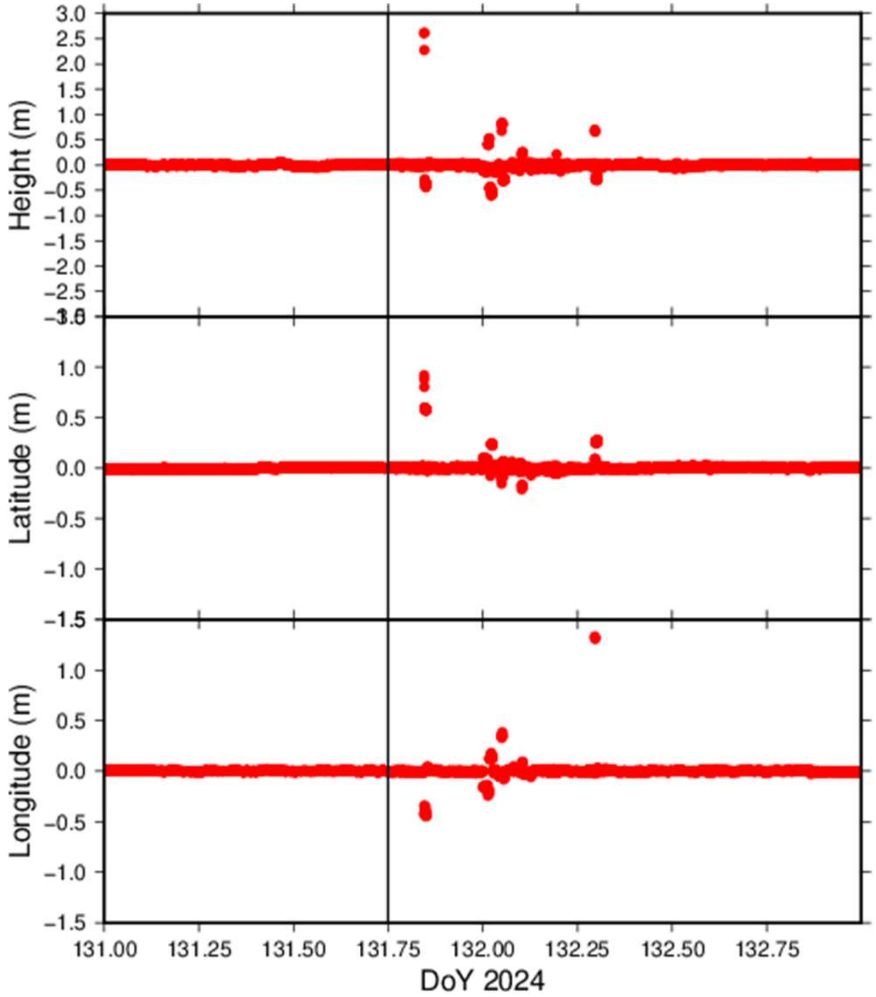
TEC Variability

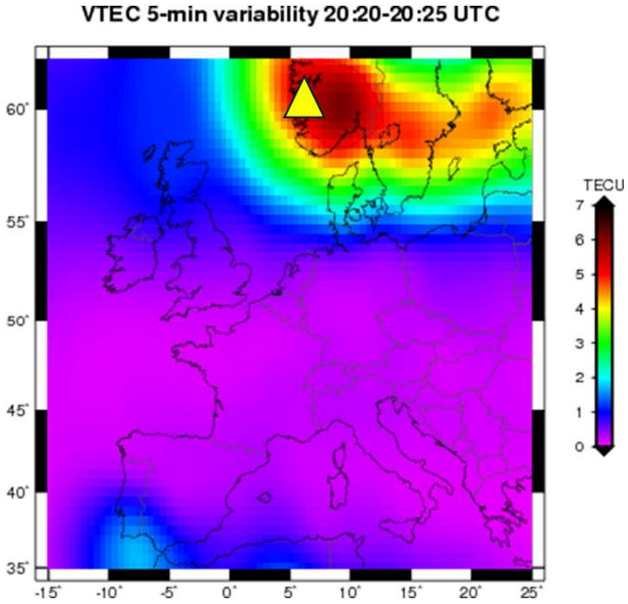
- Right plot:

TEC Differences w.r.t. median

Relative TEC Differences w.r.t. med.

IMPACT ON GNSS POSITIONING

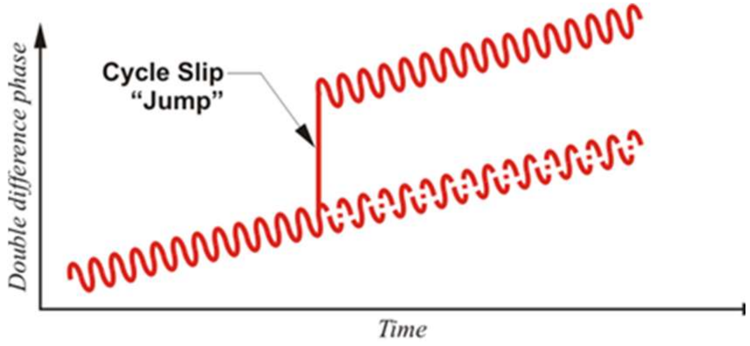


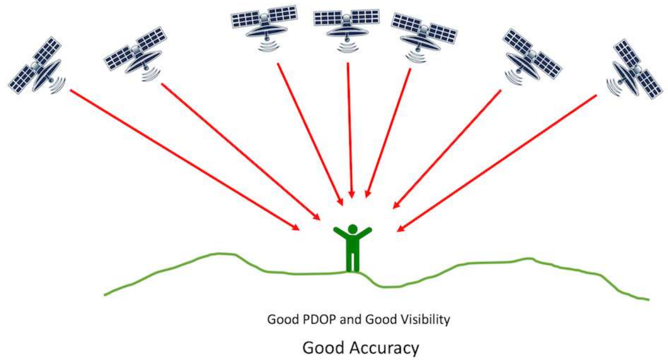


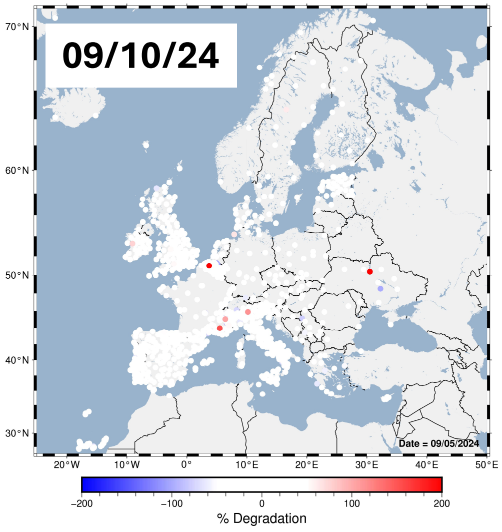
PPP-NRCAN ONLINE SOFTWARE

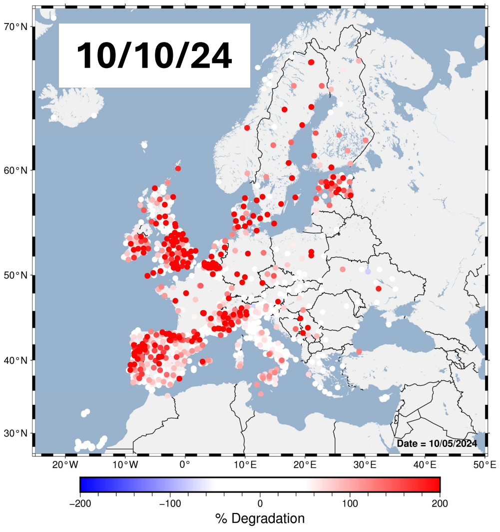
Bergeot

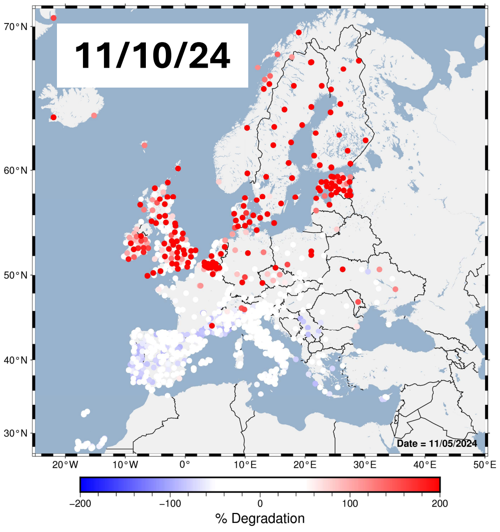
IMPACT ON GNSS POSITIONING

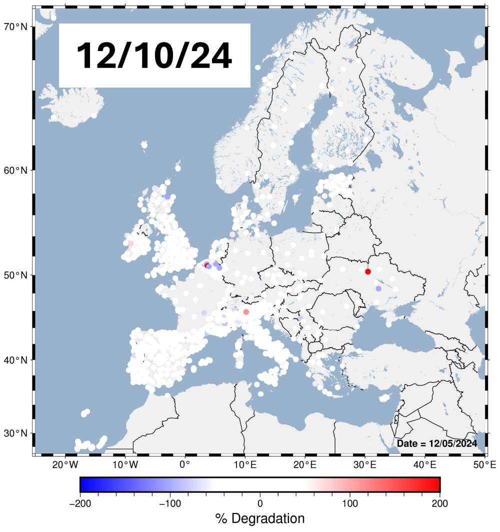






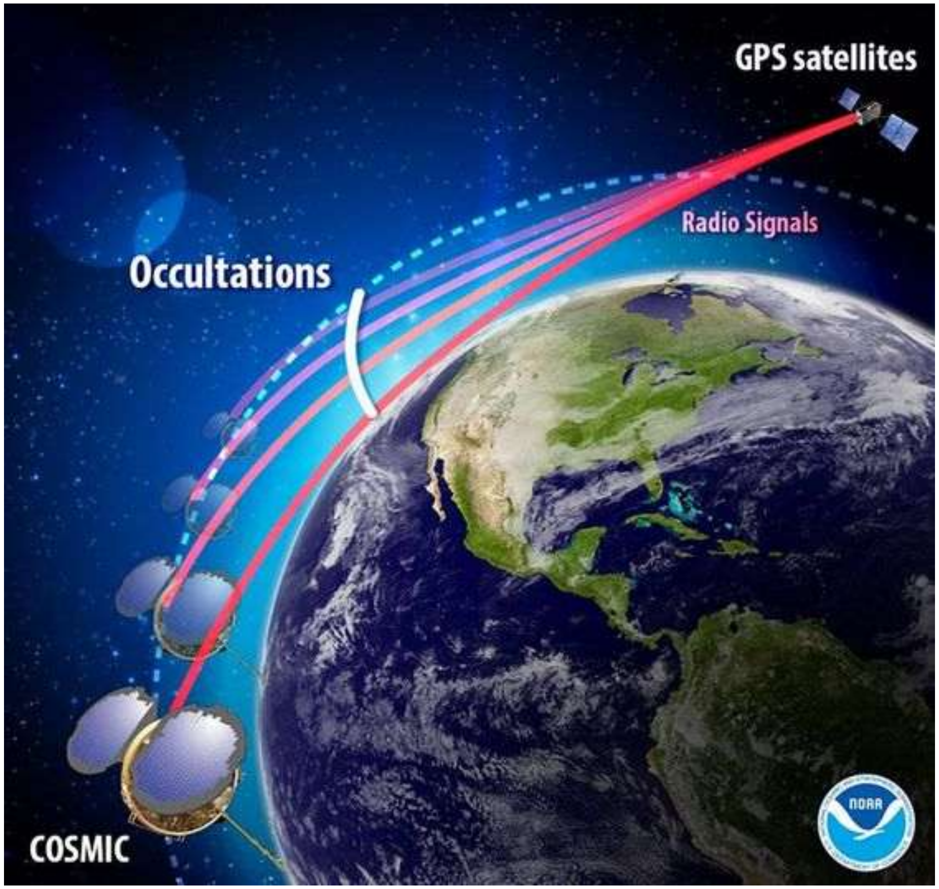






GNSS Group: Legrand J., Bamahry F.

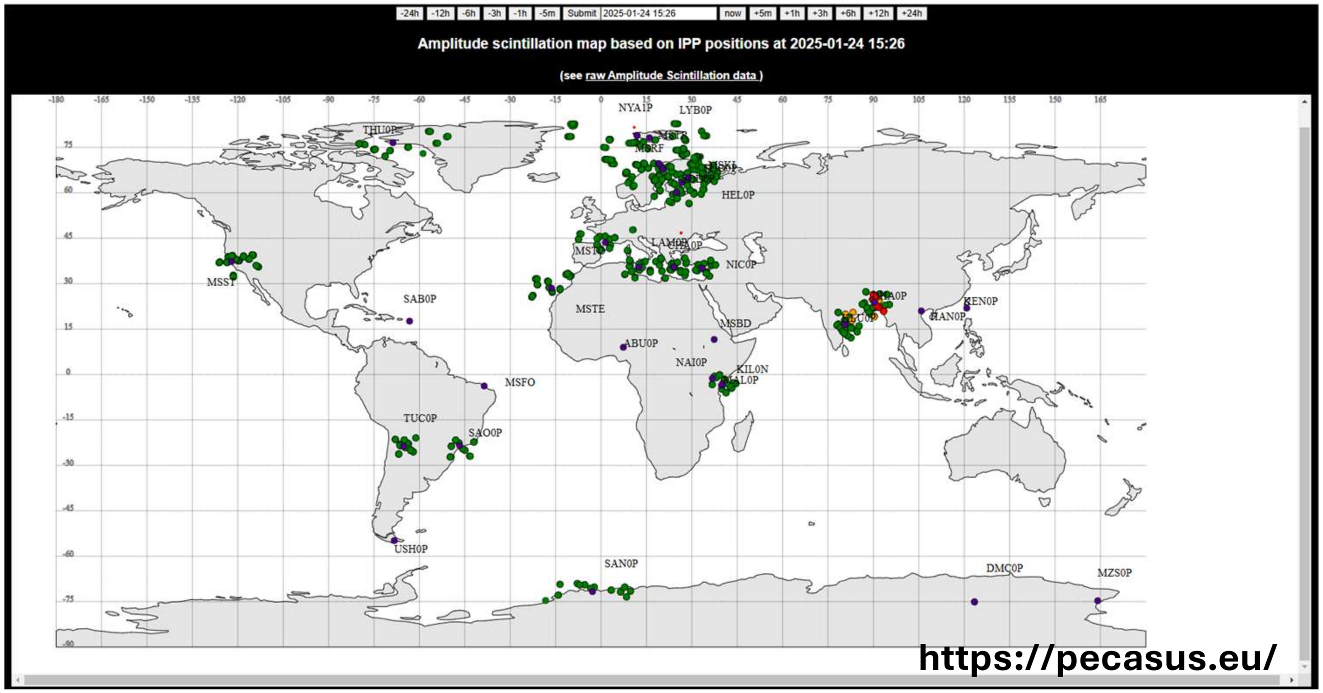
Ionospheric Monitoring with LEO



Some Low Earth Orbit satellites are equipped with GNSS receivers. The GNSS radio occultation allows to get a horizontal sounding of the ionosphere.

The bending effect of the signal propagation path must be taken into account for estimating the ionosphere.

Monitoring Ionospheric Scintillations

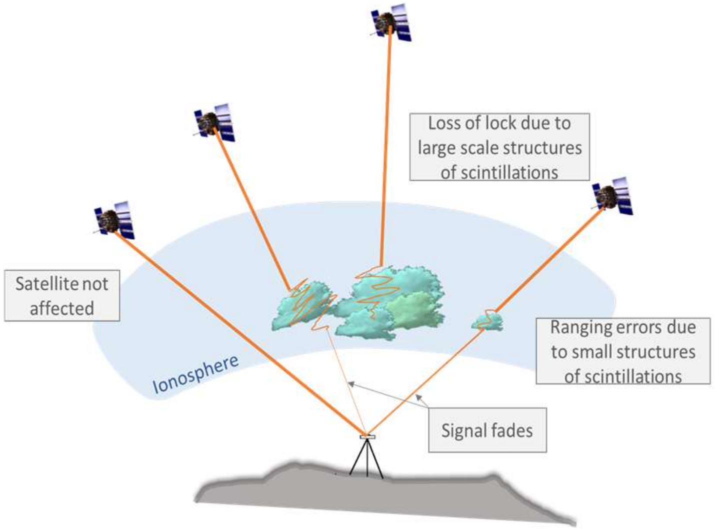


Amplitude scintillation map based on IPP positions at 2025-01-24 15:26

(see raw Amplitude Scintillation data)

https://pecasus.eu/

Amplitude Scintillation Map based on IPP positions tracked by scintillation GNSS receivers
PECASUS Dashboard



Scintillation affects the phase and the amplitude of GNSS signals, causing cycle slips up to the loss of lock.

Induce error positioning up to several meters, with worst case scenario: GNSS signal loss.

Impact on GNSS: ionospheric activity indicators

- Climatological variations of the ionosphere do not a have strong impact on GNSS application, it can be well mitigated with ionospheric model.
  - Absolute TEC values are not a good stand-alone indicator, without knowing the climatological state of the ionosphere, the GNSS location, and the local time.

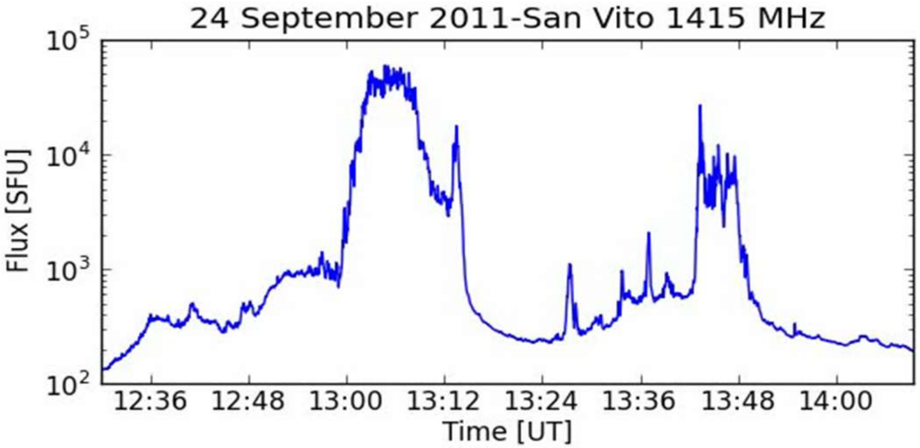
- Variations with respect to 15-days (or 27-days) at a given location and for the same local time.
  - Positive TEC events have a stronger impact on GNSS applications
  - Less impact for negative TEC events

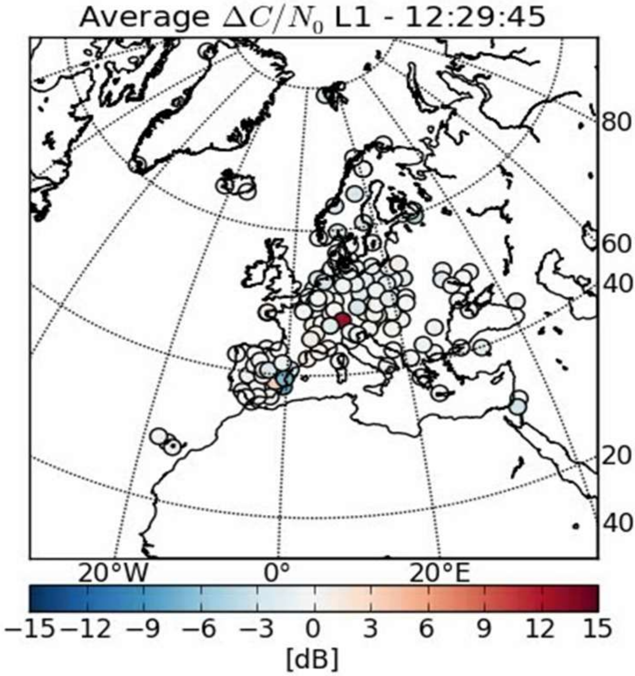
- Rapid Ionospheric variations :
  - Ionospheric scintillations, monitored with dedicated GNSS scintillations receivers
  - TEC variability, ROTI (Rate Of TEC Index)

- And also, satellites used for the positioning
  - Stronger impact of the ionosphere for low elevation satellite <30°
  - Dilution Of Precision (PDOP), Number of satellites tracked

GNSS disturbances due to Solar Radio Bursts

Solar Radio Bursts (SRB) are intense radio emissions (durations from 10s to few hours)

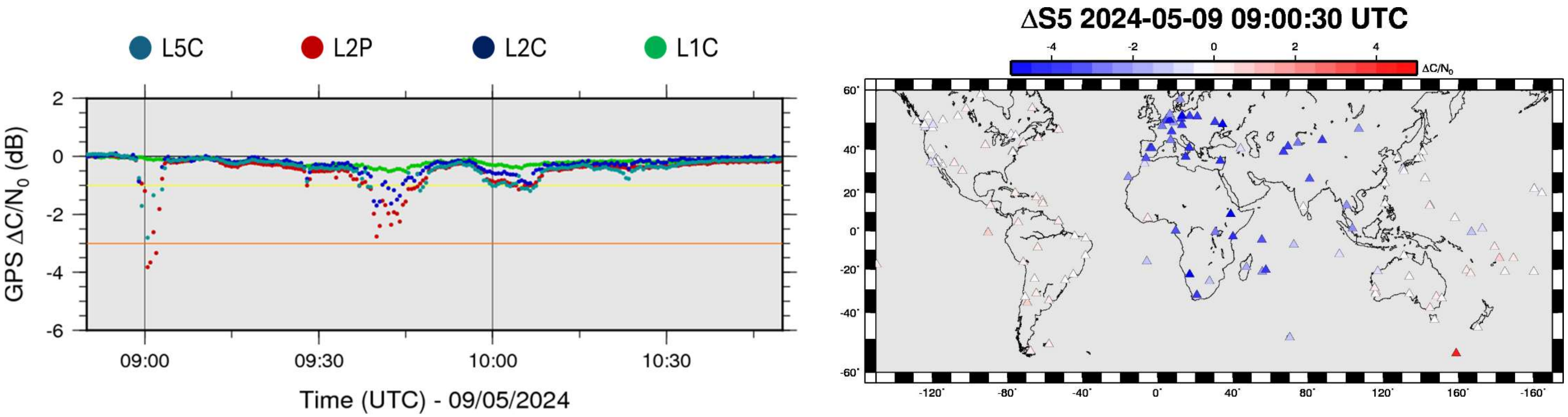




GNSS are vulnerable to Radio Frequency Interferences as the GNSS signals received on Earth is very weak.

SRBs increase the noise level of GNSS ground stations and act as a natural jammer for the GNSS.

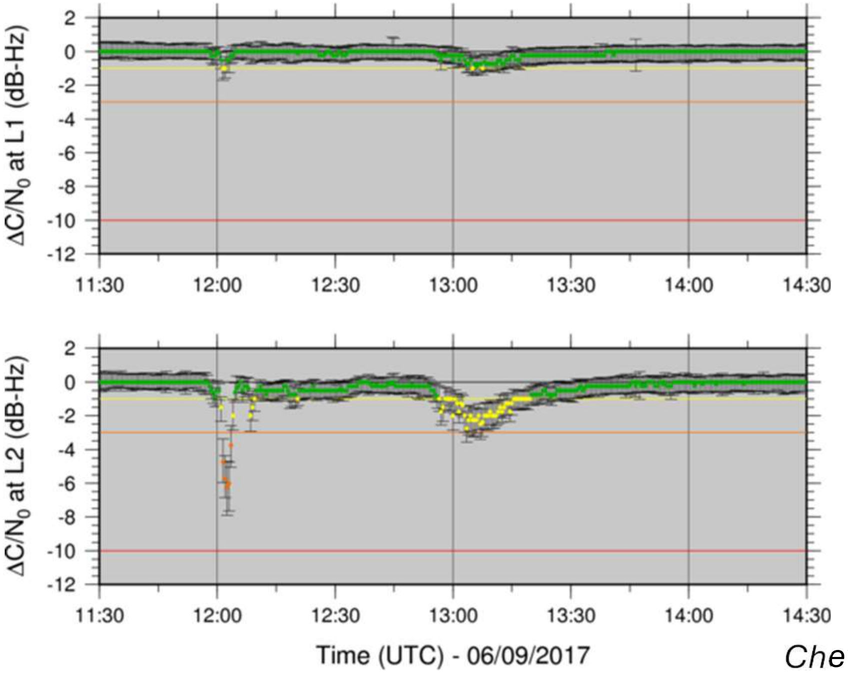
SRB IMPACT ON GPS SIGNAL RECEPTION

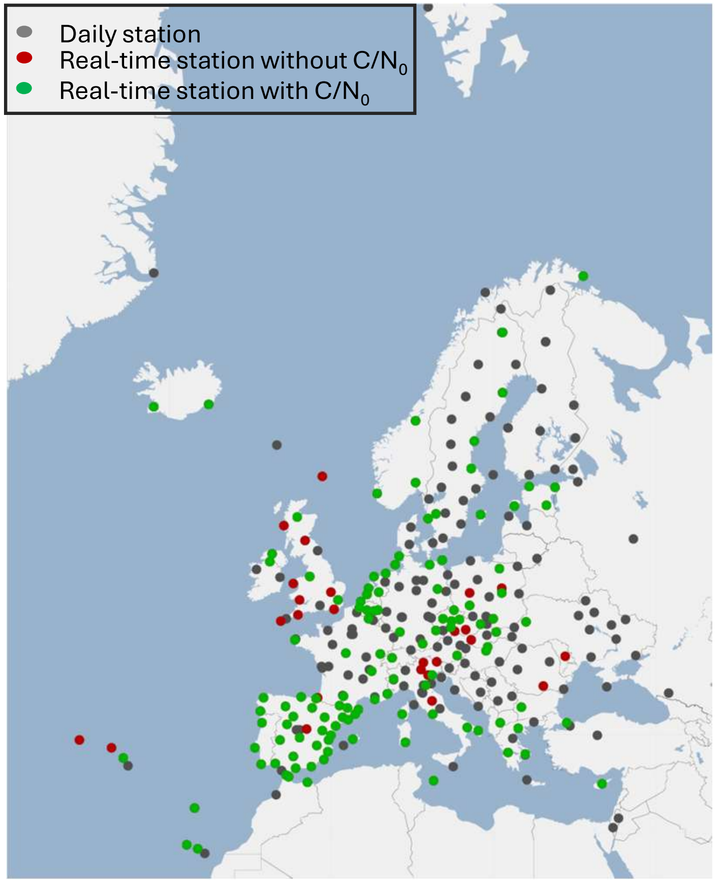


Median of the GPS abnormal variation of the L1C, L2C, L2P and L5C signal receptions from the EUREF Permanent Network due to the solar radio burst of the 9th May 2024

Monitoring of the abnormal fade of GNSS signal reception due to SRB

Level	GNSS $\Delta C/N_0$ Fade	Effect
Quiet	>-1dB-Hz	none
Moderate	-1 dB-Hz	SRB detected but should not impact GNSS applications
Strong	-3 dB-Hz	Potential impact on GNSS applications
Severe	-10 dB-Hz	Potential failure of the GNSS receivers





Chevalier et al., URSI GASS 2017

Summary

- GNSS can provide a global view of the Ionospheric Total Electron Content using large GNSS station networks

- With GNSS ground stations the electron density vertical profile cannot be directly retrieved. GNSS data are also limited over the oceans

- Ionospheric activity impacting GNSS applications can be monitored with
  - variation of TEC w.r.t. the ionosphere climatological state
  - TEC rapid variability

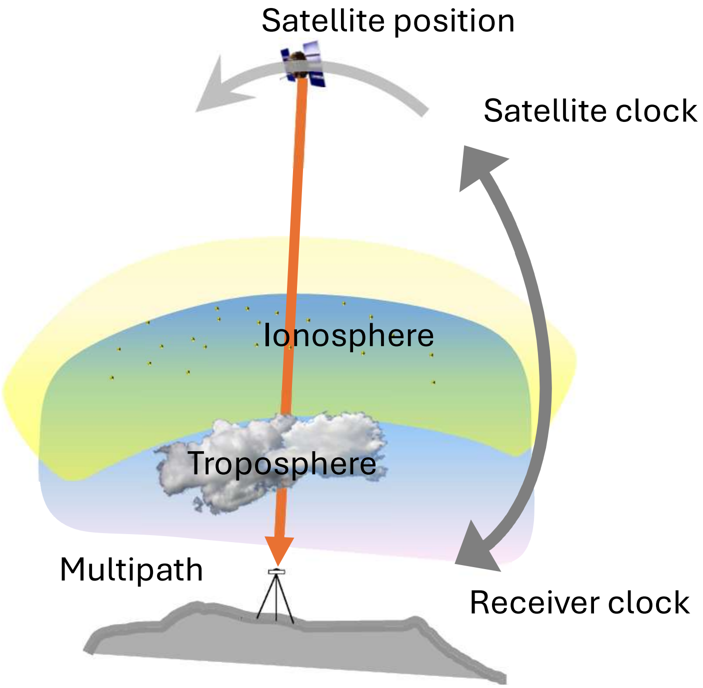
- Solar Radio Bursts in the GNSS frequency bands can be monitored using GNSS networks

Backup – GNSS Disturbances & Monitoring

What's in GNSS measurements ?

Code Pseudorange

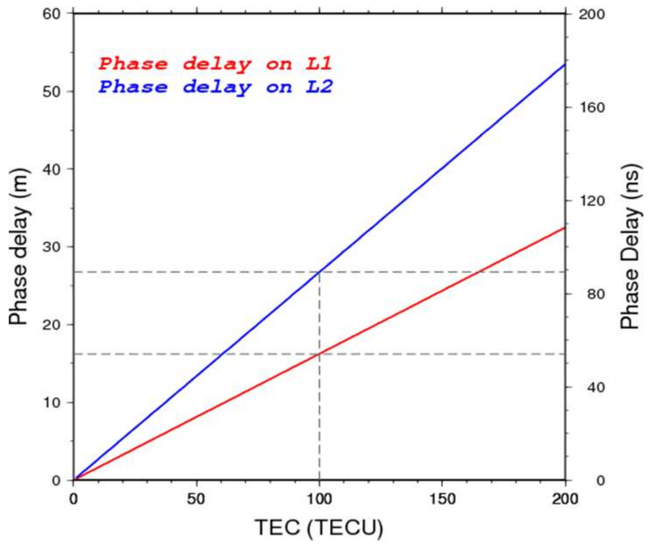
$$P_{\underset{\text{Signal freq.}}{\textcircled{1,2}}} = \underbrace{\rho_{1,2}}_{\text{Geometric range}} - \underbrace{c\Delta t_{rec} + c\Delta t_{sat}}_{\text{Clocks offset}} + \underbrace{I_{1,2}}_{\text{Ionospheric delay}} + \underbrace{Tr}_{\text{Tropospheric delay}} + \underbrace{\delta^{P}_{1,2}}_{\text{Instrumental delays}} + \underbrace{\epsilon^{P}_{1,2}}_{\text{Noise}}$$



$$I_{1,2} = 40.3 \frac{STEC}{f_{1,2}^{\;2}}$$

Geometry free combination

$$\begin{aligned} P_I &= P_2 - P_1 \\ &= I_2 - I_1 + \delta + \epsilon \\ &= 40.3 \left(\frac{1}{f_2^{\;2}} - \frac{1}{f_1^{\;2}} \right) STEC + \delta + \epsilon \end{aligned}$$



Phase measurement

$$\lambda_i\Phi_i = \rho_i - c\Delta t_{rec} + c\Delta t_{sat} + c(-I_i + Tr + \delta_i^{\varphi}\ \ ) + \lambda_i N + w_i + \varepsilon_i^{\varphi}$$

Phase noise and multipath

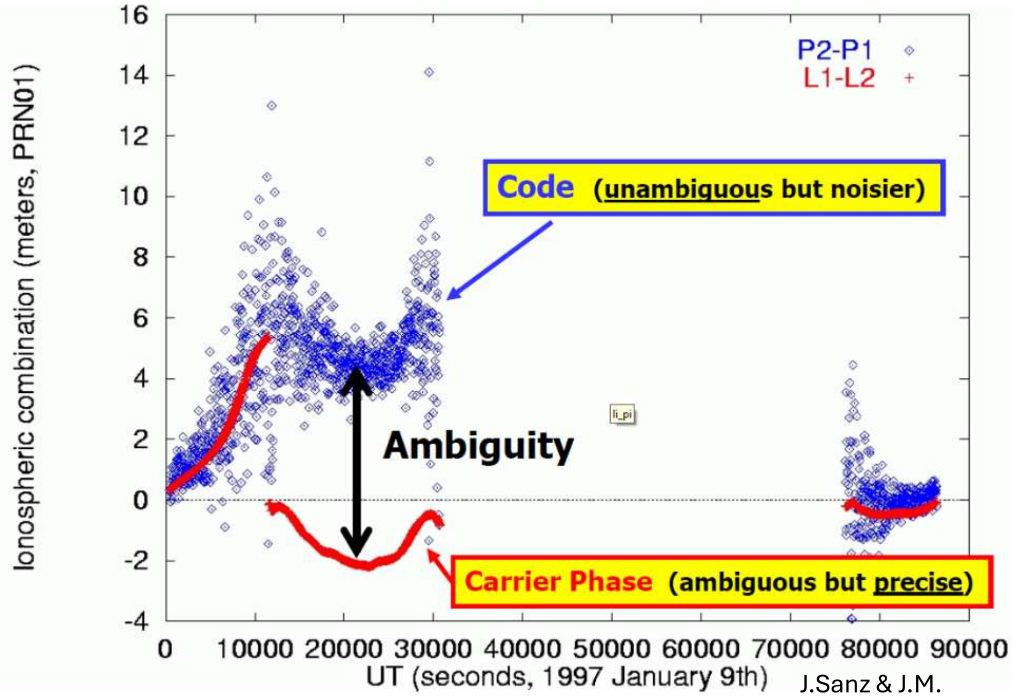
Phase delays

ambiguity

windup

Measurement in cycles

λ_i = wavelength of f_i

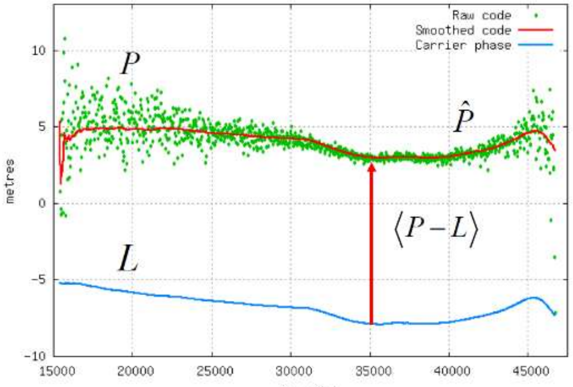


J.Sanz & J.M. Juan

Geometry free combination

$$\begin{aligned} L_I &= L_1 - L_2 \\ &= I_2\ - I_1 + \lambda_i N + \epsilon \end{aligned}$$

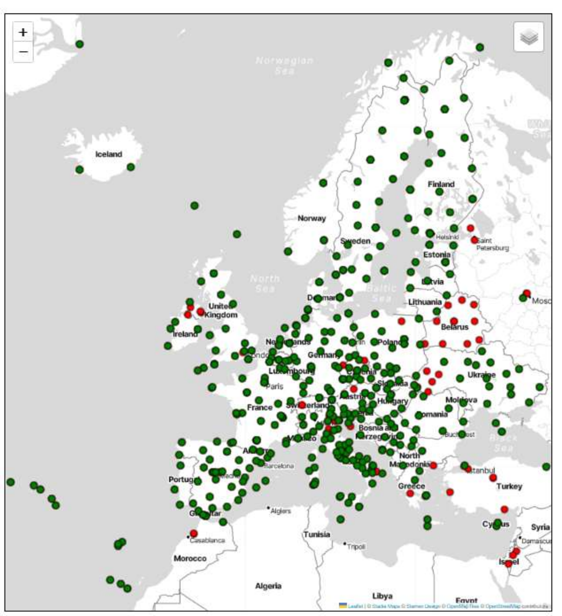
The **noisy unambiguous code** can be **smoothed** with the **precise ambiguous carrier**



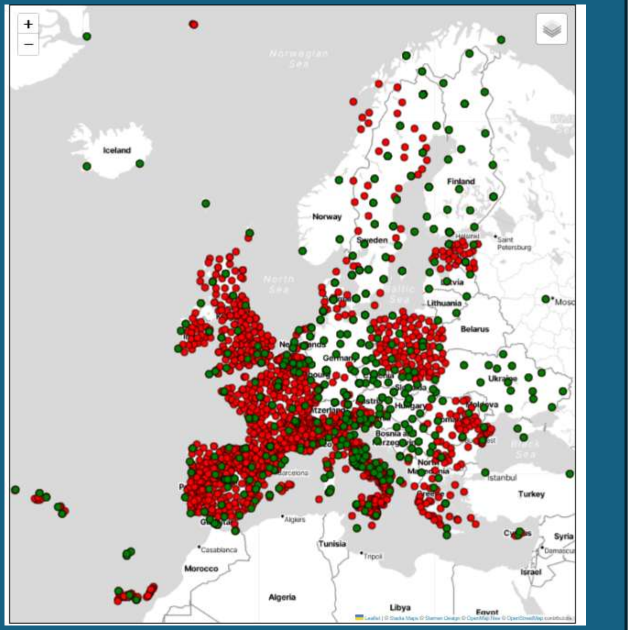
J.Sanz & J.M.

GNSS-NETWORKS

EUREF 500+ GNSS

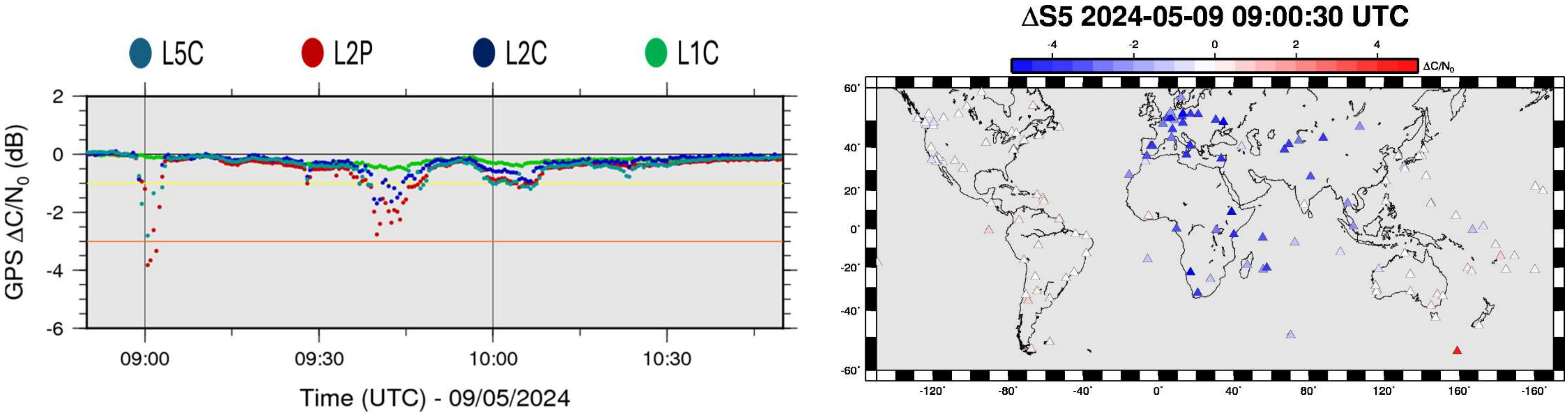


EPOS 2700+ GNSS



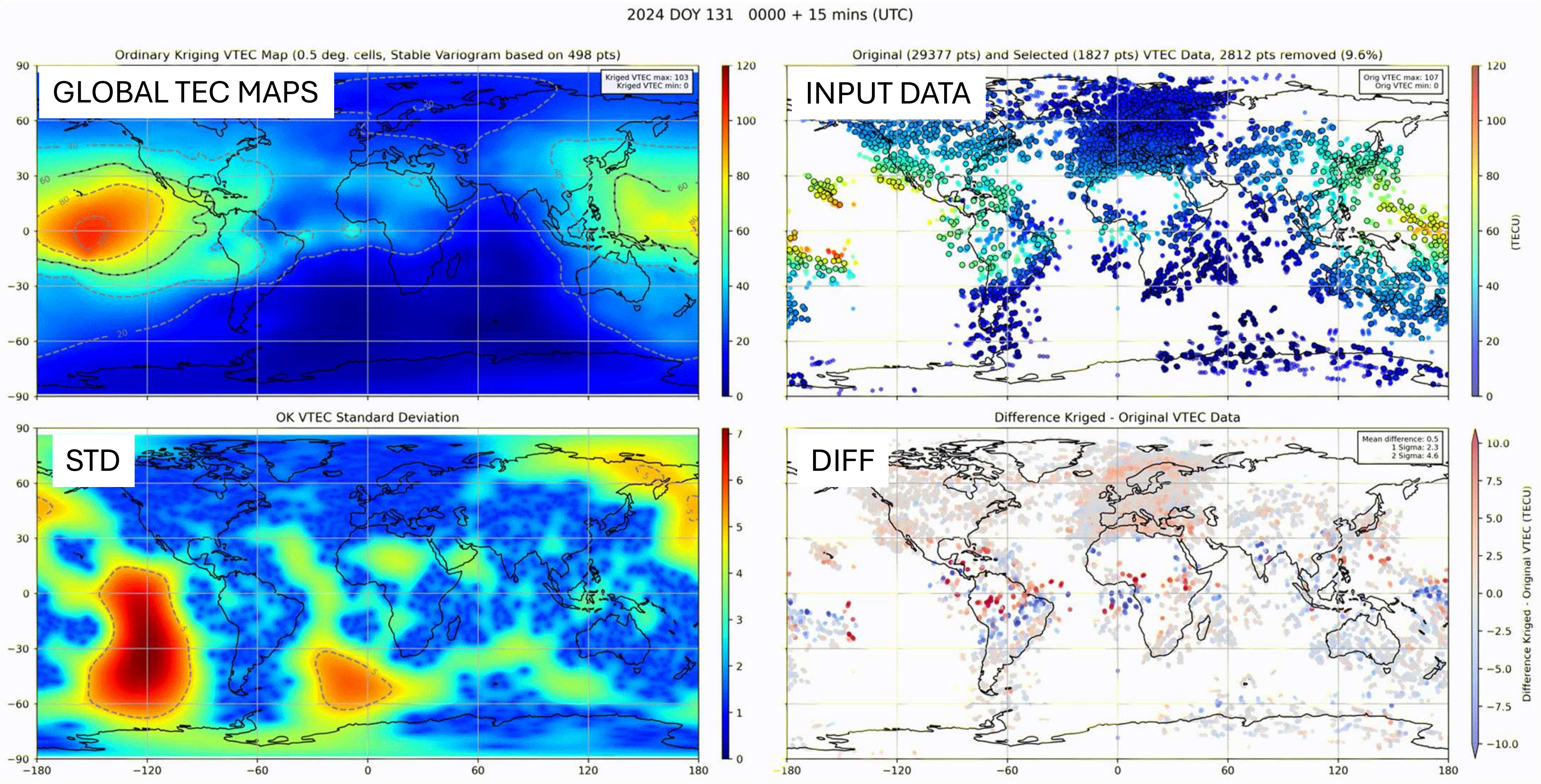
GNSS group - ROB

SRB IMPACT ON GPS SIGNAL RECEPTION



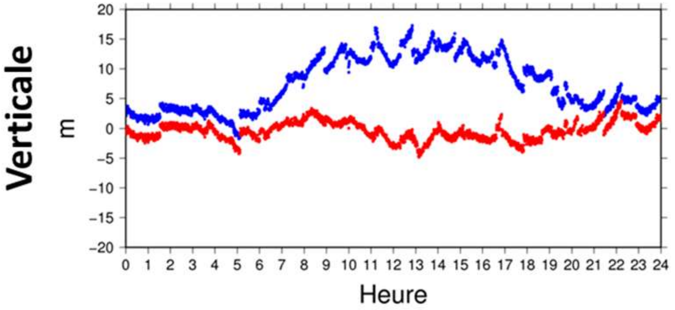
Median of the GPS abnormal variation of the L1C, L2C, L2P and L5C signal receptions from the EUREF Permanent Network due to the solar radio burst of the 9th May 2024

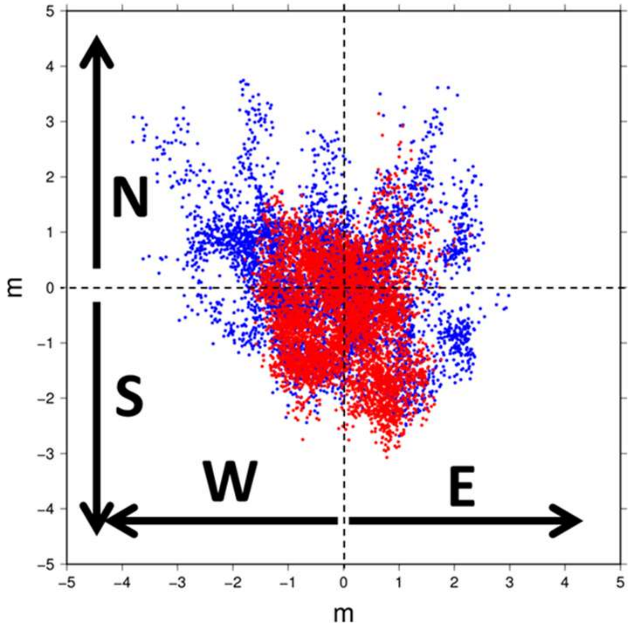
ROB GLOBAL TEC MAPS



Dreyer J.

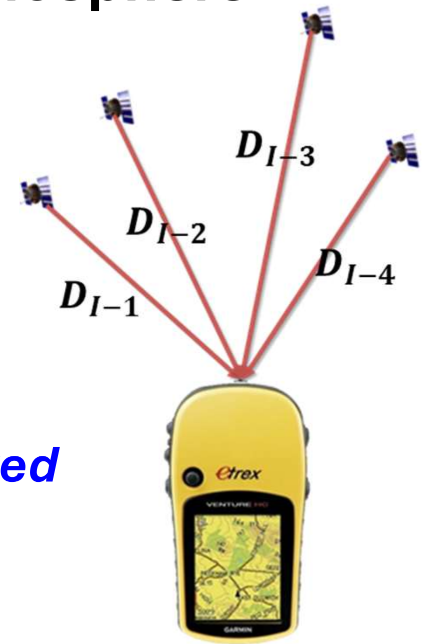
GNSS disturbances due to Ionosphere

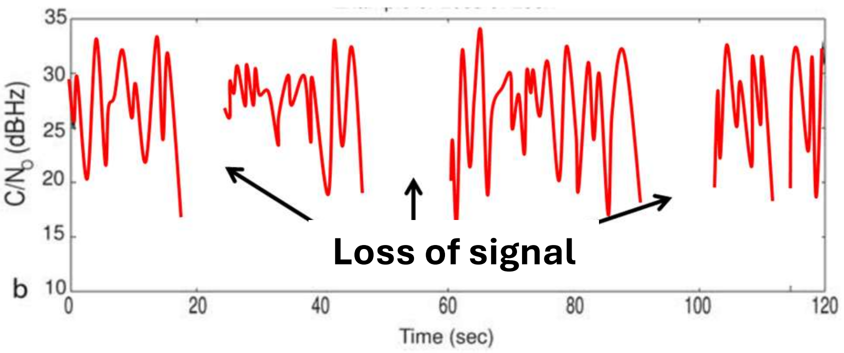




D_{Iono} *corrected*

D_{Iono} *uncorrected*





GNSS disturbances due to Ionosphere

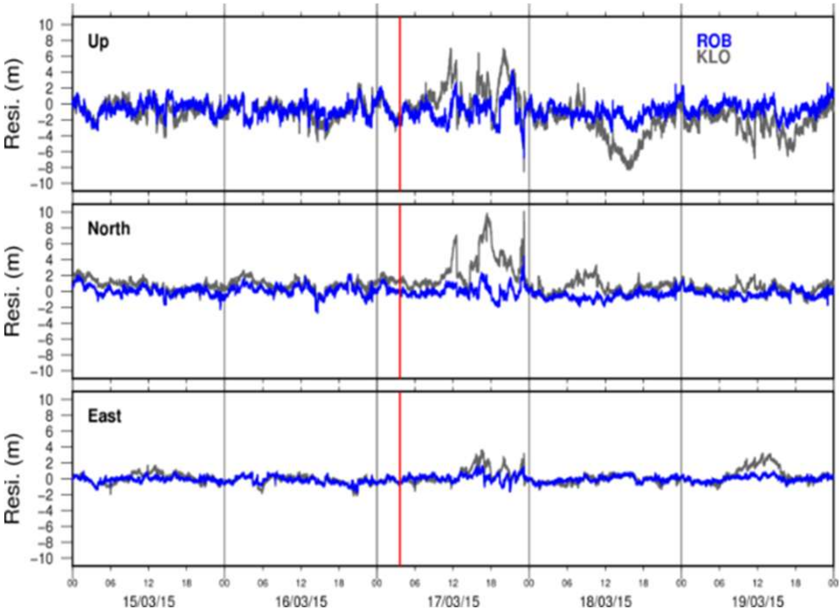
For a GNSS permanent station

	Dispersive Ionospheric Effect (GPS L1)		
Ionosphere	**1st Order**	**2nd Order**	**3rd Order**
100 TECU	16 m	0-2 cm	0-2 mm


@NASA, *Christie Ponder*

The 2003 Halloween solar storms were so powerful that auroras were seen as far south as Texas and Florida. This aurora image was taken near Houston Texas on Oct. 29, 2003.

Position of the GNSS station at Brussels during 2015 March Storm (*W. Huang and P. Defraigne*)



Correction using Klobuchar ionospheric model

East	10 ± 80 cm
North	100 ± 140 cm
Up	120 ± 210 cm

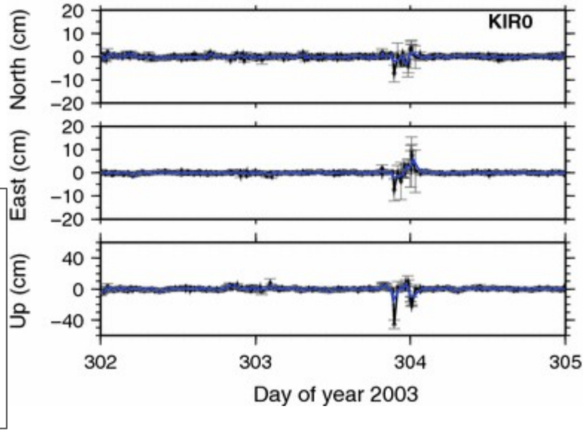
Correction using ROB-TEC products

East	**6 ± 40 cm**
North	**9 ± 66 cm**
Up	**76 ± 150 cm**

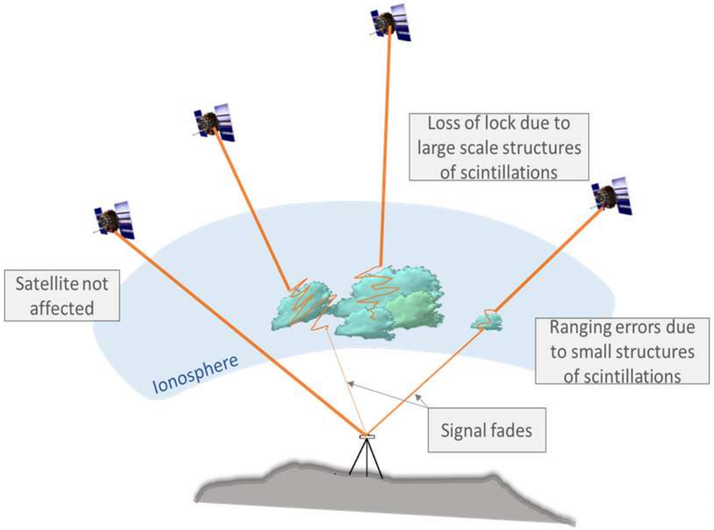
Repeatability of the kinematic positions in Northern Europe (*Bergeot et al.*)

Quiet ionosphere: in horizontal ≤1 cm
in vertical ≈2.5 cm

Halloween storm 2003:
North, East : **12.8cm and 8.1 cm**
Vertical: **26.1 cm**

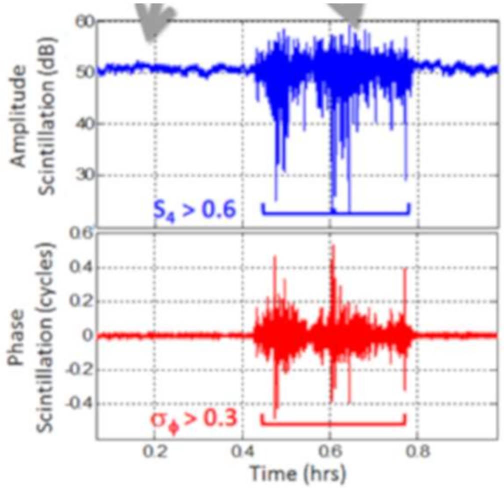


GNSS disturbances due to Ionosphere

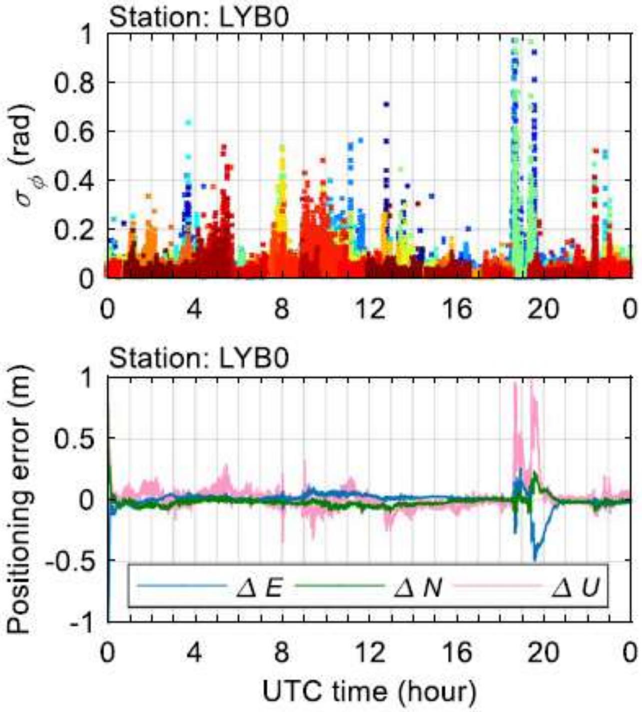


Scintillation affects the phase and the amplitude of GNSS signals, causing cycle slips up to the loss of lock.

Induce error positioning up to several meters, with worst case scenario: GNSS signal loss.

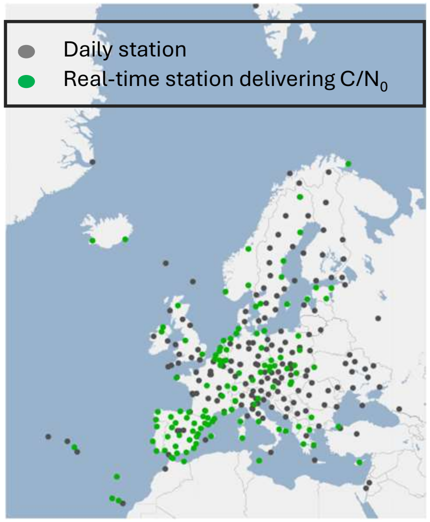


Data supplied by J.-M. Sleewaegen, Septentrio, Belgium



Scintillation index and error positioning ≥0.5m using single-frequency PPP with a reference GNSS station in Norway. Guo et al., 2020

Data and Method



- GPS **carrier to noise density** (**C/N$_0$**) observations corresponding to **L1C/A** and **L1P(Y)+L2P(Y)** signals from the EUREF Permanent Network (EPN)
- Estimation of the **C/N$_0$ abnormal fade for each satellite-receiver pair at each epoch** (30s sampling) by comparing with **the C/N$_0$ quiet normal behaviour**, i.e. the median <C/N$_0$(*t, rec, sat*)> of the 7 previous ground track repeat cycles (1 sidereal day for GPS).

$$\Delta C/N_0\,(t,\ rec,\ sat) = C/N_0\,(t,\ rec,\ sat) - <C/N_0\,(t,\ rec,\ sat)>$$

- Estimation of a **<ΔC/N$_0$>$_{L1,L2}$ over the GNSS network** at each epoch (Figure 3), to highlight SRBs as the source of signal reception fade and discard other potential sources such as scintillations, local RFI or hardware problems.

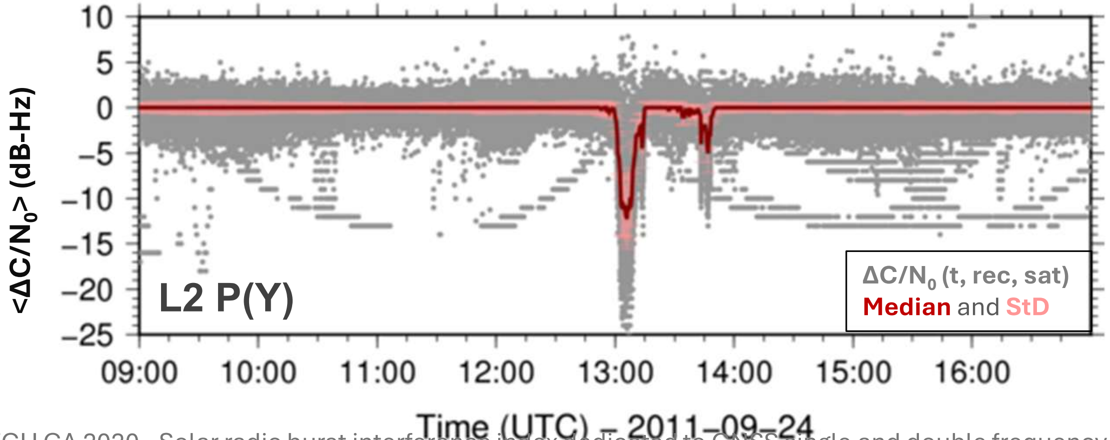


Figure 3: abnormal GPS L2 P(Y) ΔC/N$_0$ fade for each observations of the EPN (grey) and the median <ΔC/N$_0$>$_{L2}$ (in red) over the EPN during the SRB 24/09/2011

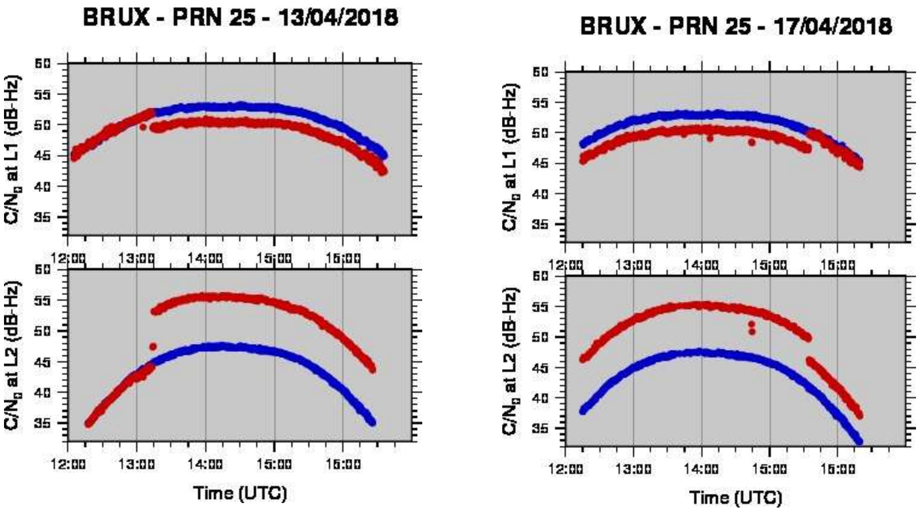
EGU GA 2020 - Solar radio burst interference index dedicated to GNSS single and double frequency users - Chevalier et al.

Backup slide – GPS FLEX POWER

False SRB alerts, real signal reception changes

GPS Flex Power

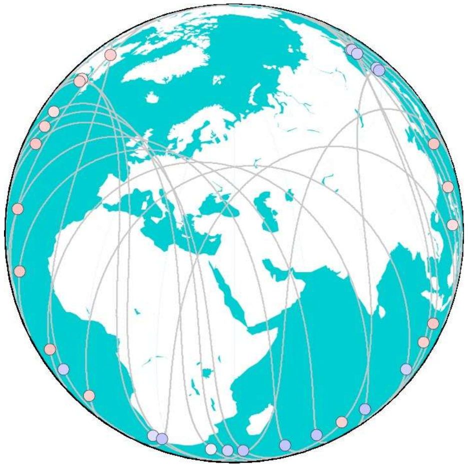
- “Anti-jam flex power” on **block IIR-M, IIF** and **IIIA** GPS satellites
- **Modulation of power distribution** between the L1, L2 signal components, operated since 2017 (IIR-M and IIF) without being reported.
- Operated **globally** or within **specific zones** (hours to months)
- When applied, **increase or decrease of Carrier to Noise density ratio (C/N_0)** are observed by the ground stations.



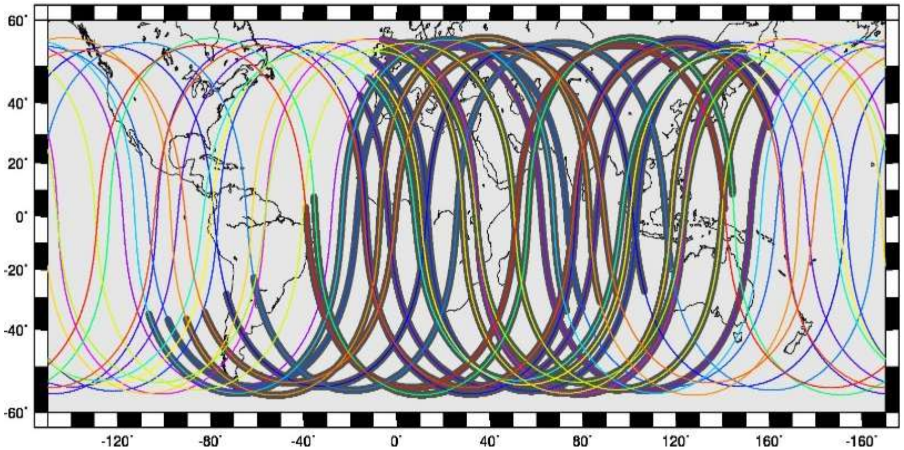
Flex power campaign of the 13th April 2018 operated on the block IIF and IIR-M satellites.
top plot: C/N_0 (in red) and its expected behaviour (in blue) for the track of PRN25 by BRUX

Where is flex power activated?

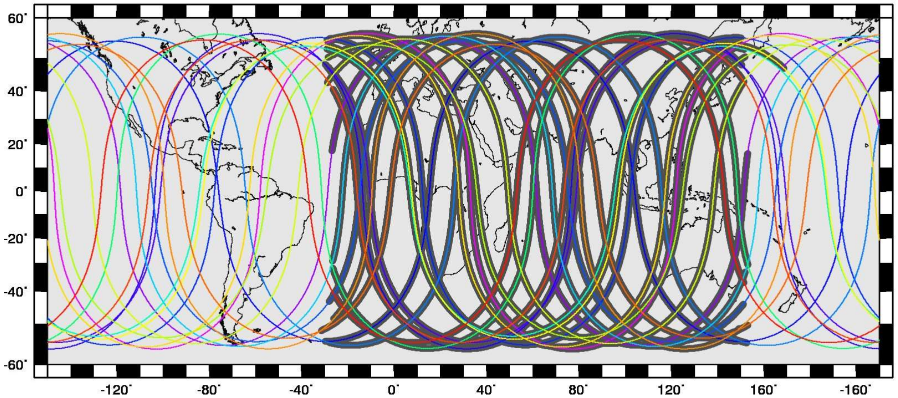
- Globally or over a large continental area
  - Activation/deactivation for satellites visible from a point on the ground
  - Can combine inclusion and exclusion zones
  - Activation between 2 longitudes



Mode I: Jan 2017 – Feb 2020



Mode X: Aug. 2020

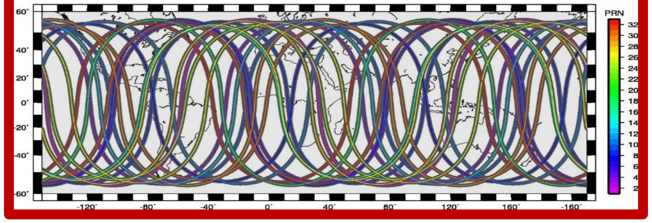


Mode VI: Nov 2021 - Jun 2022

Which activation area by mode?

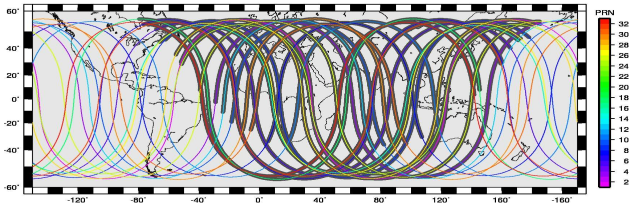
Most operated modes

Global



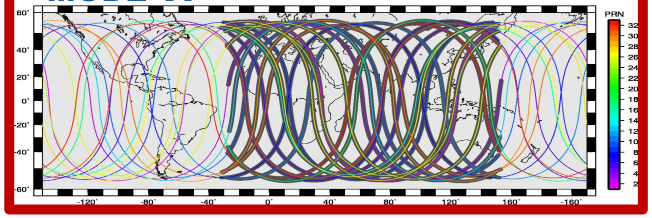
MODE V

2020 105



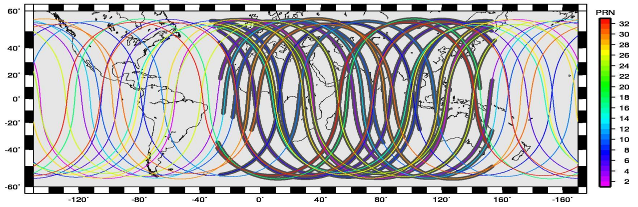
MODE VI

2020 126



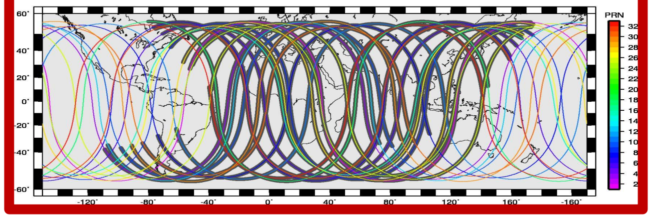
MODE VII

2020 128

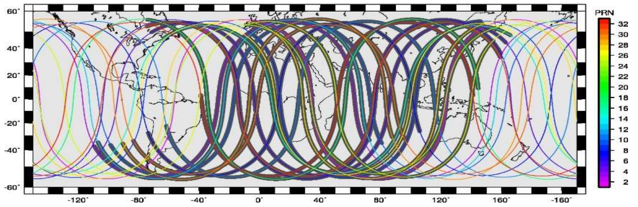


MODE VIII

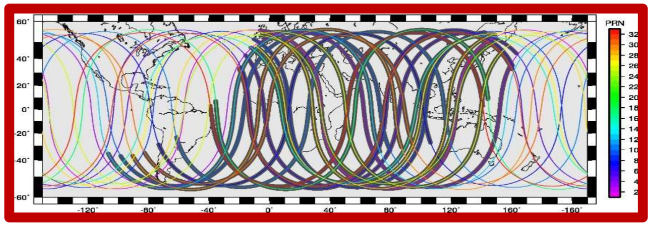
2020 167



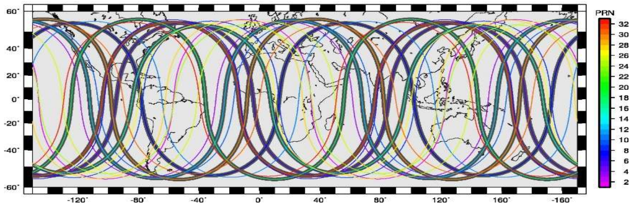
MODE IX



MODE X



MODE XI



MODE XII