Role of the ionosphere and space weather in military communications

SWIC

Solar-Terrestrial Centre of Excellence

8-10 September 2025

Space Weather Monitoring with GNSS

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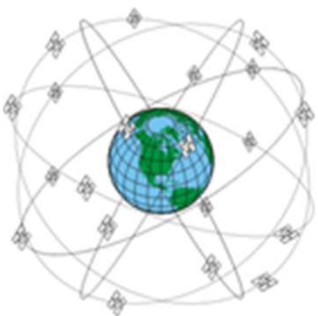
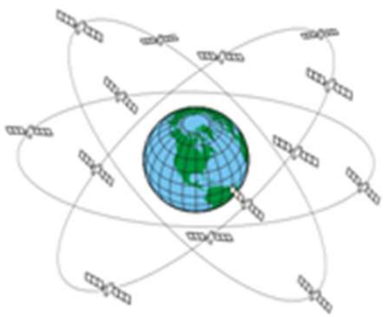
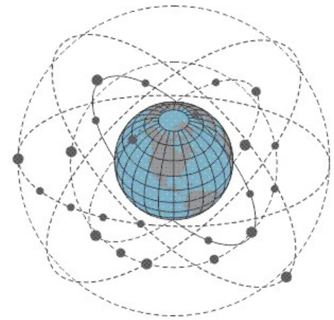
Royal Observatory of Belgium
10/09/2025

GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

GPS
- 6 Orbital planes
- 24 Satellites + Spare
- 55^0 Inclination Angle
- Altitude 20,200km

Galileo
- 3 Orbital planes
- 27 Satellites + 3 Spares
- 56^0 Inclination Angle
- Altitude 23,616km

GLONASS
- 3 Orbital planes
- 21 Satellites + 3 Spares
- 64.8^0 Inclination Angle
- Altitude 19,100km

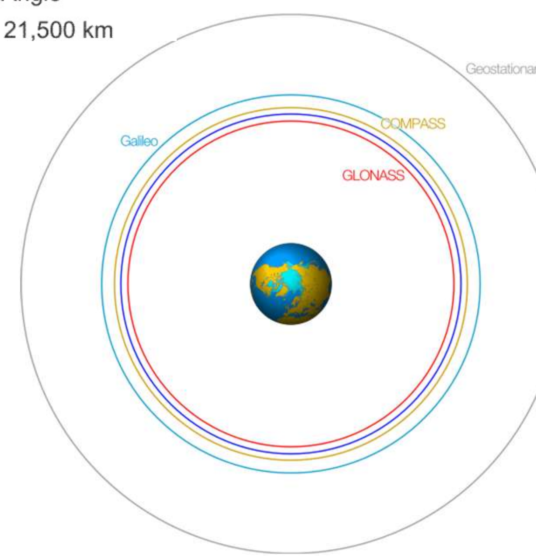
BeiDou

6 Orbital planes

35 Satellites + 5 GEO + 27 MEO + 3 IGSO

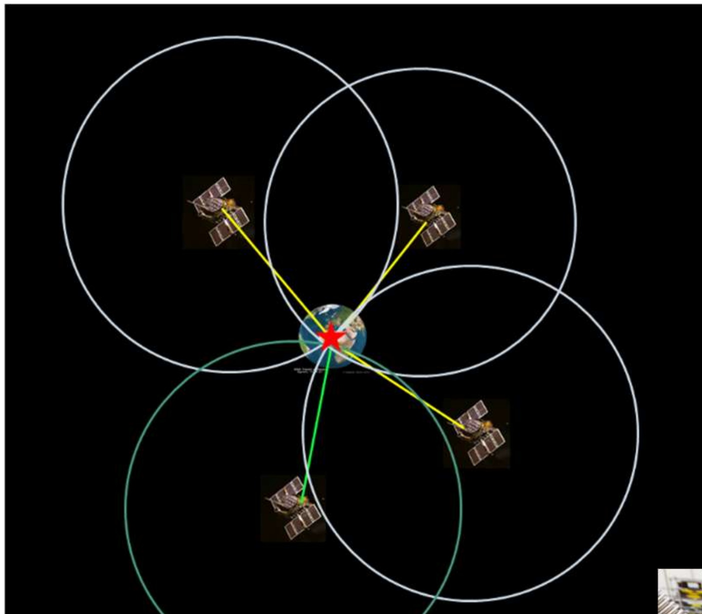
55^{O} Inclination Angle

Altitude 38,300 km, 21,500 km



Satellites signal continuously provide :
- **Satellite ID**
- **Satellite position**
- **Time of the signal transmission**

GNSS positioning basics



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

➡ **At least 4 satellites needed:**

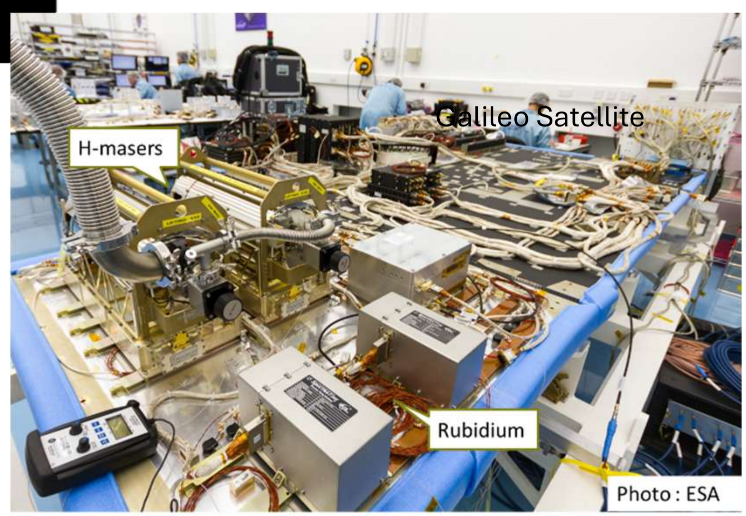
1. **Estimation of the distance between receiver and satellites :**

v=d/t

v= speed of light 299 792 458 m/s

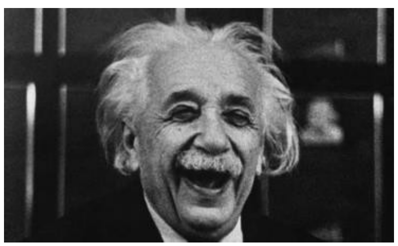
delay of 10 ns (0.00000001 second) ➡ 3m error

2. **Triangulation**

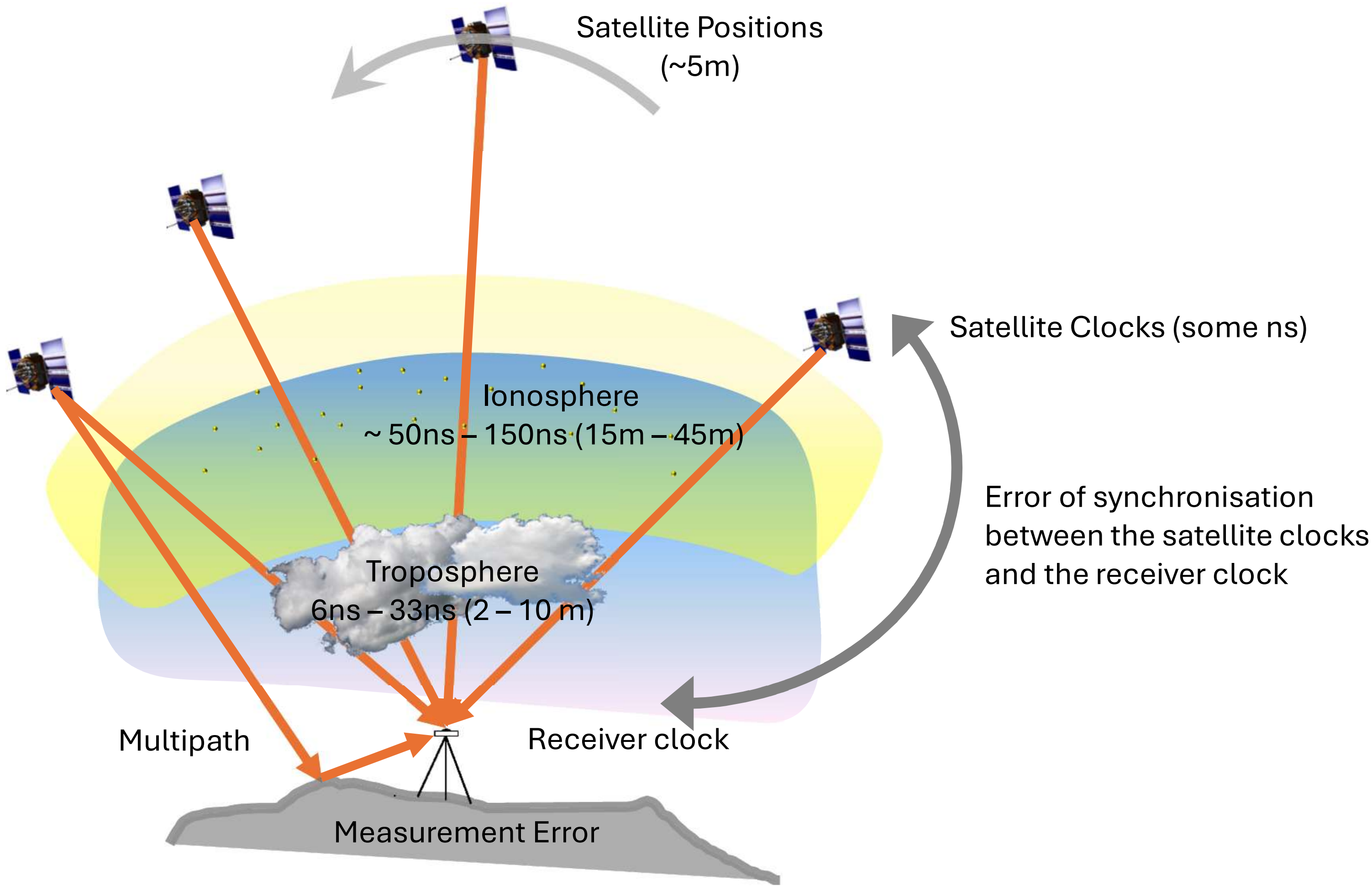


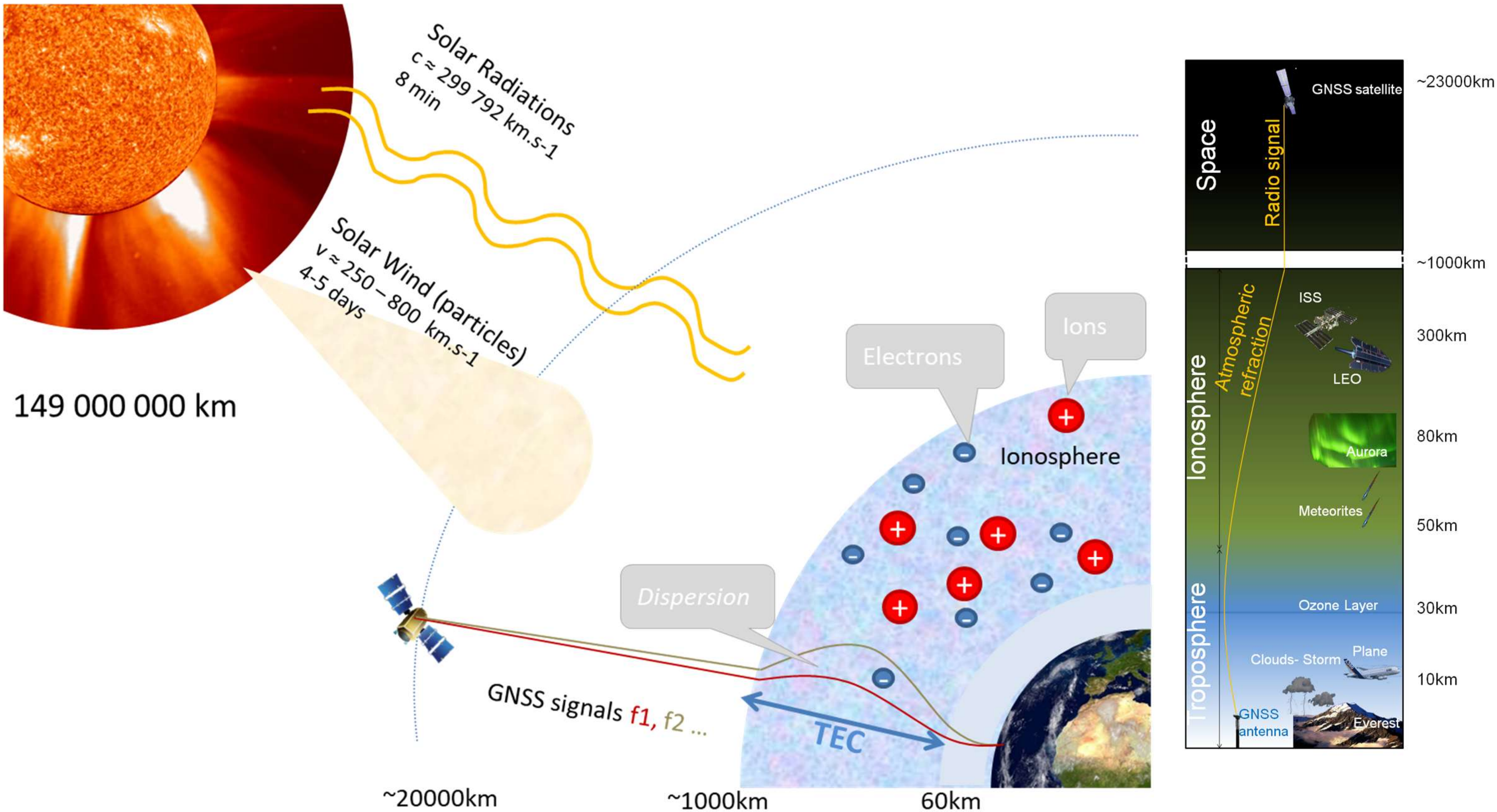
Precise **atomic clocks** in satellites are kept synchronized by the ground control stations

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

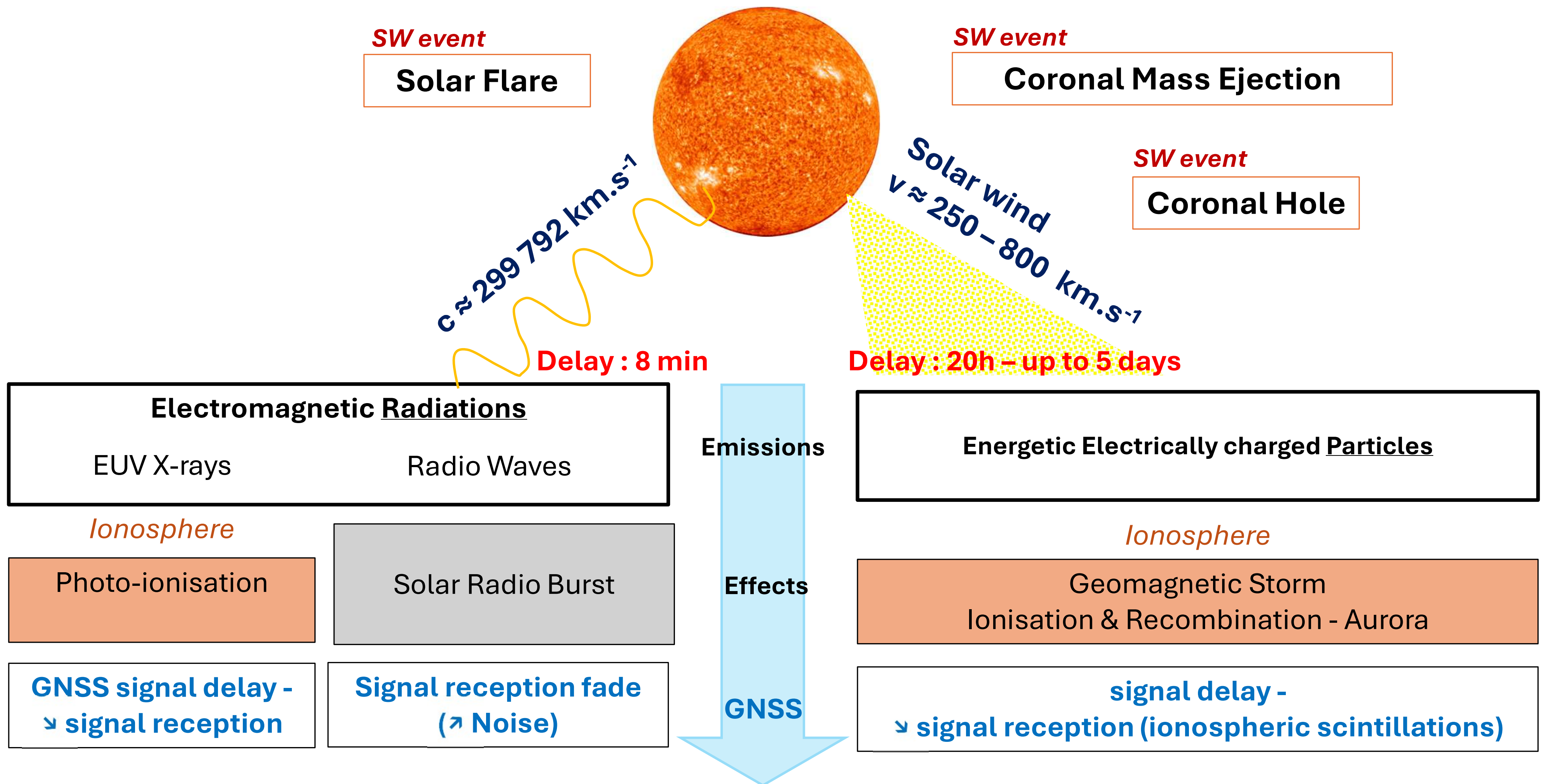


Relavistic effects are corrected in the navigation message and by the receiver, otherwise the error would increase by ~10km everyday.




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

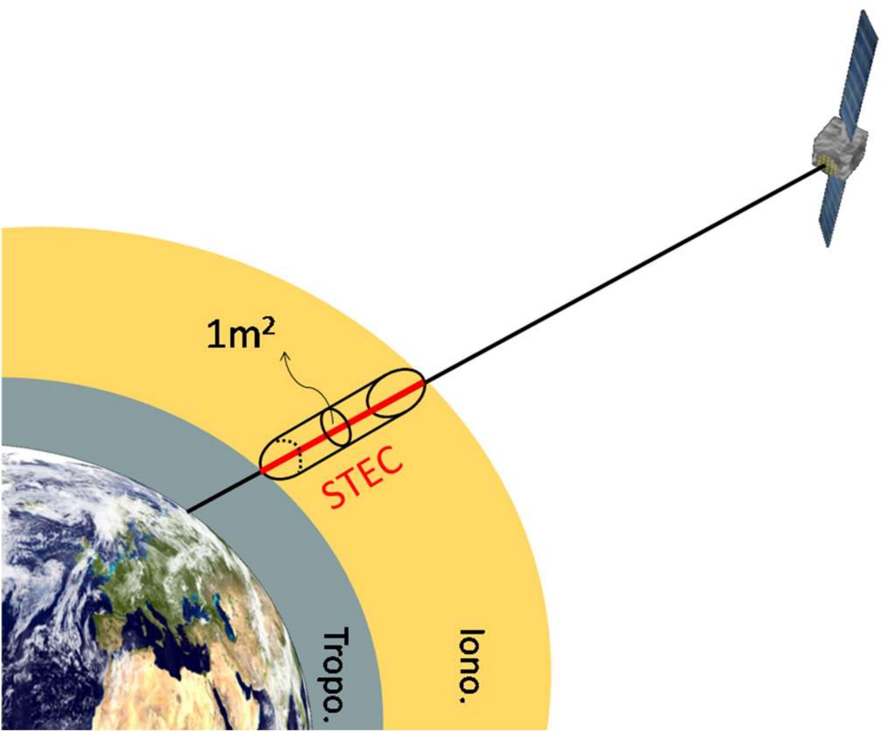
The Sun, Source of Space Weather impacting GNSS



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

** For a permanent GNSS station*

NO MORE IONOSPHERIC PROBLEM FOR GNSS ?

Well, still…

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

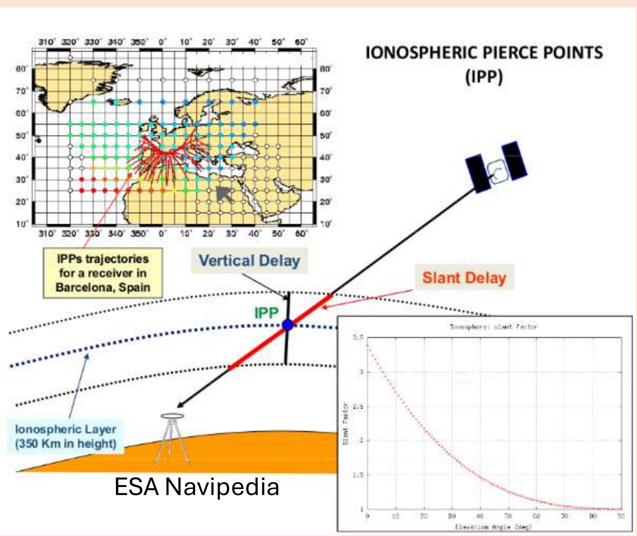
- Double-frequency GNSS receivers **expensive €**.
- Double frequency combination relies on the **tracking quality** of the GNSS signals (**hardware and software**).
- Additional frequencies are **not all public**, and require specific cross-corelated tracking technics
- New public civilian signals such as GPS L2C and Galileo E5, are protected for **safety-related application,** but not yet commonly used

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**.

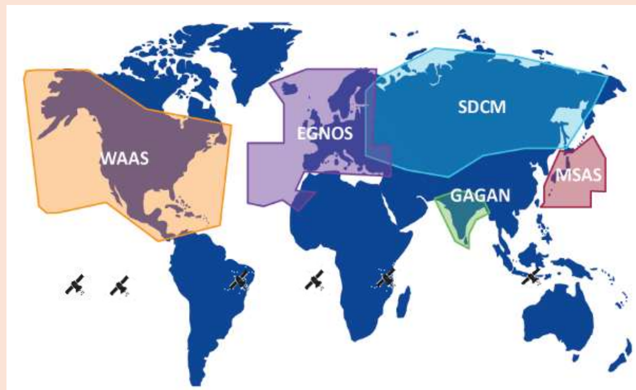
GNSS single-frequency users are not left behind for mitigating the ionospheric effect

Most common (public and free)

Broadcasted parameters in the navigation message with **Klobuchar** and **NeQuick ionospheric models**, correcting more than **50%** of the "normal" **ionospheric range error**. **Do not include space weather events**

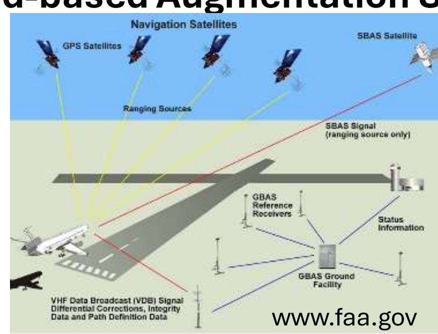


Satellite-based Augmentation Systems



(public and free)

Ground-based Augmentation Systems

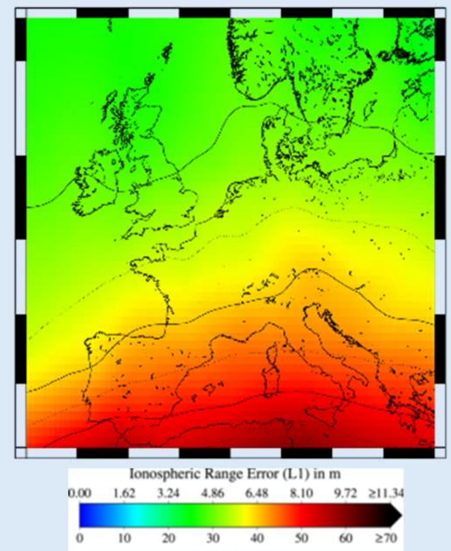


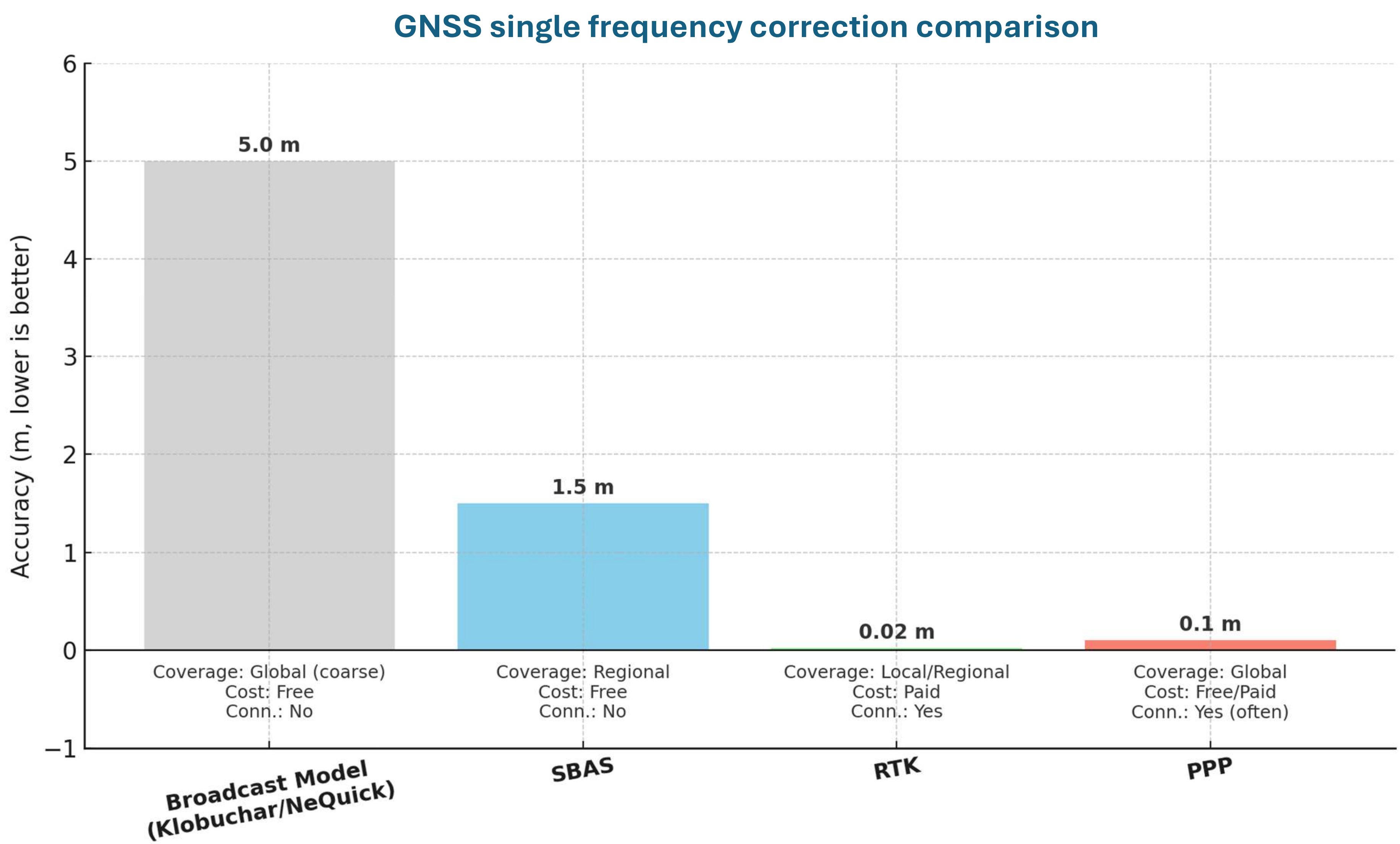
Differential GNSS

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

For SW monitoring

Ionospheric TEC Maps

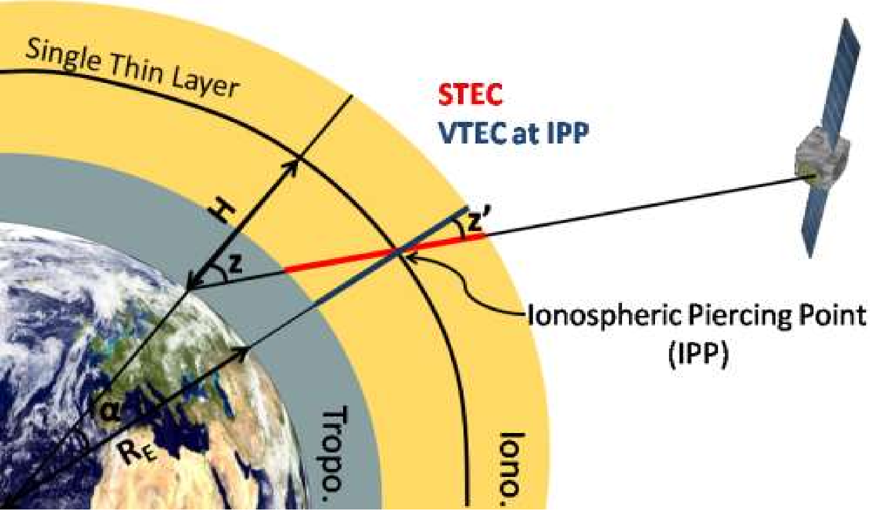



GNSS single frequency correction comparison
Accuracy (m, lower is better)
6
5
4
3
2
1
0
−1
5.0 m
1.5 m
0.02 m
0.1 m
Coverage: Global (coarse)
Cost: Free
Conn.: No
Coverage: Regional
Cost: Free
Conn.: No
Coverage: Local/Regional
Cost: Paid
Conn.: Yes
Coverage: Global
Cost: Free/Paid
Conn.: Yes (often)
Broadcast Model (Klobuchar/NeQuick)
SBAS
RTK
PPP

Monitoring the 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>

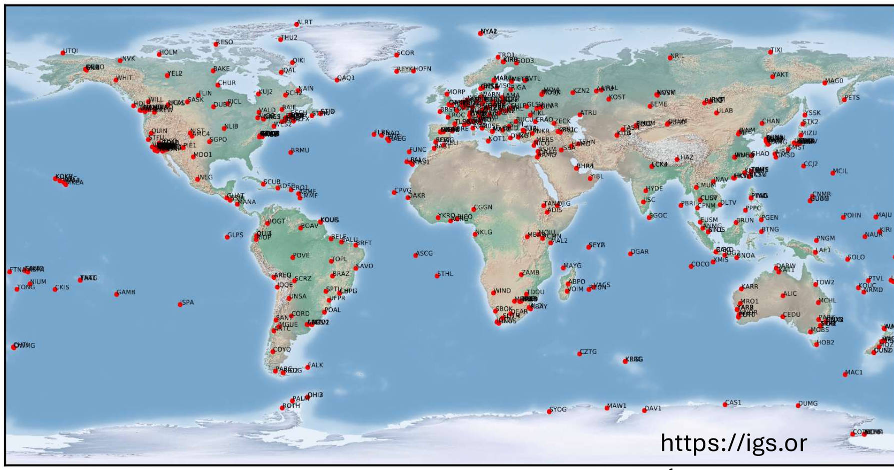
« ionosphere-free » combination ➡ removes 99.9% of the ionospheric delay

« 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 $$STEC = \int_R^S Ne.dl$$

GNSS Permanent Station Networks



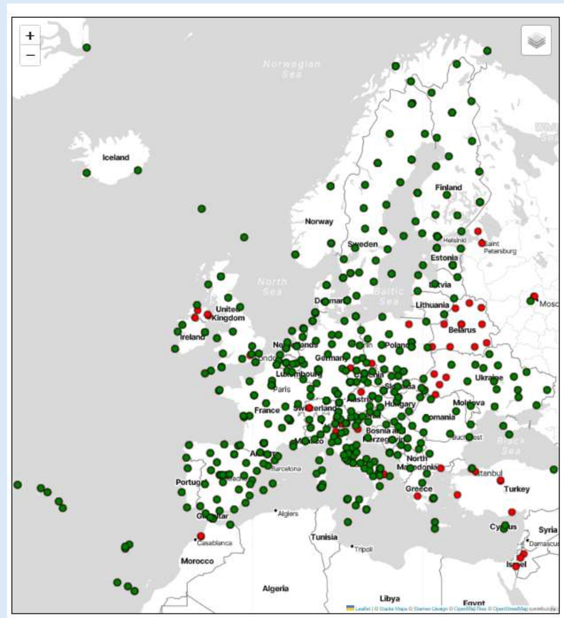
https://igs.or
g

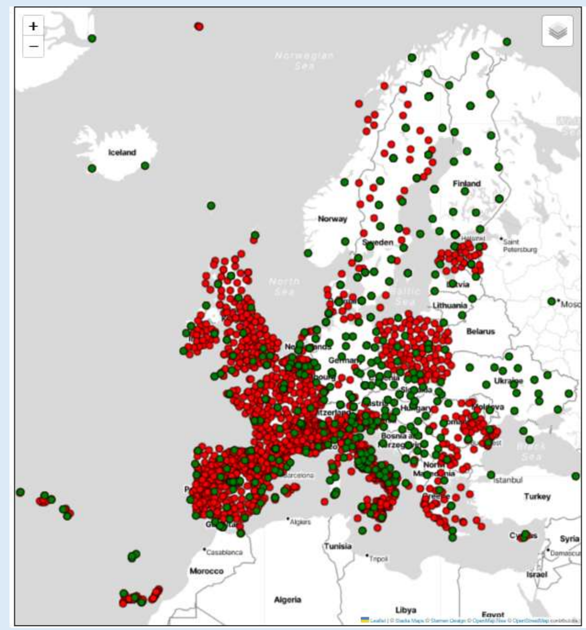
International GNSS Service (IGS)

EUREF Permanent Network
500+ GNSS

www.epncb.oma.be

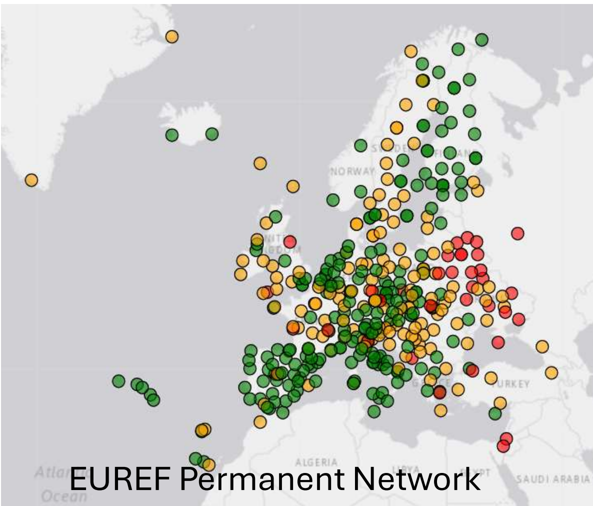
EPOS
2700+ GNSS





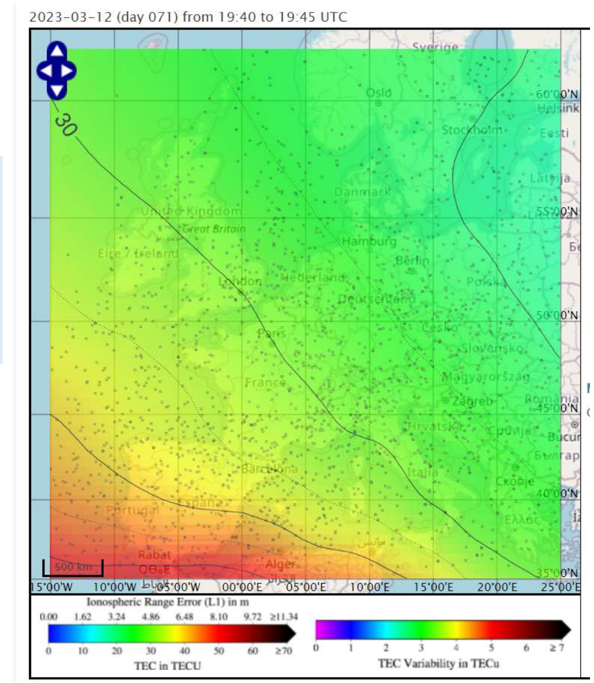
GNSS group – ROB
https://www.gnss.be/

Ionosphere monitoring based on GNSS

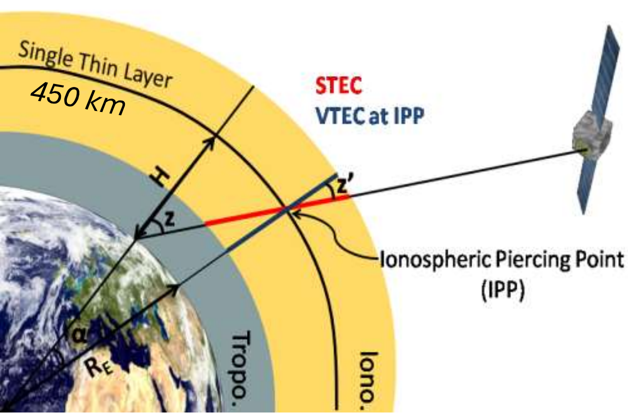


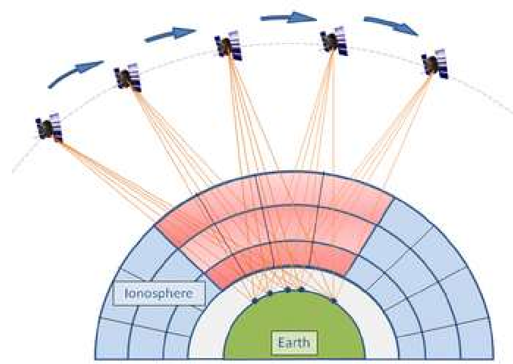
Source of error becomes source of information
ionospheric total electron content is derived from the GNSS station observations

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



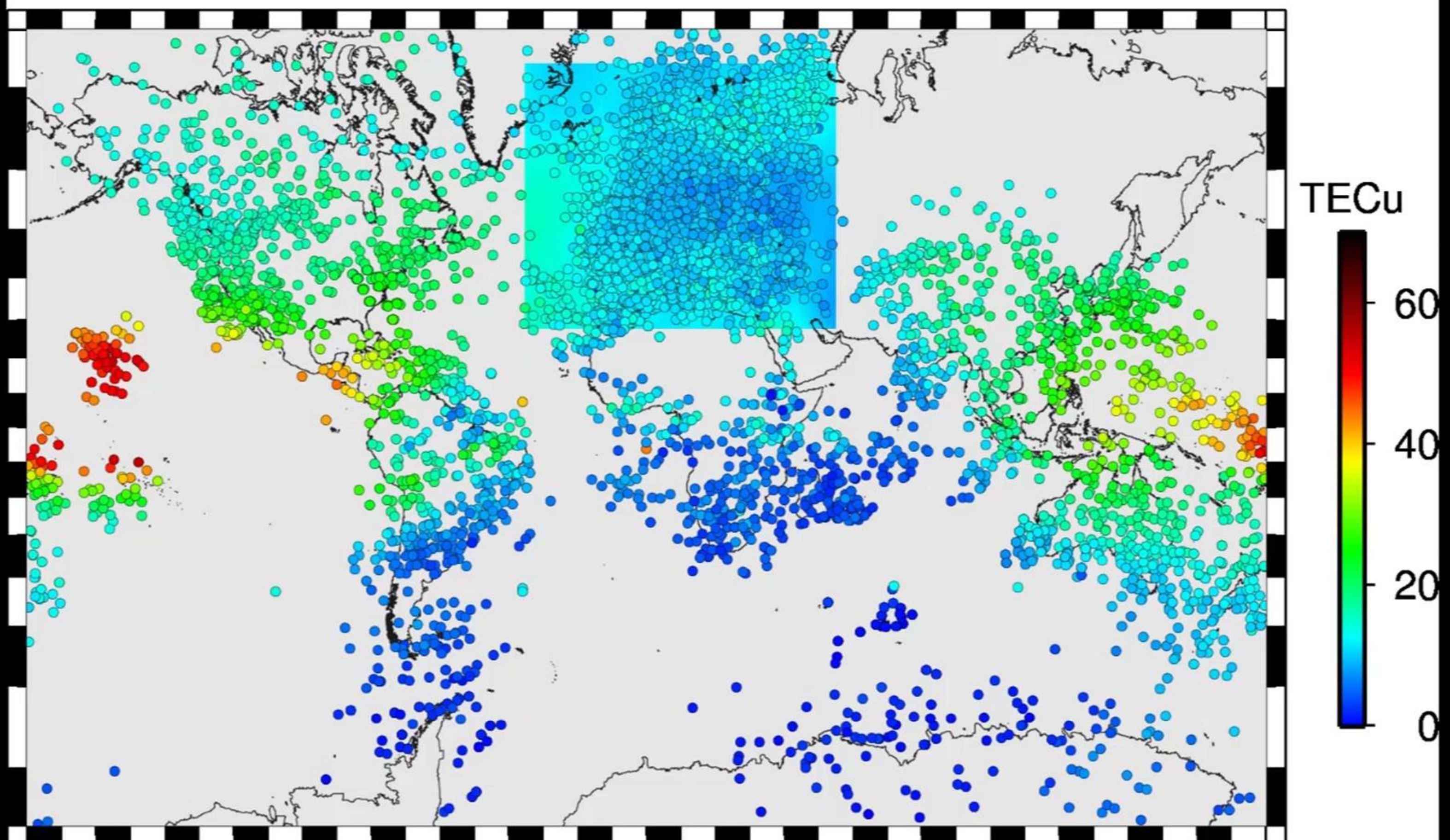
https://www.gnss.be/SpaceWeather/





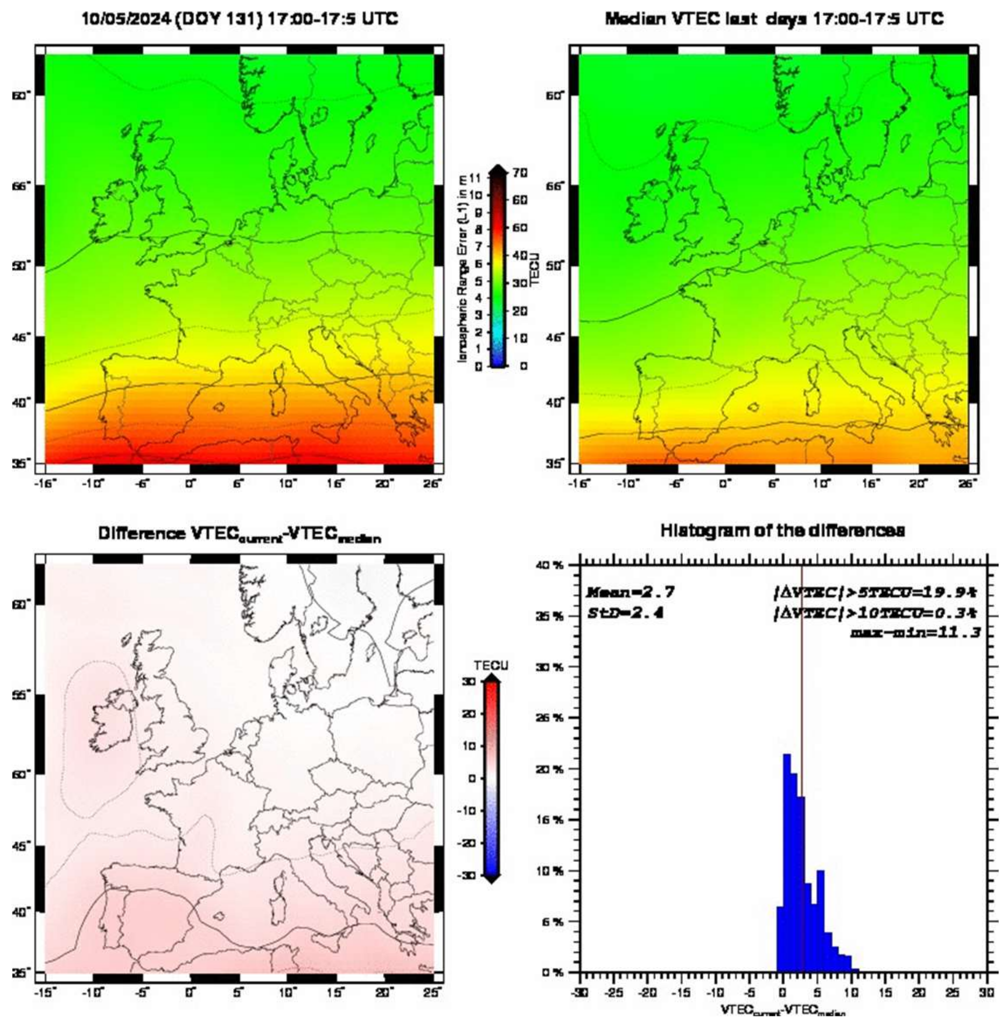
Bergeot, 2014

TEC IPPs



Ipp Total : 9172 Ipp Interp : 5781

Monitoring the ionospheric activity



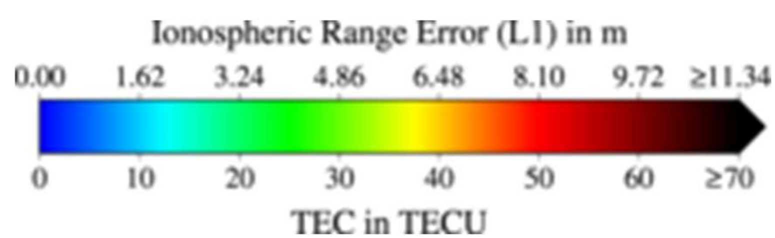
10-11 MAY MOTHER'S DAY STORM

Near-Real Time European TEC Maps

5-min, GPS+GLONASS+GALILEO,

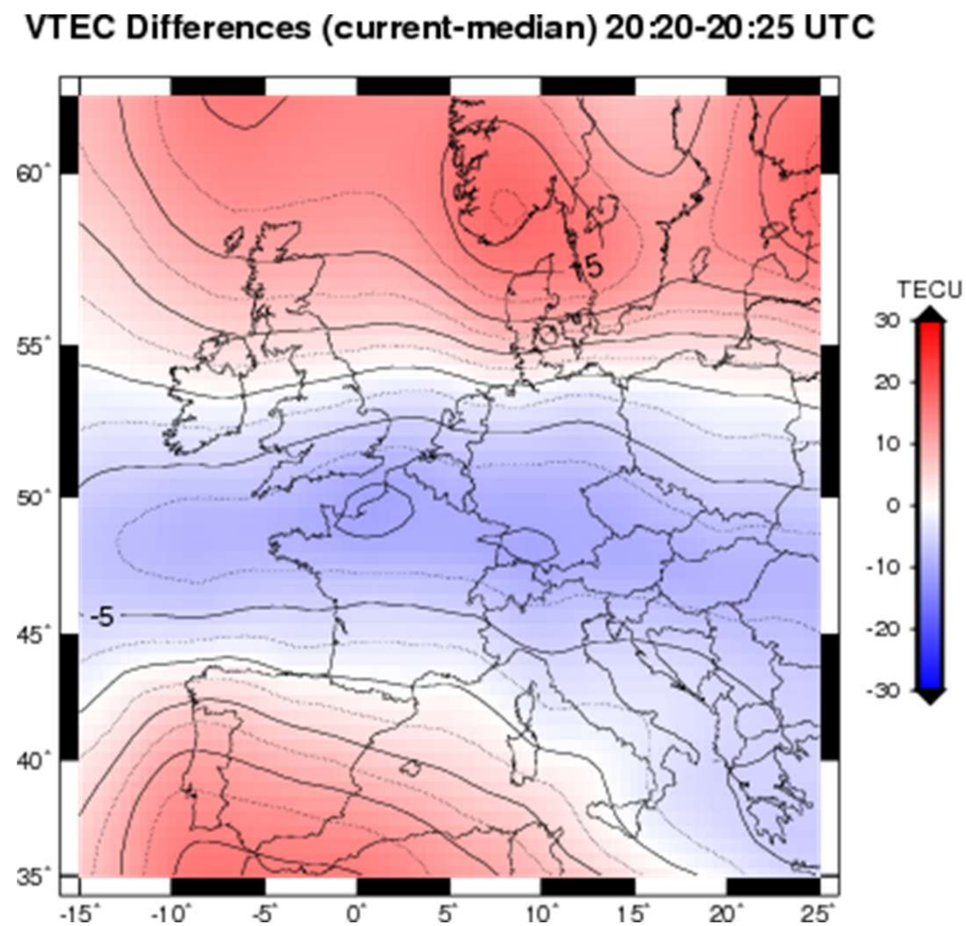
~180 EPN stations

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

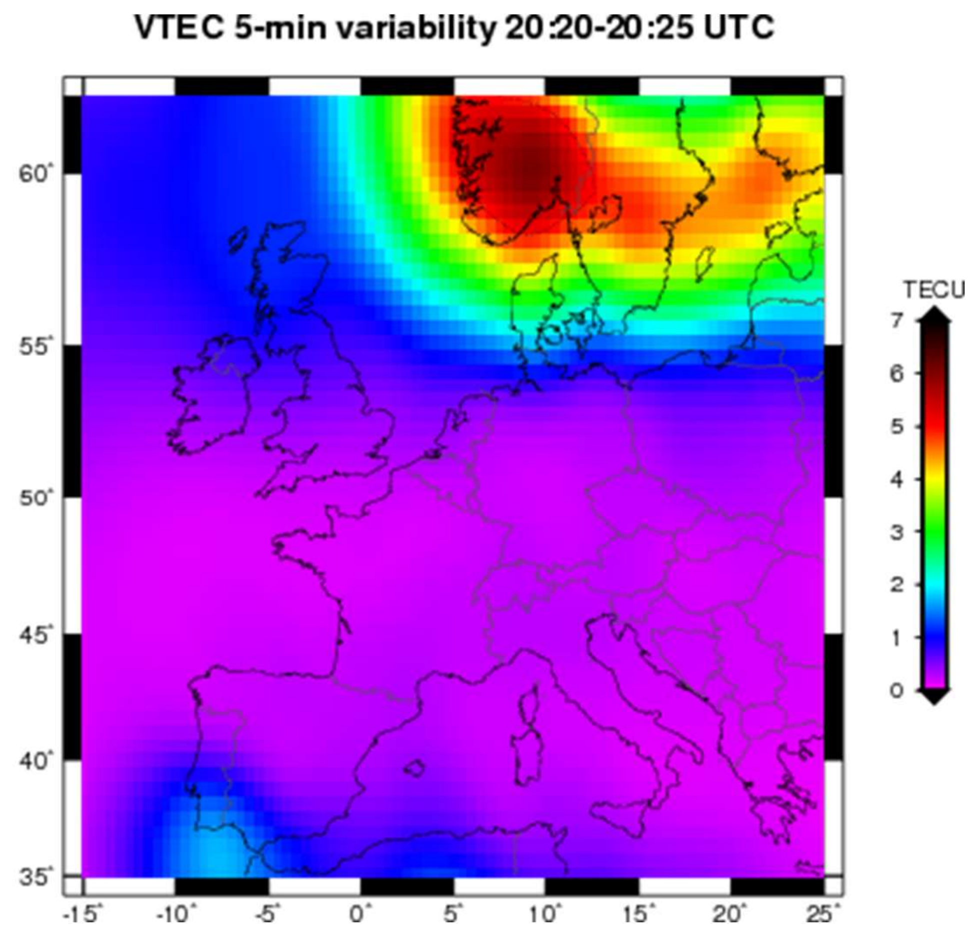


Monitoring the ionospheric activity – Key indicators

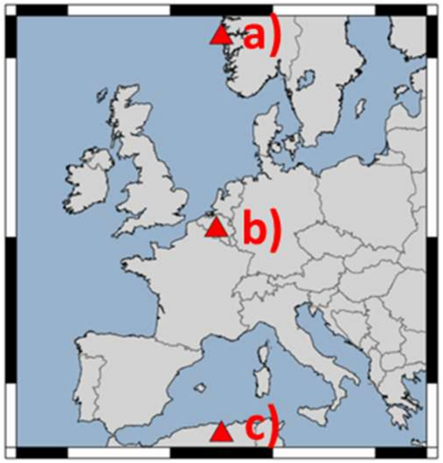
With respect to the « quiet » condition



Rapid ionospheric changes, critical for GNSS applications



Monitoring the ionospheric activity with Time Series



- Left plot:

TEC current

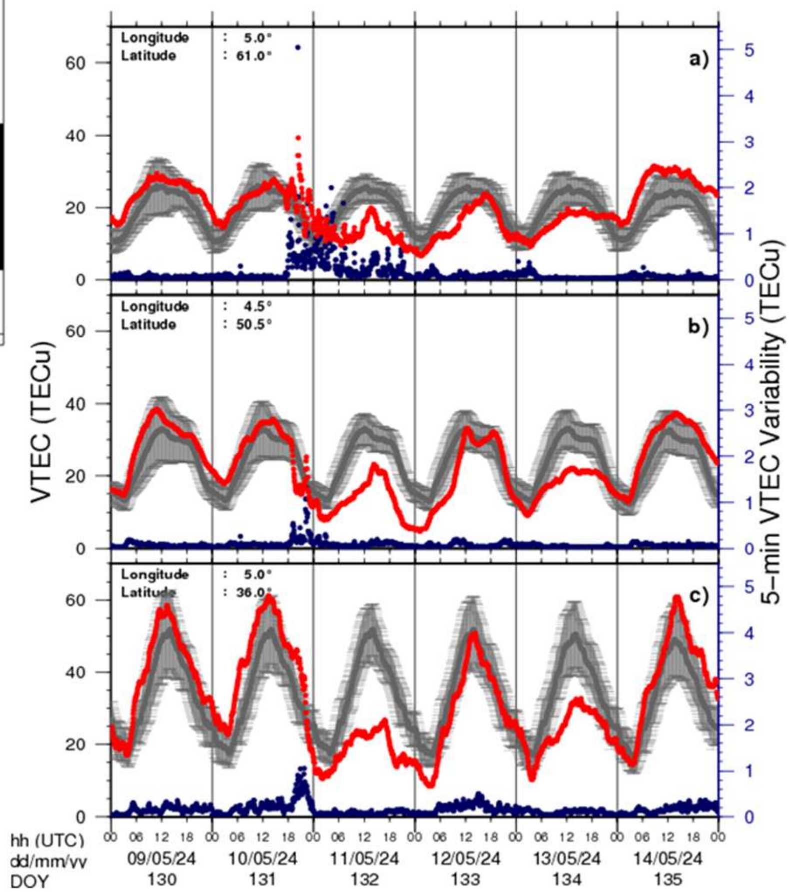
15-days median TEC

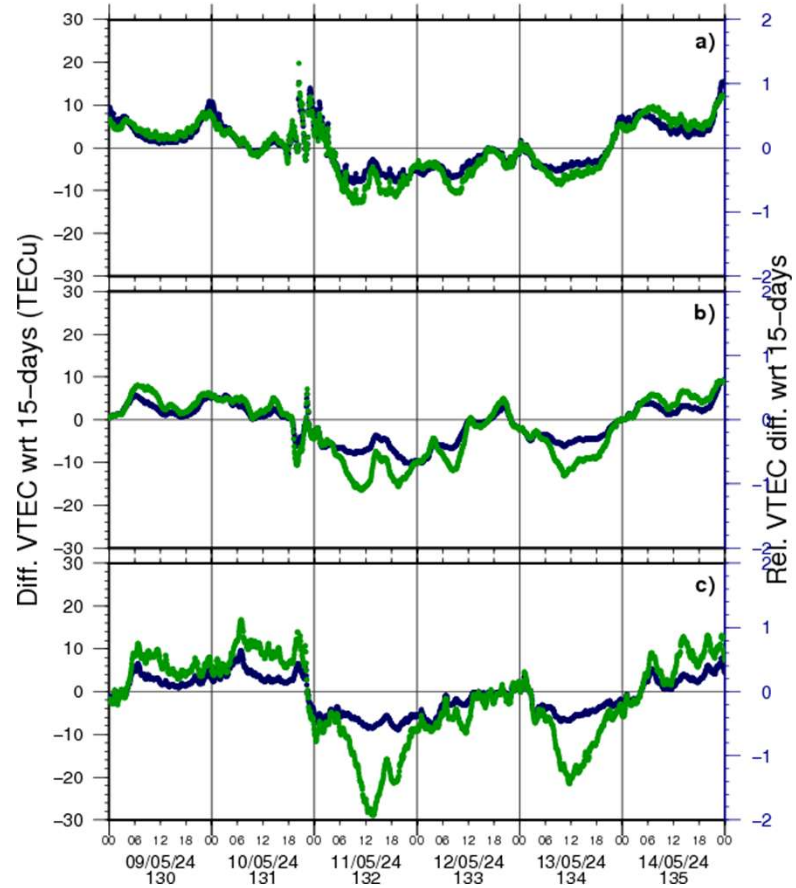
TEC Variability

- Right plot:

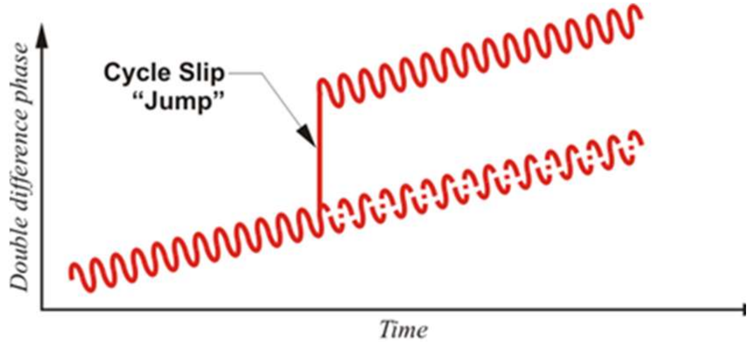
TEC Differences w.r.t. median

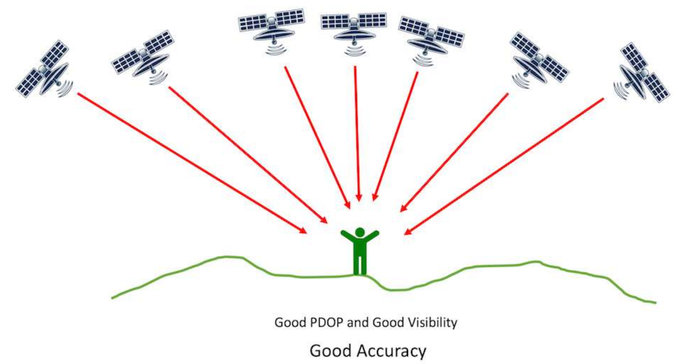
Relative TEC Differences w.r.t. med.



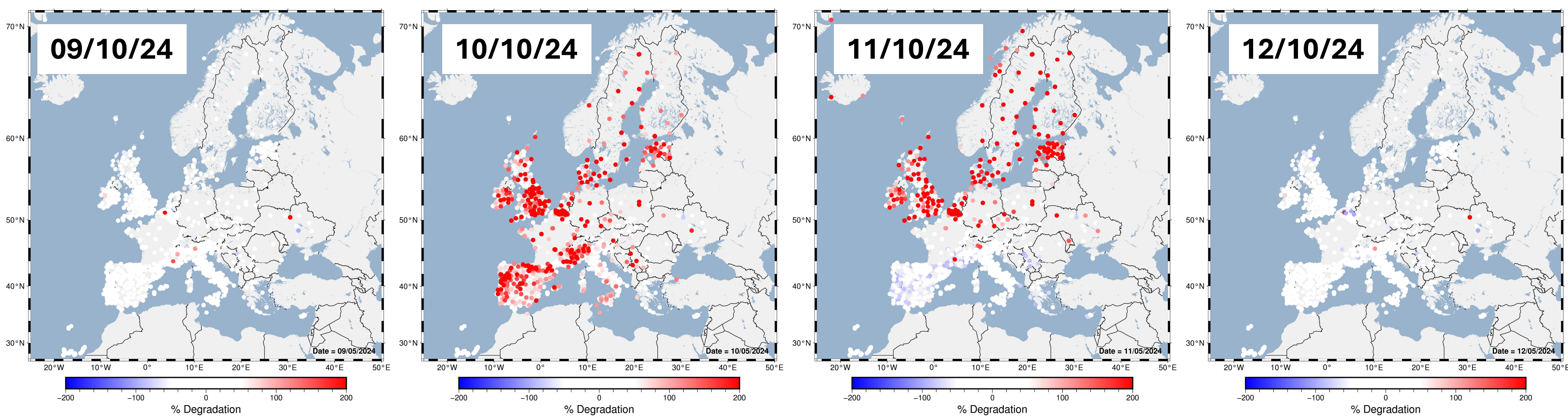


SW IMPACT ON GNSS SIGNAL QUALITY



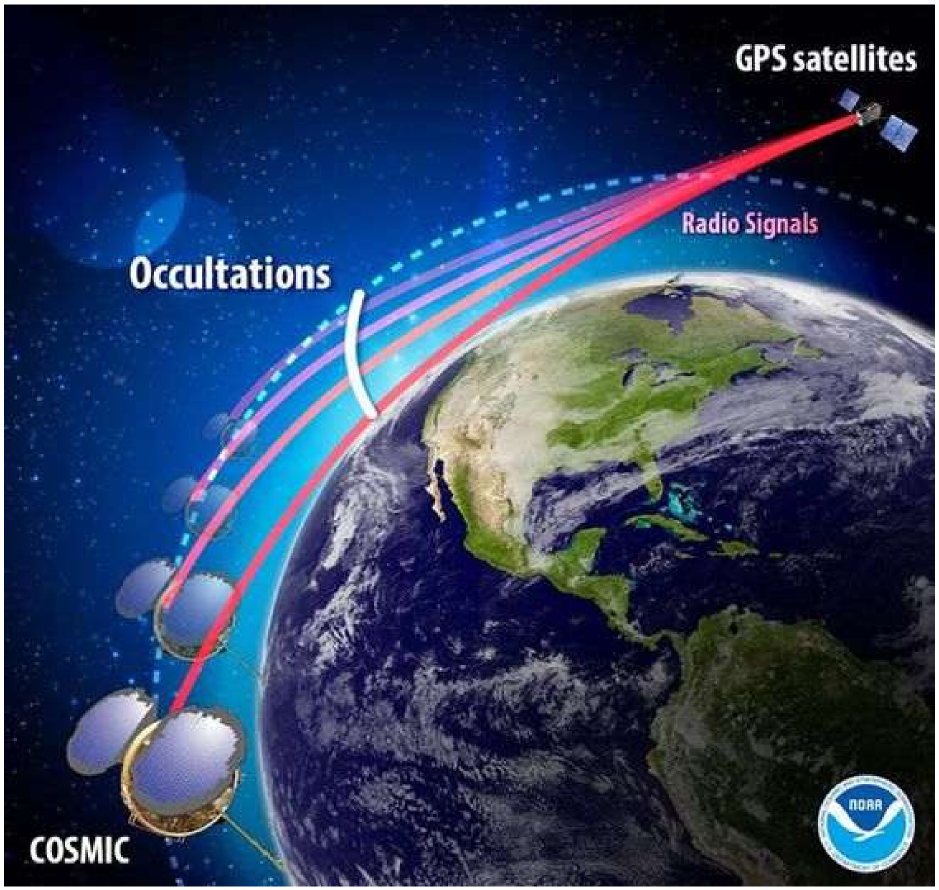


daily GNSS station quality check are operated at ROB



Bamahry F., Legrand J.

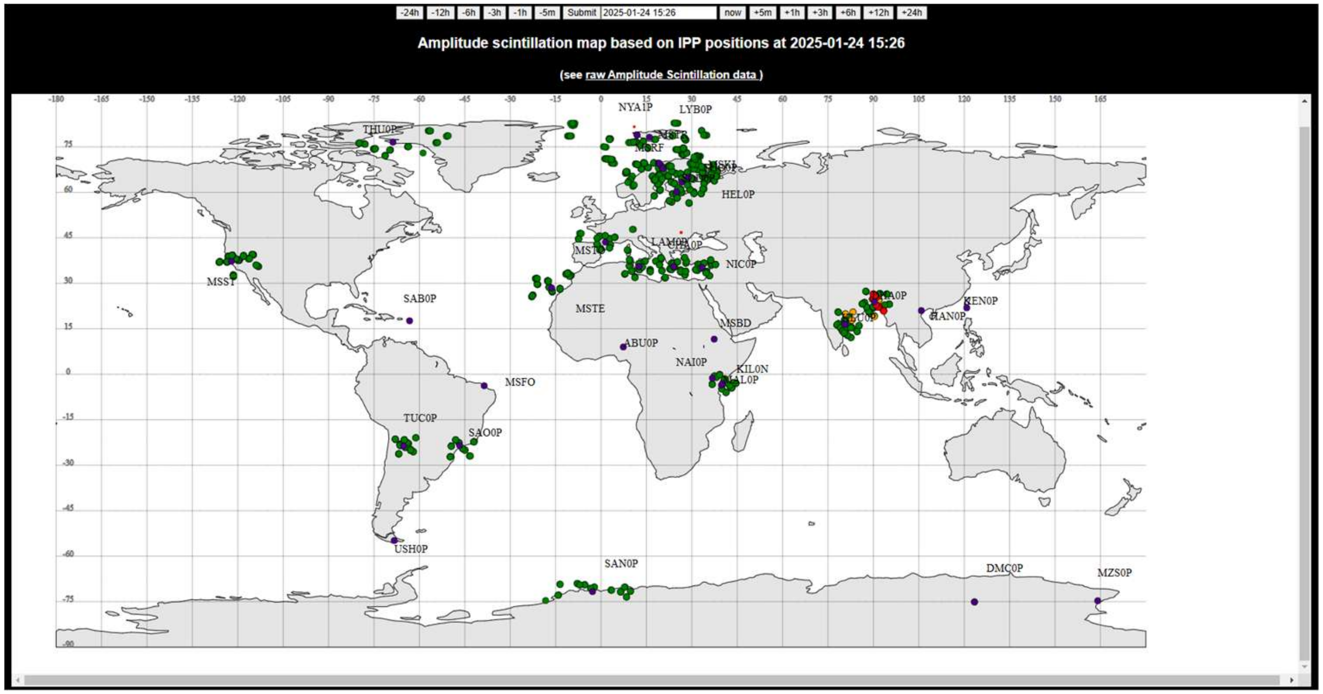
Ionospheric Monitoring with LEO



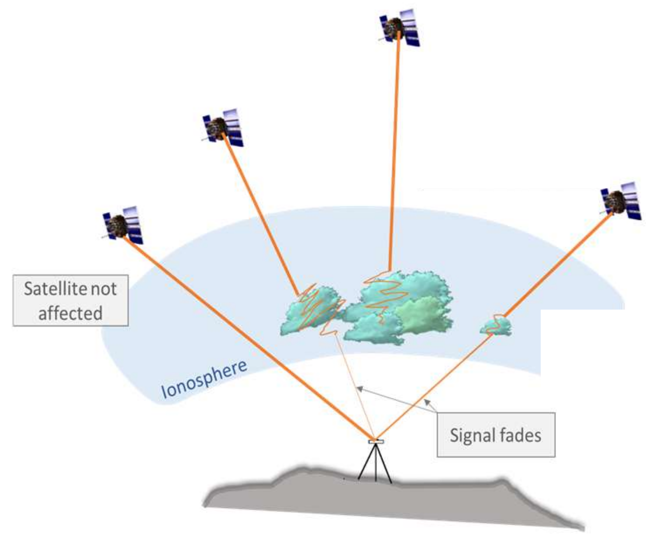
Some **Low Earth Orbit (LEO)** satellites are **equipped with GNSS receivers**. The **GNSS radio occultation** allow to do horizontal sounding of the ionosphere.

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

Monitoring Ionospheric Scintillation effects



Amplitude Scintillation Map based on scintillation GNSS receiver observations
ROB PECASUS Dashboard



Scintillation affects the phase and the amplitude of GNSS signals, causing :
- cycle slips, inducing error positioning up to several meters
- GNSS signal loss, no position at all

Summary of the ionospheric activity key indicators for GNSS

- **Climatological variations of the ionosphere do not have a strong impact on GNSS applications**, it can be well mitigated with integrated ionospheric models.

- **Absolute TEC values are thus not a good stand-alone indicator**, without knowing the climatological state of the ionosphere, the GNSS location, and the local time.

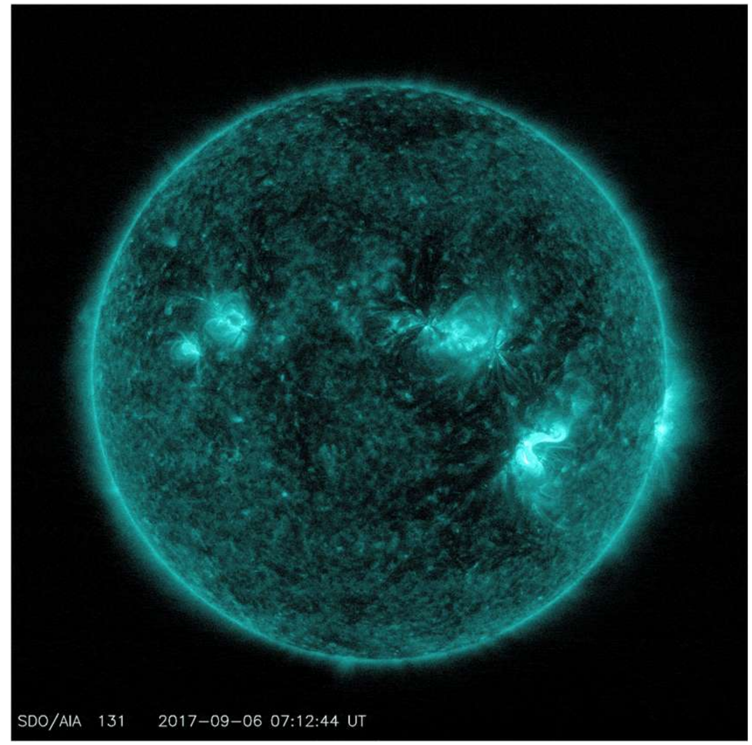
- **TEC variations with respect to the "normal"** (median of the 15-days or 27-days) at a given location and for the same local time is a good ionospheric activity indicator

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

For GNSS applications, other sources of errors should be considered:
Satellite elevation, number of satellites tracked, cycle slips…

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.

Good to make the difference between this natural jammer and an intentional enemy jamming…

But no possible forecasting, once a SRB impacting GNSS is detected, your receiver has already been or is being under jamming…

GNSS disturbances due to Solar Radio Bursts

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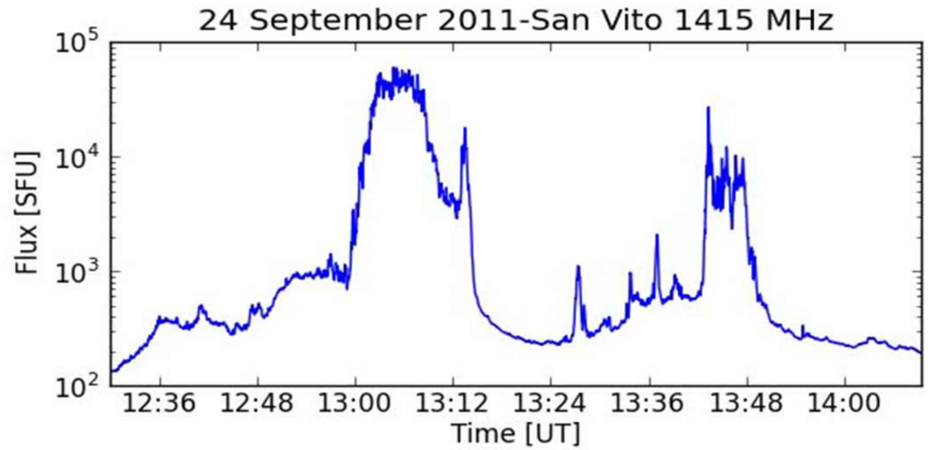

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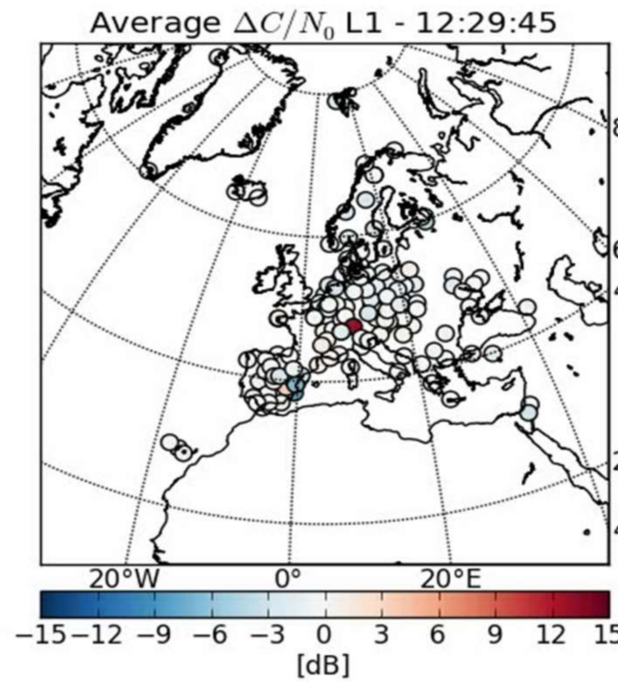
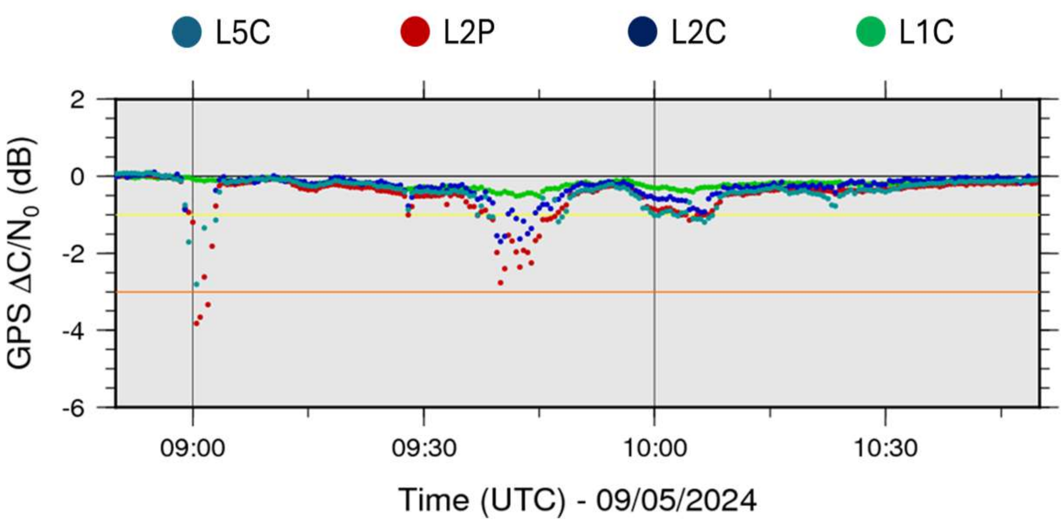
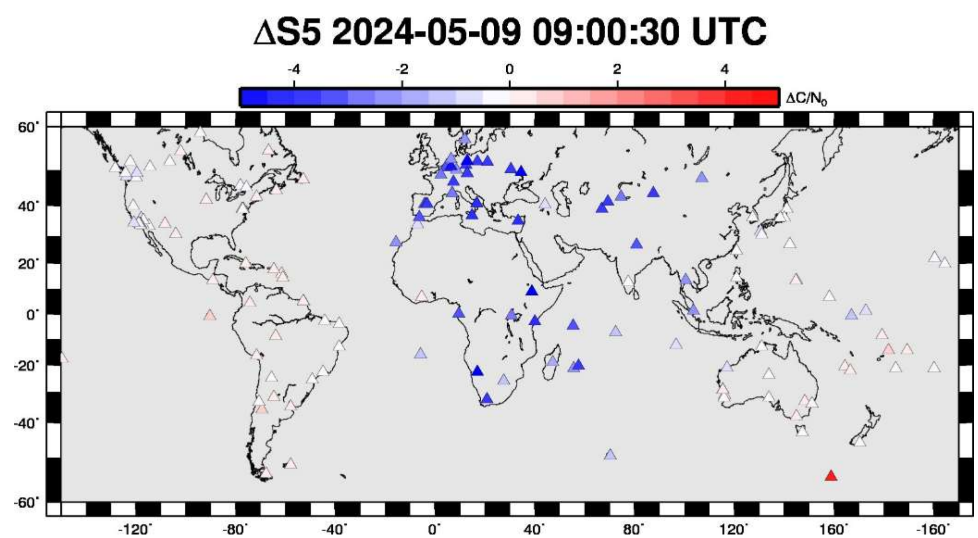
Level	GNSS $\Delta C/N_0$ Fade	Effect
Quiet	>-1dB-Hz	none
Moderate	-1 dB-Hz	SRB detected but should not impact GNSS applications
Strong	-3 dB-Hz	Potential impact on GNSS applications
Severe	-10 dB-Hz	Potential failure of the GNSS receivers



MONITORING 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

Summary

- The large number of **GNSS stations** distributed **globally** provide a **reliable and continuous monitoring** of the **Ionospheric Total Electron Content and its activity**

- **Ionospheric activity indicators** :
  - **variation of TEC w.r.t. the ionospheric climatological state**
  - **TEC rapid variability**

- However, GNSS data are also limited **over the oceans** and the **ionospheric vertical profile cannot be directly retrieved**.

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