Role of the ionosphere and space weather in military communications

SWIC

Solar-Terrestrial Centre of Excellence

15-17 March 2026

Royal Observatory
of Belgium

Solar-Terrestrial
Center of Excellence

Space Weather Monitoring with GNSS

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18/03/2026

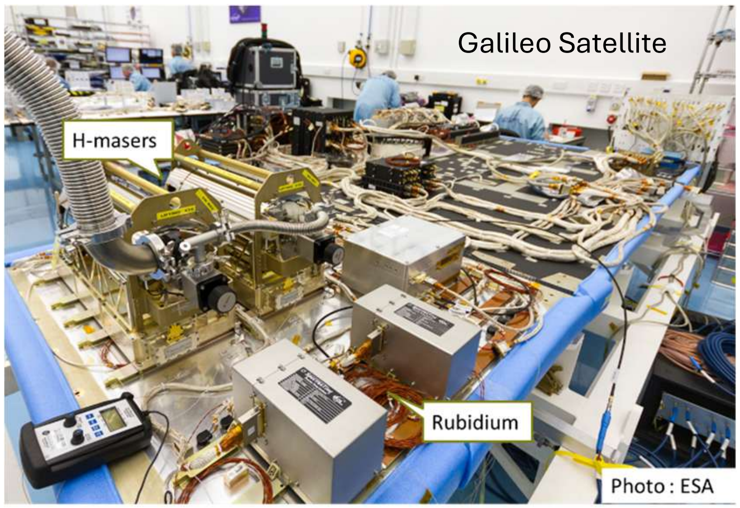
GNSS Team - Space Weather activities

GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

GNSS positioning basics

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

➡ **At least 4 satellites needed:**



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

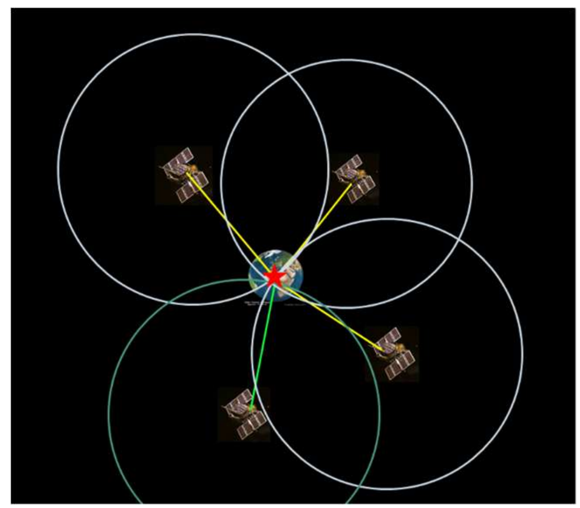
1. **Estimation of the distance between receiver and satellites :**

v=d/t

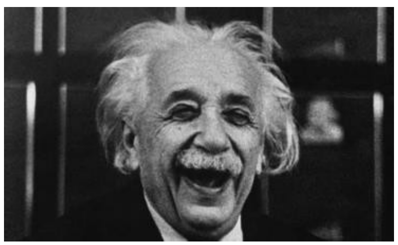
v= speed of light 299 792 458 m/s

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

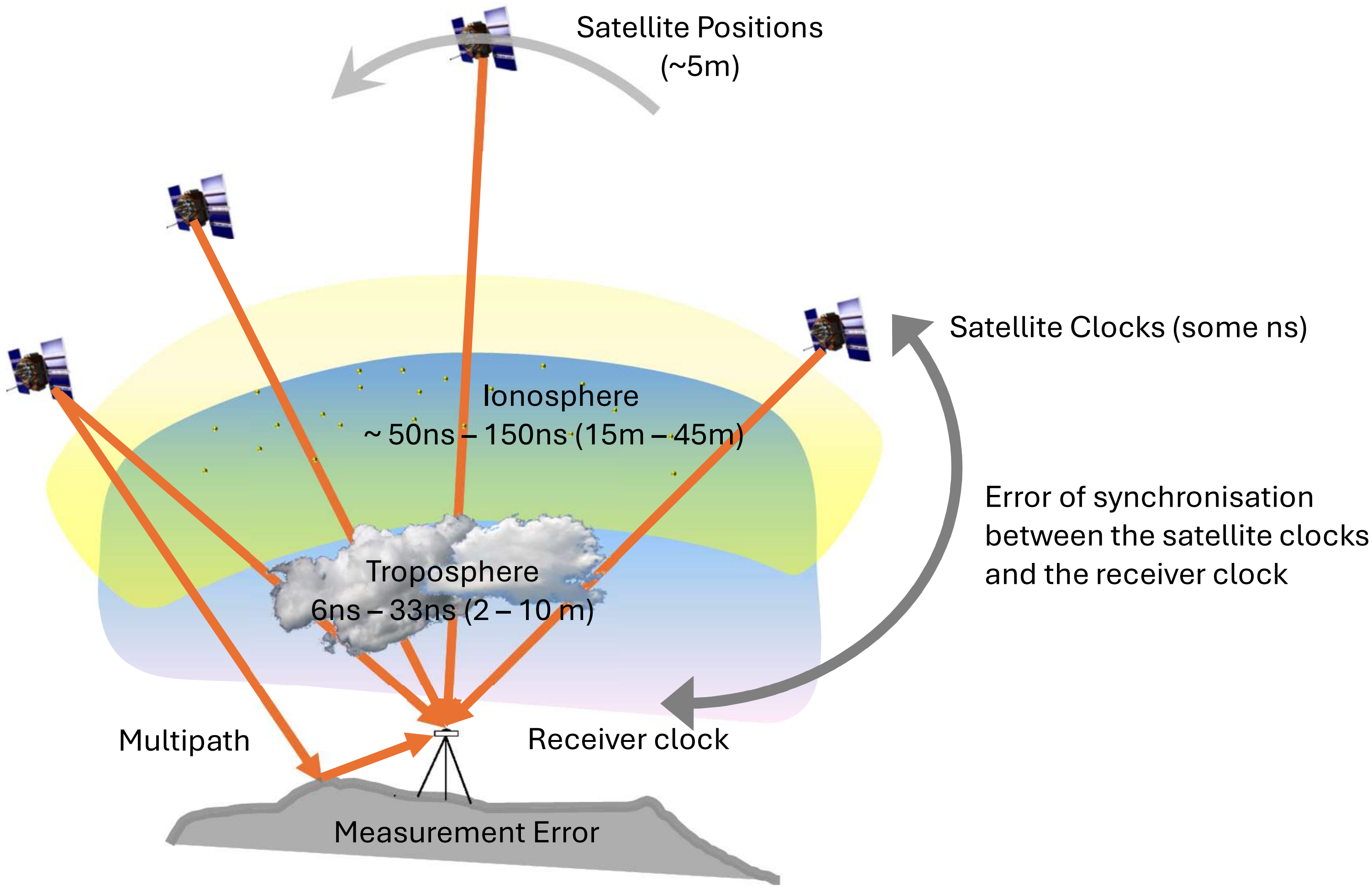
2. **Triangulation**



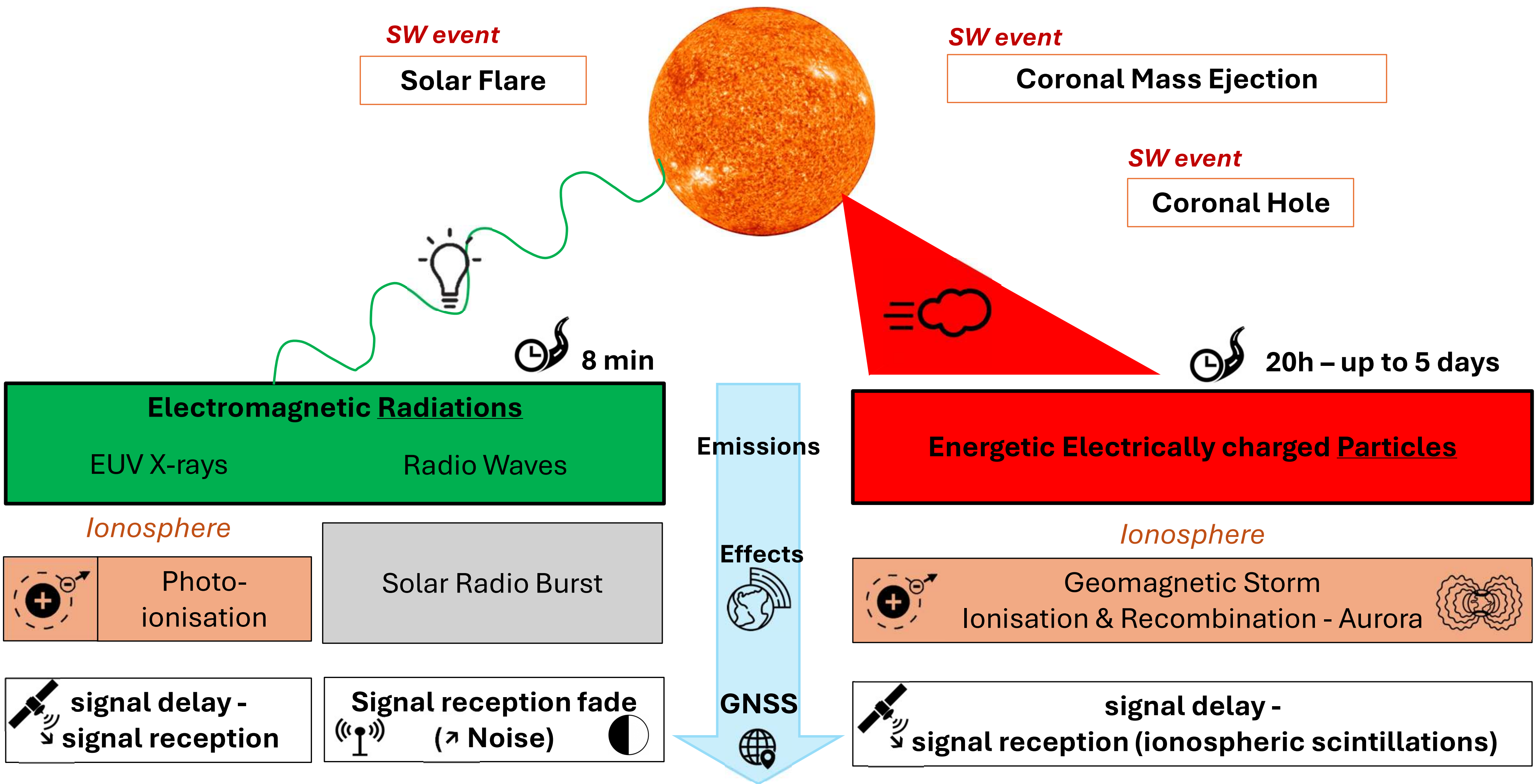
Race at the ns level, don't loose time on the way !
Error sources affecting the GNSS positioning quality



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



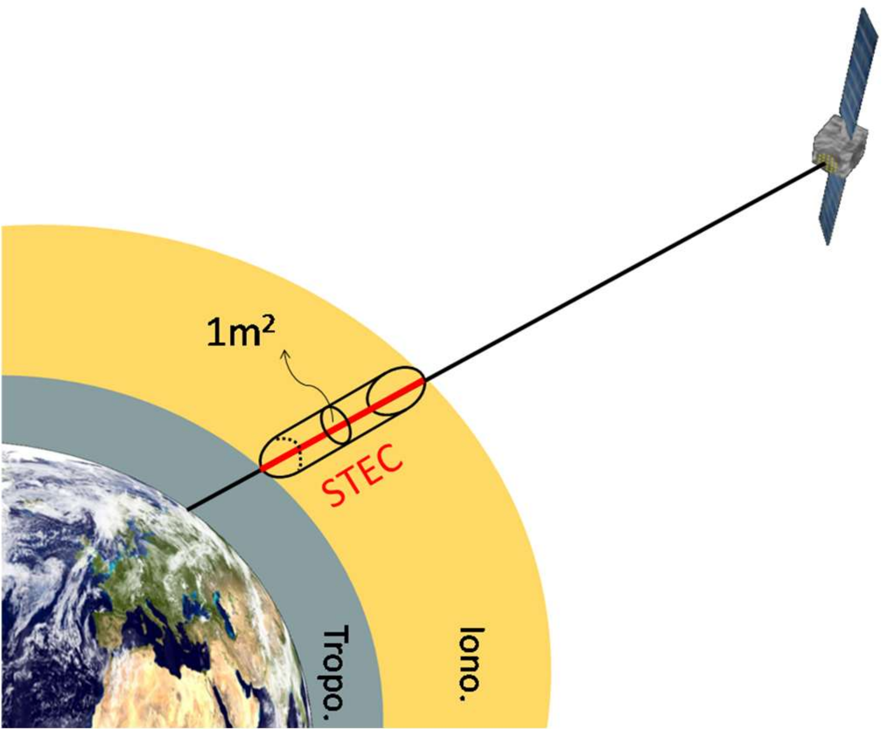
The Sun, Source of Space Weather affecting GNSS



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

** For a permanent GNSS station*

GNSS vs Ionosphere

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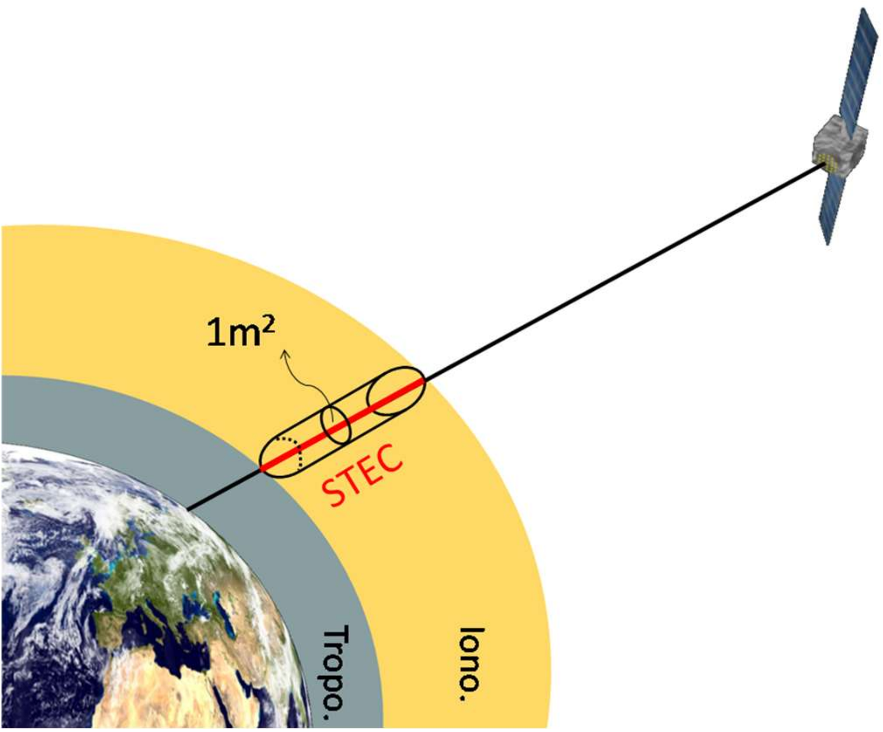


Using 2 GNSS signals at 2 frequencies:

« 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)

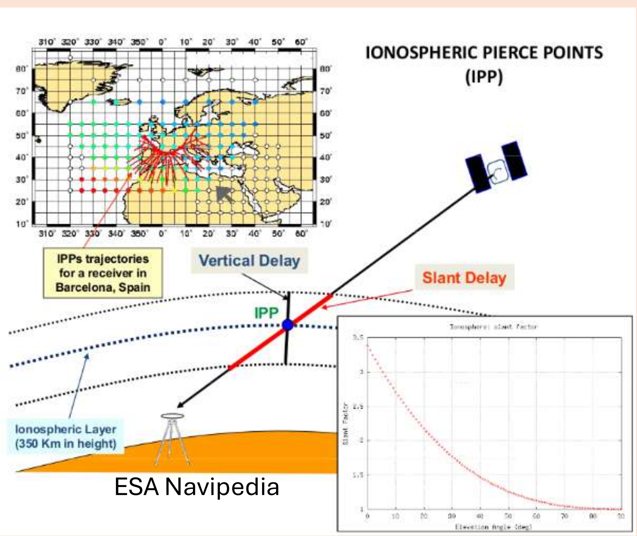
- Double-frequency GNSS receivers >**expensive €**.
- Frequency combination relies on the **tracking quality** of the GNSS signals (**hardware and software**).
- Additional frequencies are **not all public**, and require specific tracking technics
- New public civilian signals (GPS L2C, Galileo E5) are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

For **GNSS single frequency users, abnormal ionospheric activity** remains a problem.
Double-frequency receivers are also **affected by space weather** events in the ionosphere (**scintillations**) or radio frequency interferences (**solar radio bursts**), generating **GNSS signals fading up to the loss of lock**.

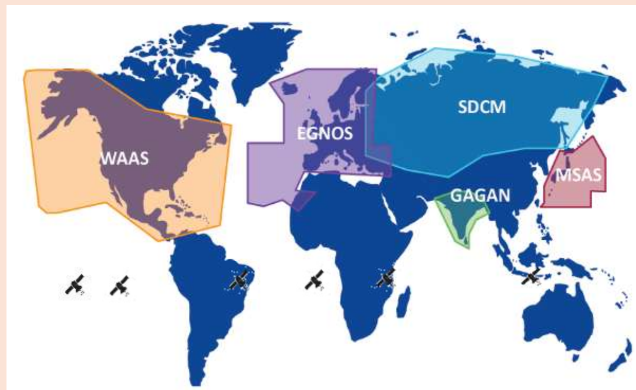
GNSS single-frequency users are not left behind for mitigating the ionospheric effect

Most common (public and free)

Broadcasted parameters in the navigation message allows **Klobuchar** and **NeQuick ionospheric models** to correct **>50%** of the “normal” **ionospheric range error**. But it does **not include Space weather events.**

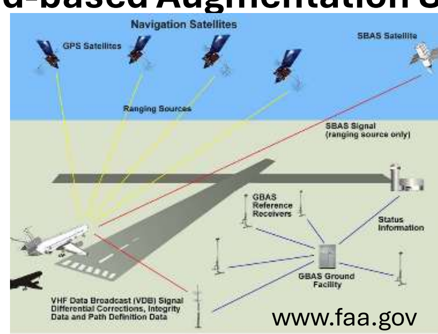


Satellite-based Augmentation Systems



(public and free)

Ground-based Augmentation Systems

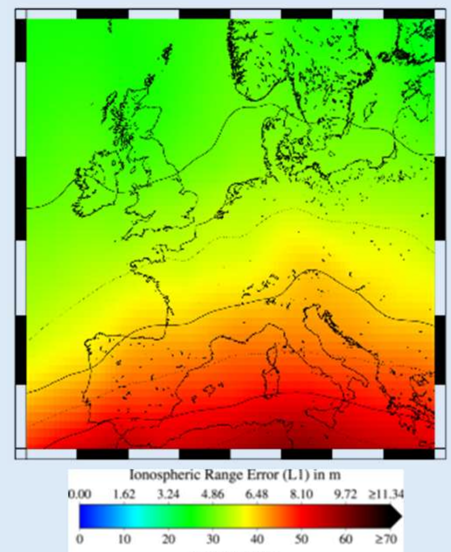


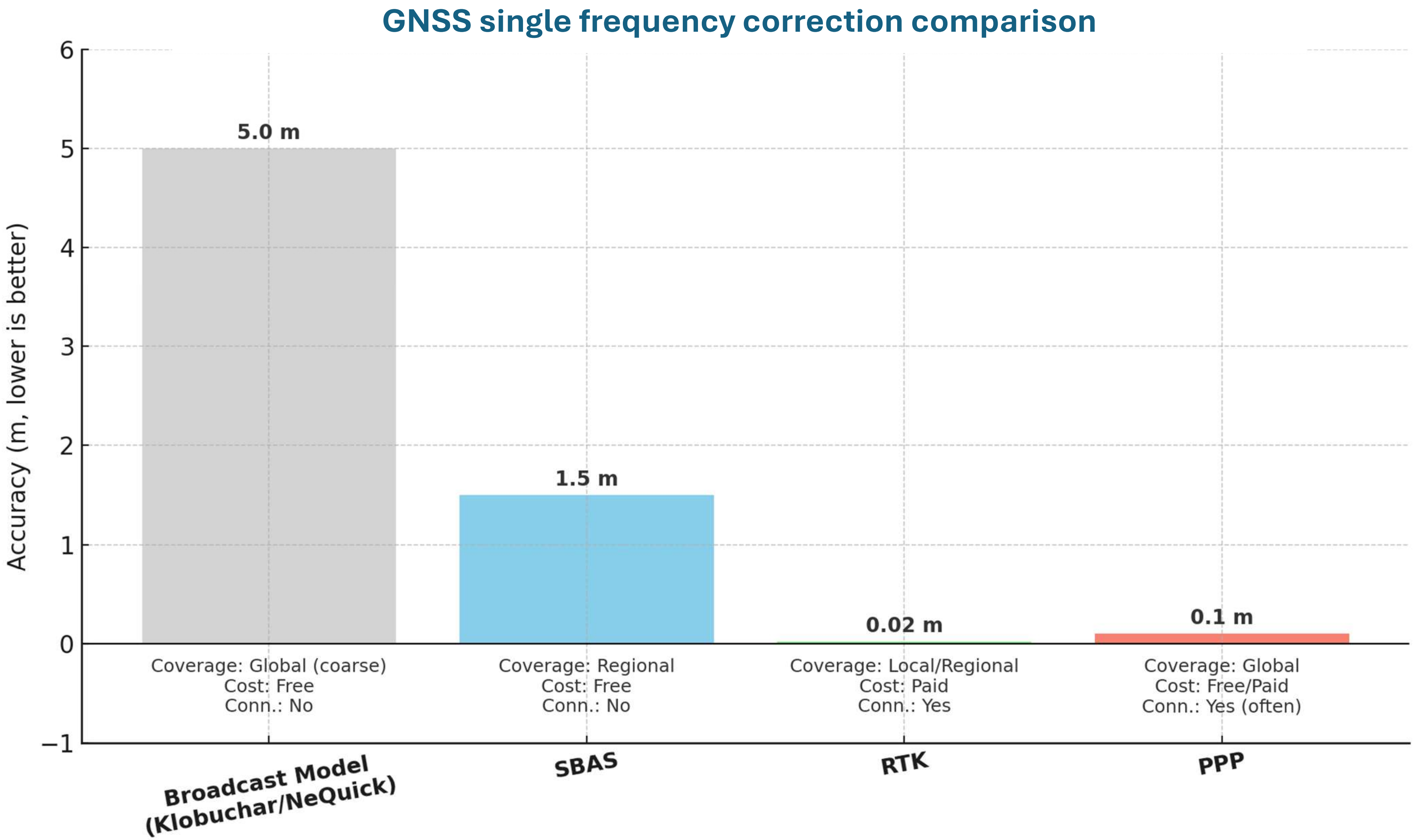
Differential GNSS

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

For SW monitoring

Ionospheric TEC Maps

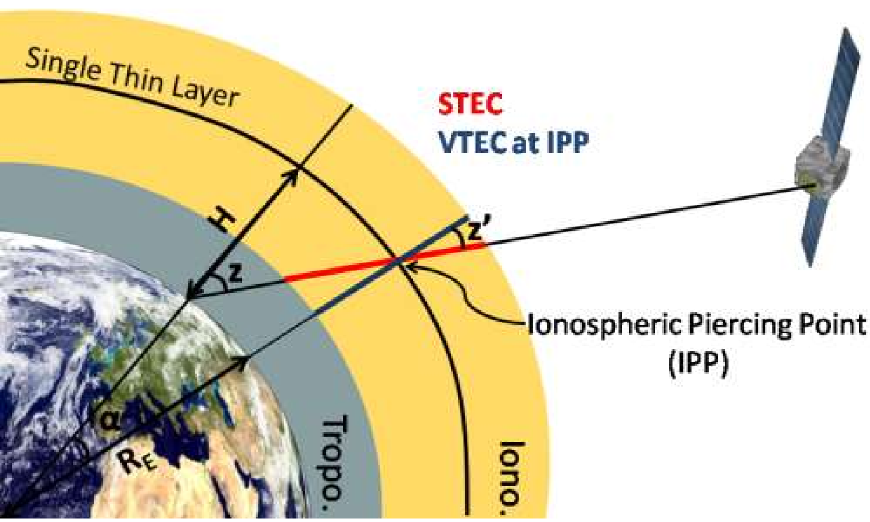



GNSS single frequency correction comparison
Accuracy (m, lower is better)
6
5
4
3
2
1
0
−1
5.0 m
1.5 m
0.02 m
0.1 m
Coverage: Global (coarse)
Cost: Free
Conn.: No
Coverage: Regional
Cost: Free
Conn.: No
Coverage: Local/Regional
Cost: Paid
Conn.: Yes
Coverage: Global
Cost: Free/Paid
Conn.: Yes (often)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

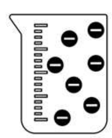


<u>Using 2 GNSS signals at 2 frequencies:</u>

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

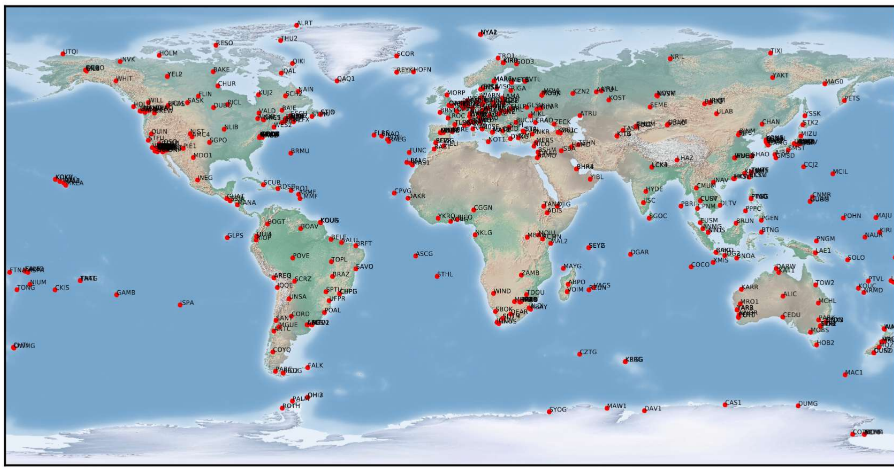
« geometry-free » combination → Estimate the ionospheric delay (+hardware delays)

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



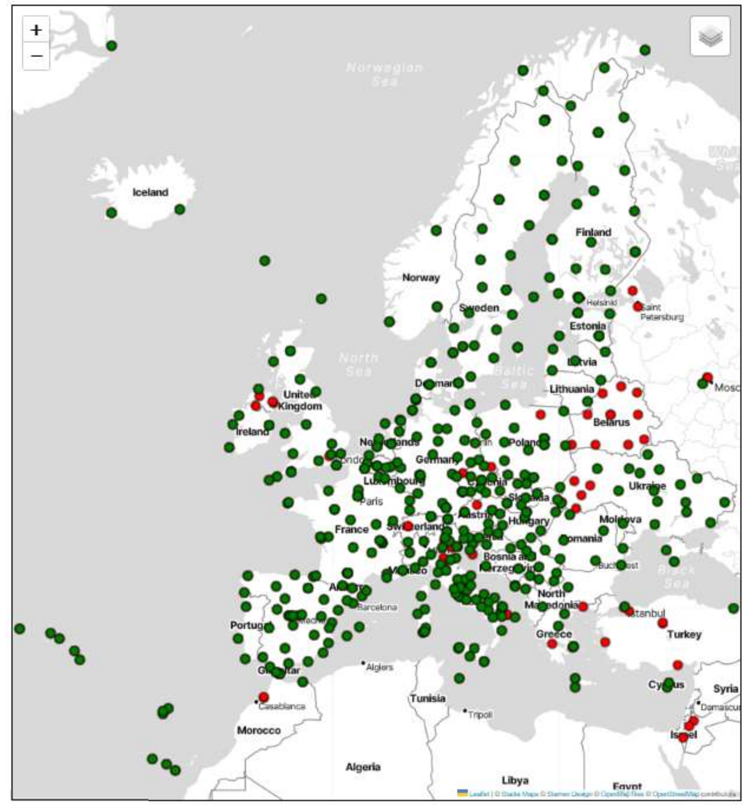
Slant Total Electron Content $$STEC = \int_{R}^{S} Ne.dl$$

GNSS Permanent Station Networks



IGS INTERNATIONAL GNSS SERVICE

https://igs.org/

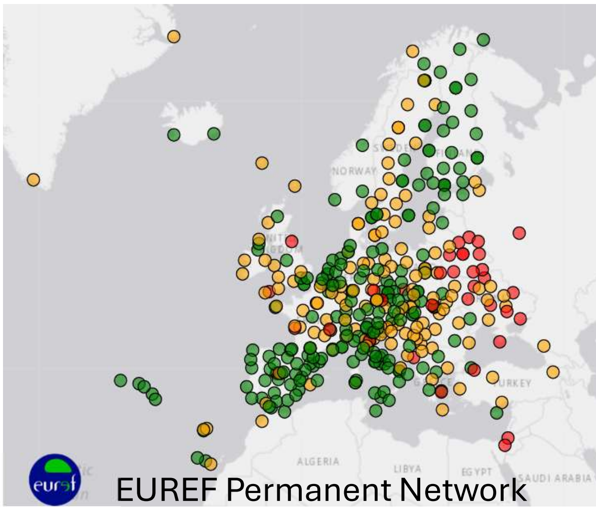


EUREF Permanent GNSS Network

500+ GNSS coordinated @ROB

https://epncb.oma.be/

Ionosphere monitoring based on GNSS

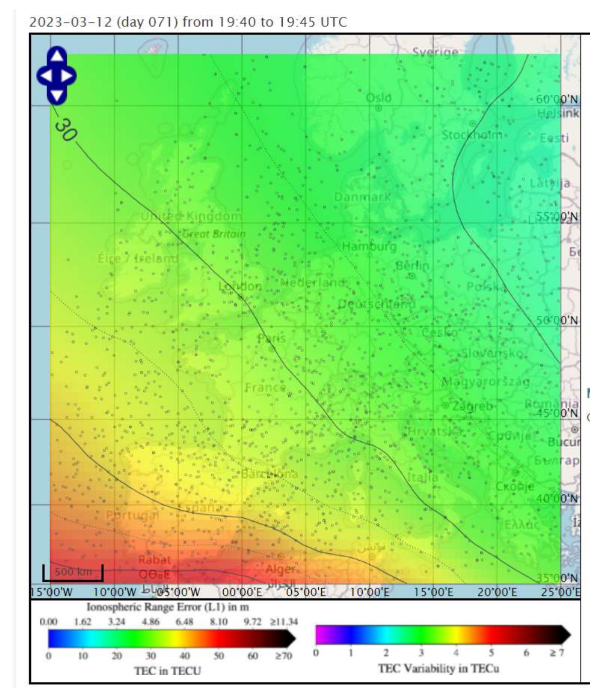


Source of error becomes source of information

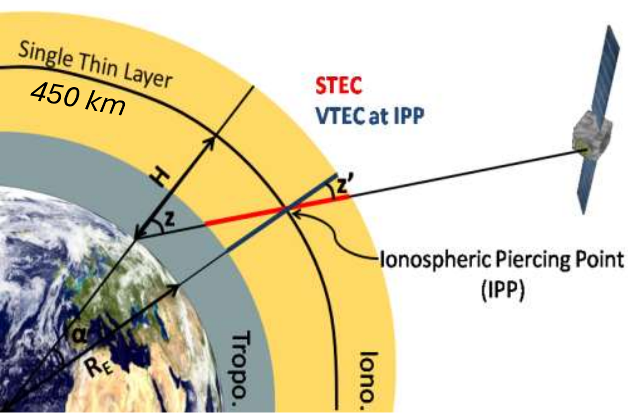
ionospheric Total Electron Content **TEC** is derived from the GNSS station observations

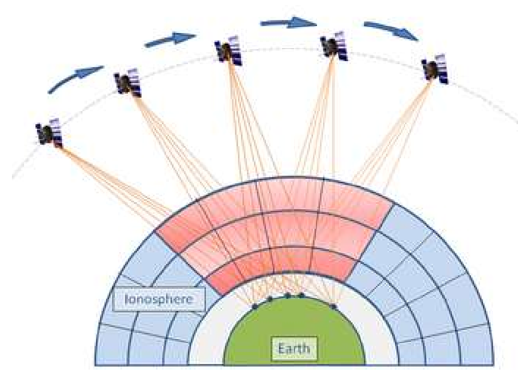
NRT European TEC Maps

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



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



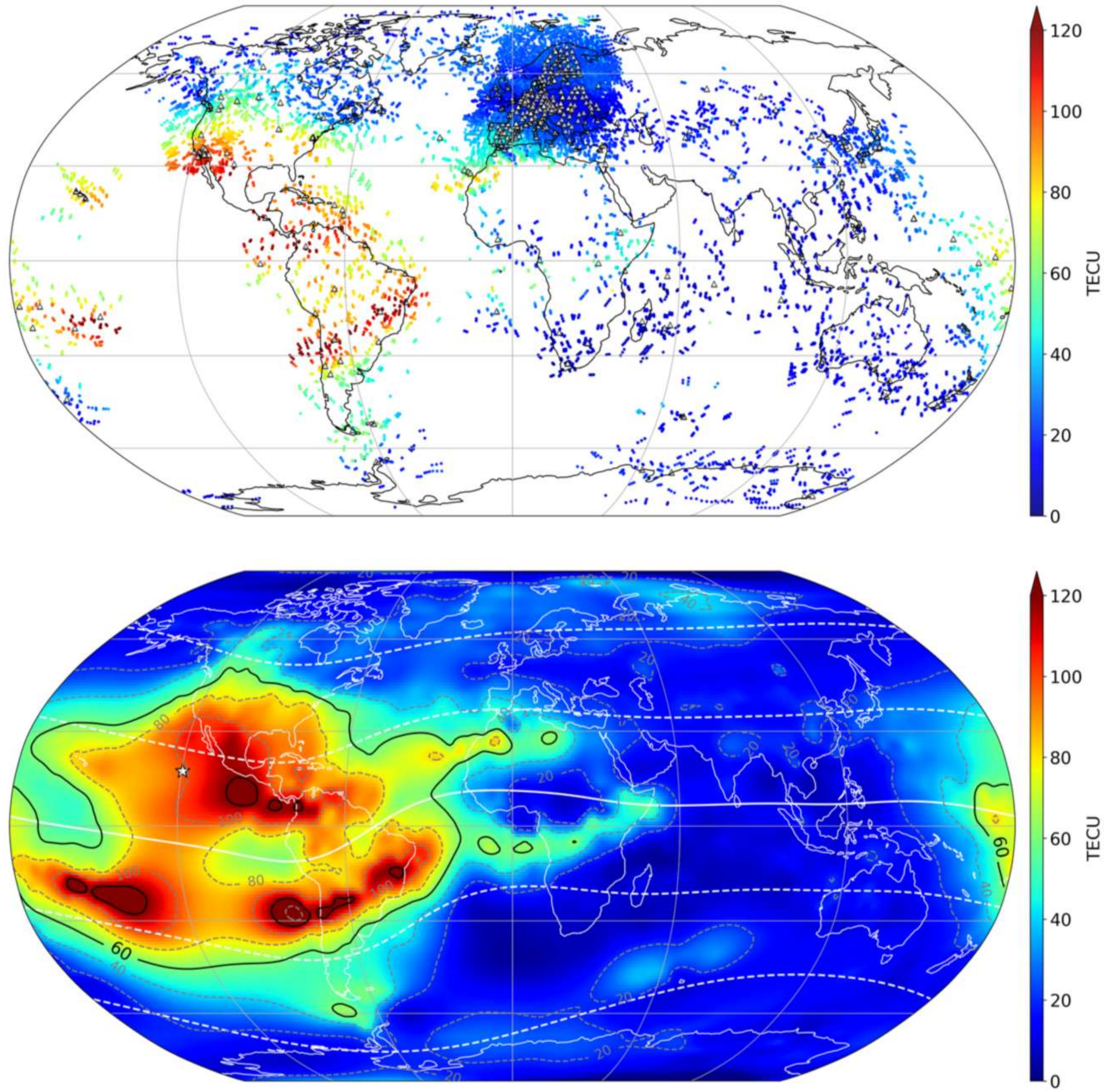


Bergeot, 2014

Global Ionosphere monitoring based on GNSS

On-going project and soon publicly available at :

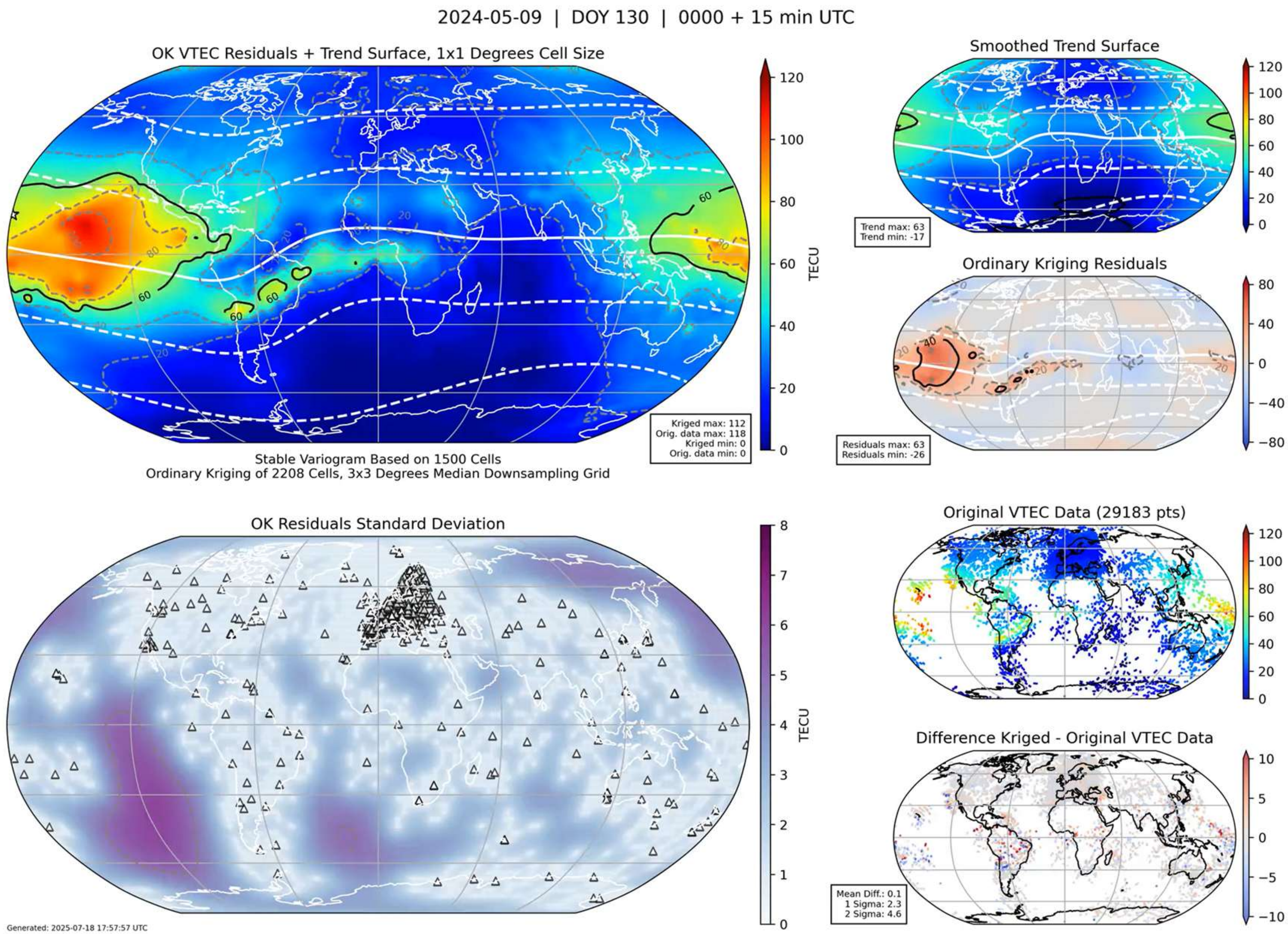
https://gnss.be/SpaceWeather/



Dreyer J. et al., EGU 2025

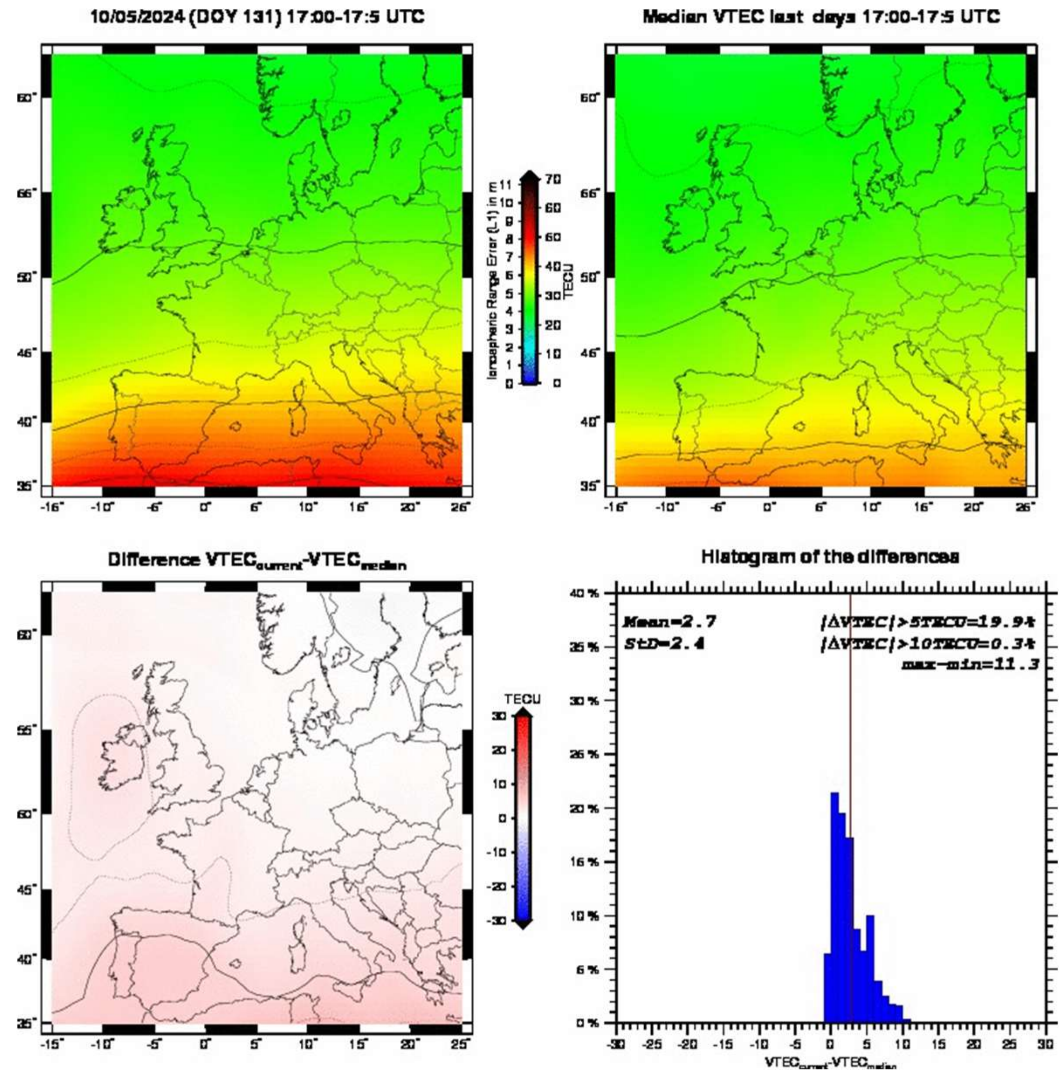
ROB Global Ionospheric TEC Maps based on GNSS

>550 stations
GPS, Galileo and GLONASS



Dreyer J. et al., EGU 2025

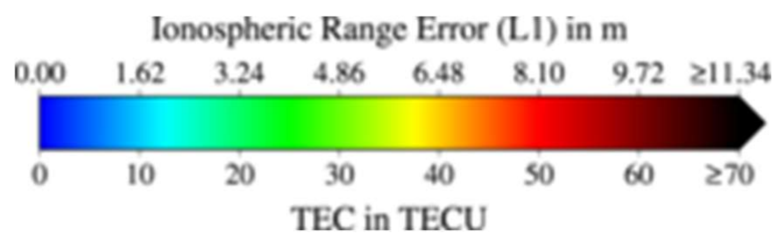
Monitoring the ionospheric activity - Tools



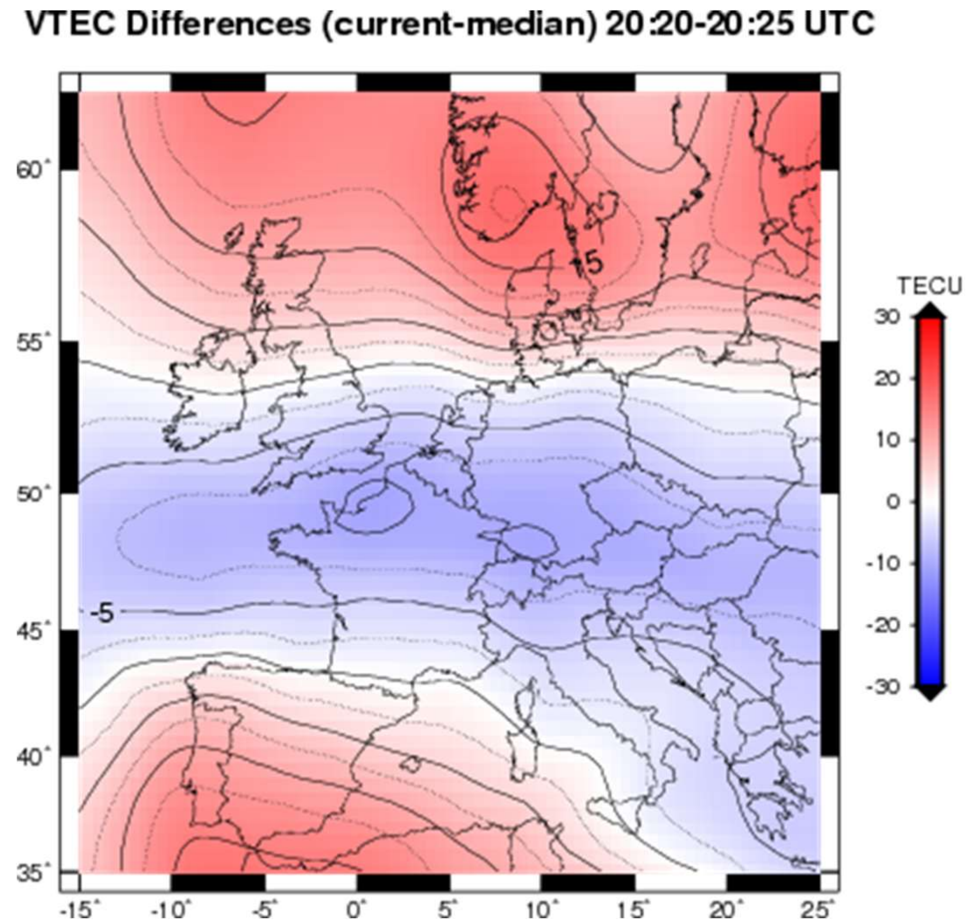
10-11 MAY MOTHER'S DAY STORM

Near-Real Time European TEC Maps
5-min, GPS+GLONASS+GALILEO,
~180 EPN stations

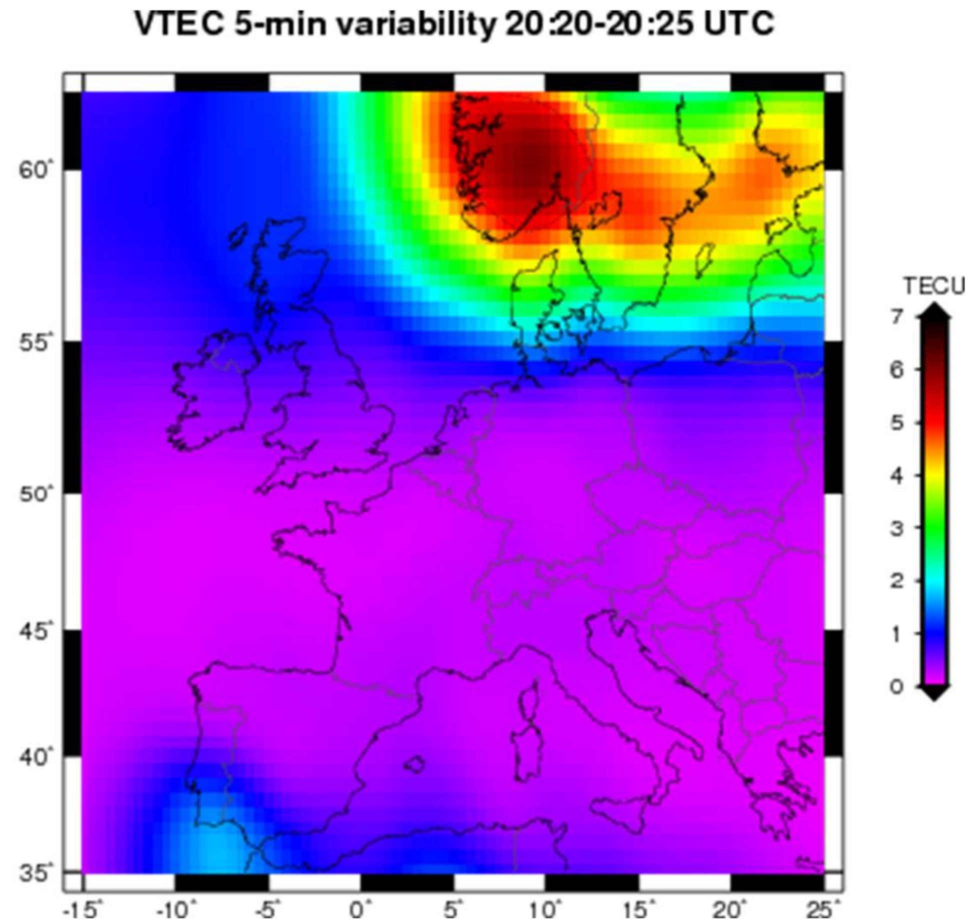
https://gnss.be/SpaceWeather/



Monitoring the ionospheric activity – Key indicators

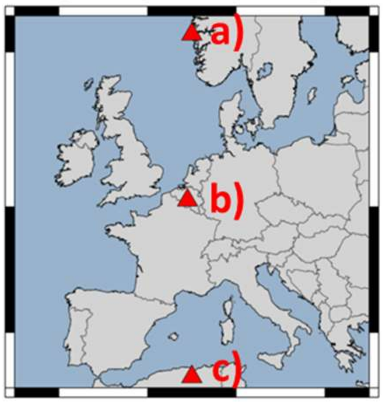


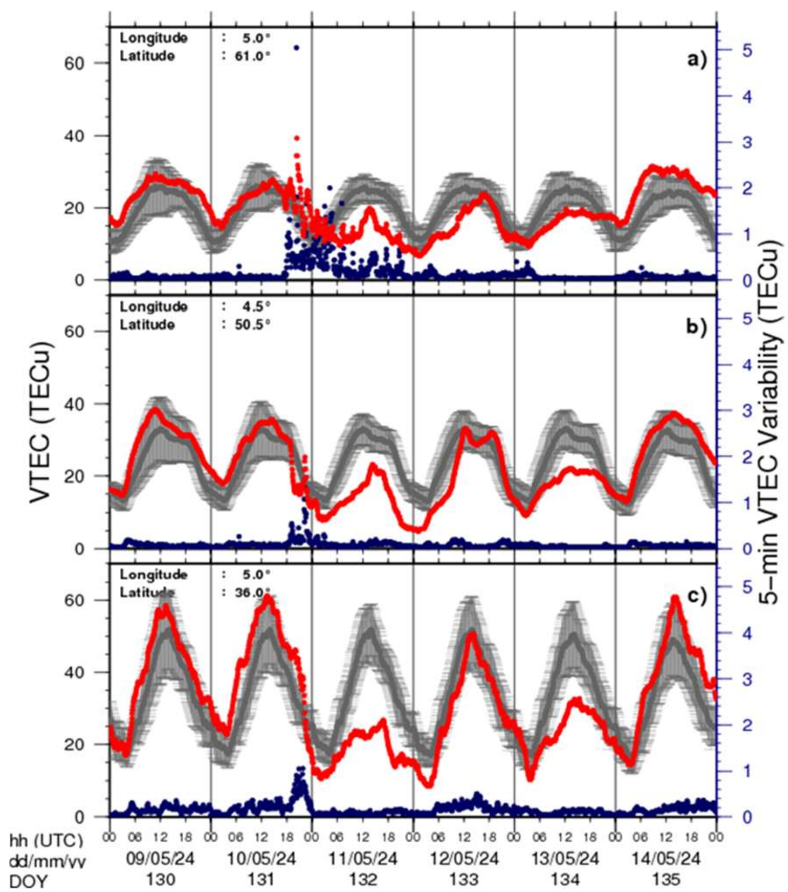
With respect to the « quiet » conditions

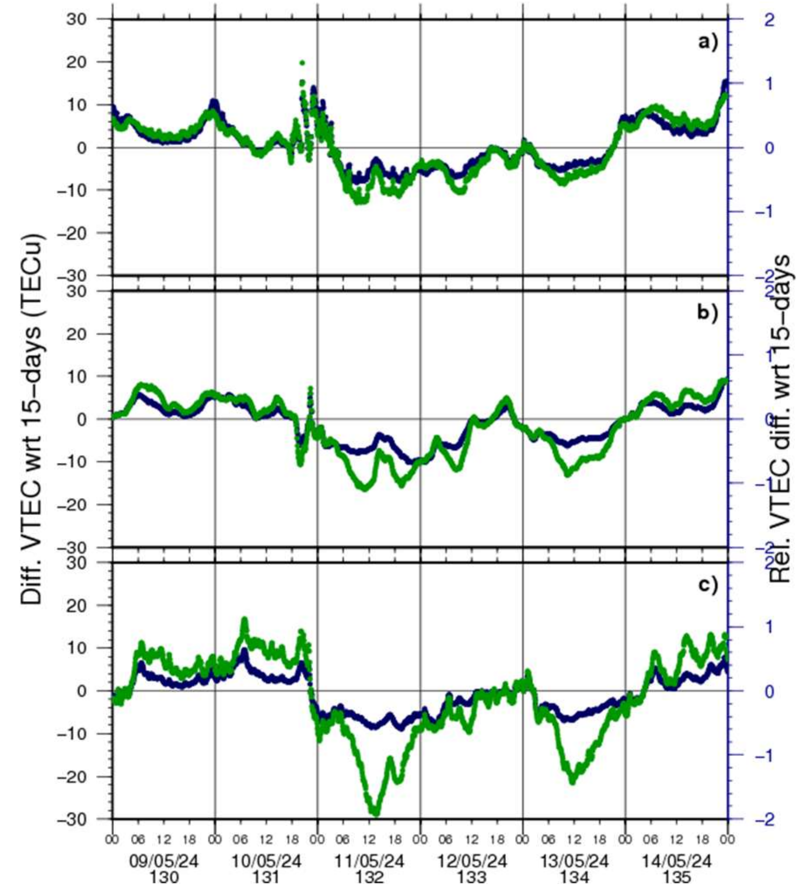


Rapid ionospheric changes are critical for GNSS applications

Monitoring the Ionospheric Activity - TEC Time Series







- Left plot:

TEC current

15-days median TEC

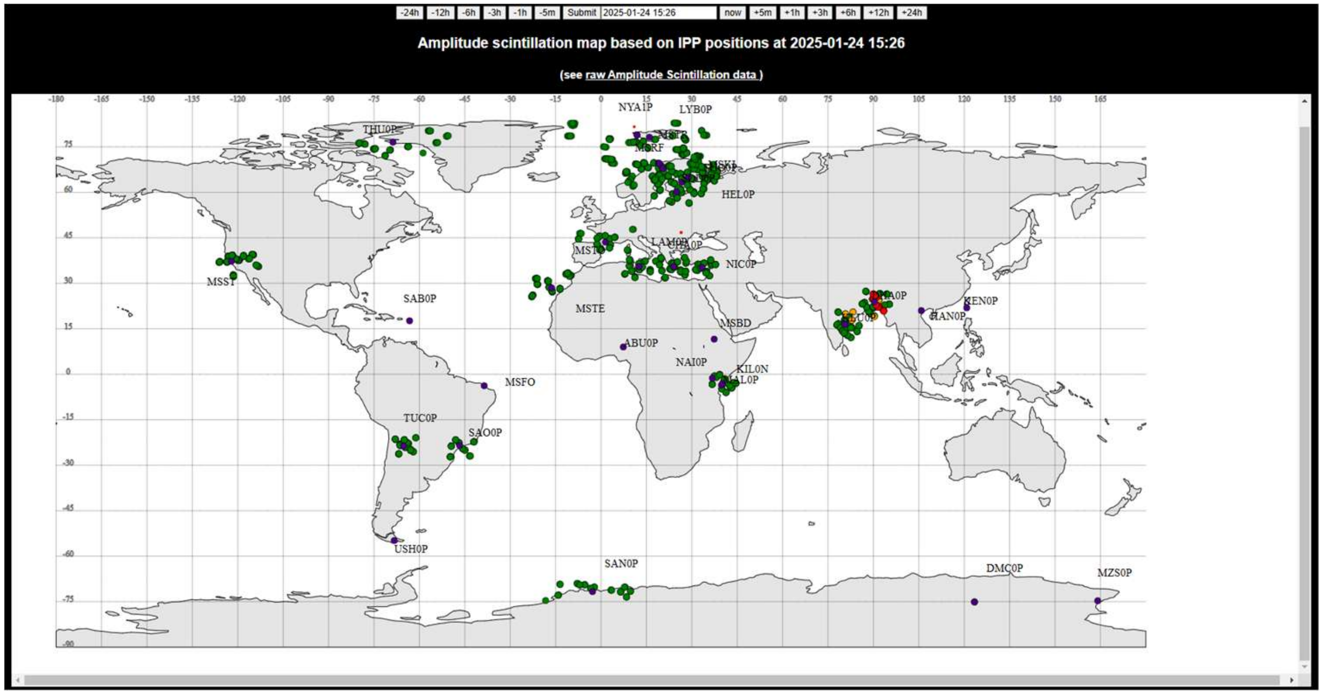
TEC variability

- Right plot:

TEC differences w.r.t. median

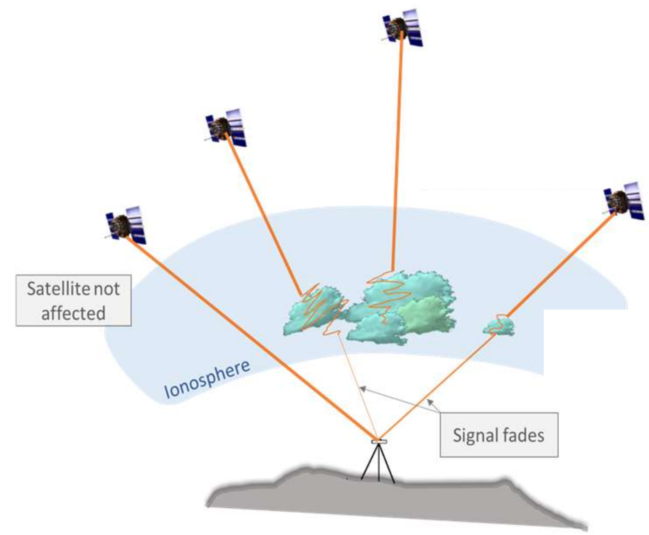
Relative TEC differences w.r.t. med.

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 "quiet"** (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 or 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

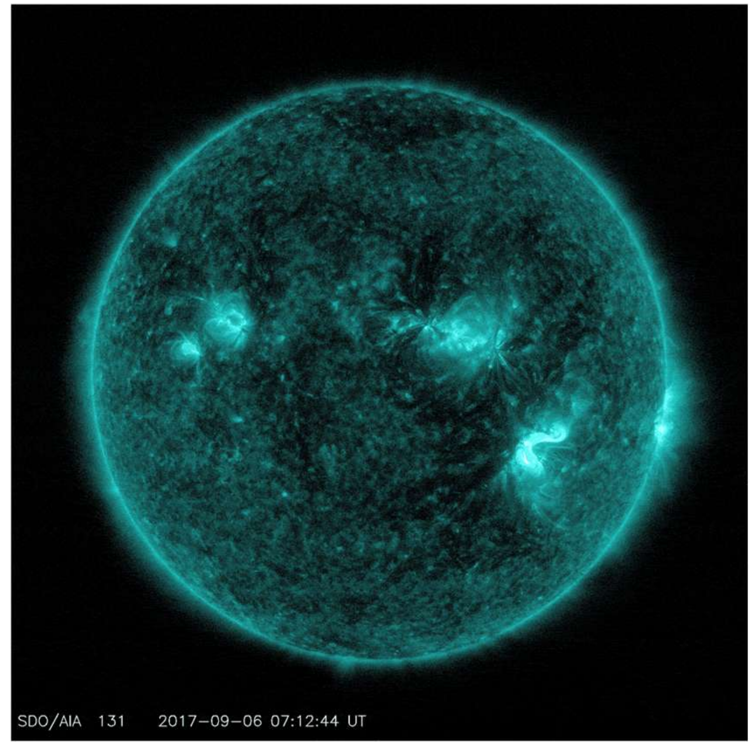
10 seconds to few hours

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

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

But not possible to warn, once a SRB impacting GNSS is detected, your receiver has already been or is being jammed...

Good to make the difference between this natural jammer and intentional jammings...



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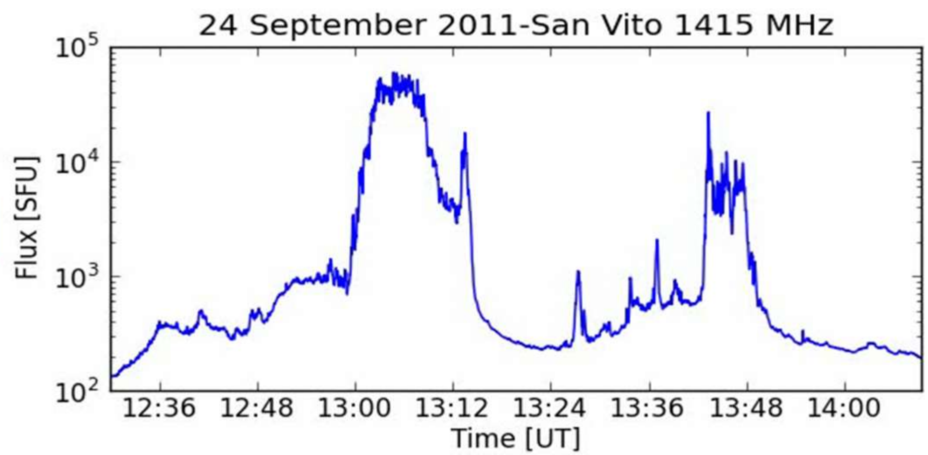
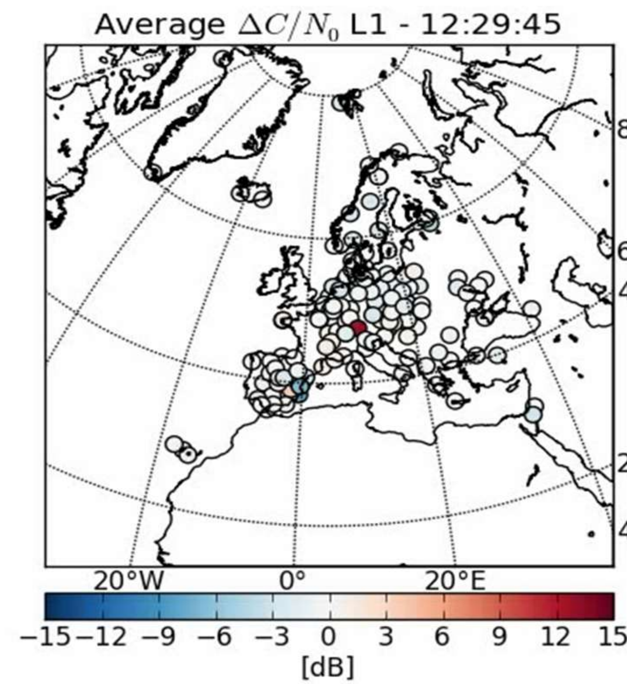
Level	GNSS $\Delta C/N_0$ Fade	Effect
Quiet	>-1dB-Hz	none
Moderate	-1 dB-Hz	SRB detected but should not impact GNSS applications
Strong	-3 dB-Hz	Potential impact on GNSS applications
Severe	-10 dB-Hz	Potential failure of the GNSS receivers





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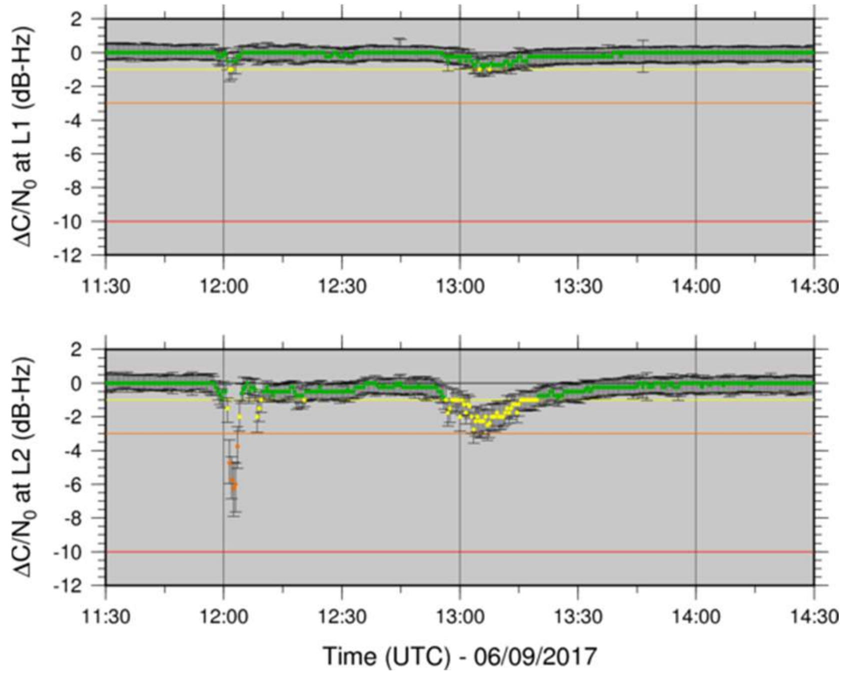
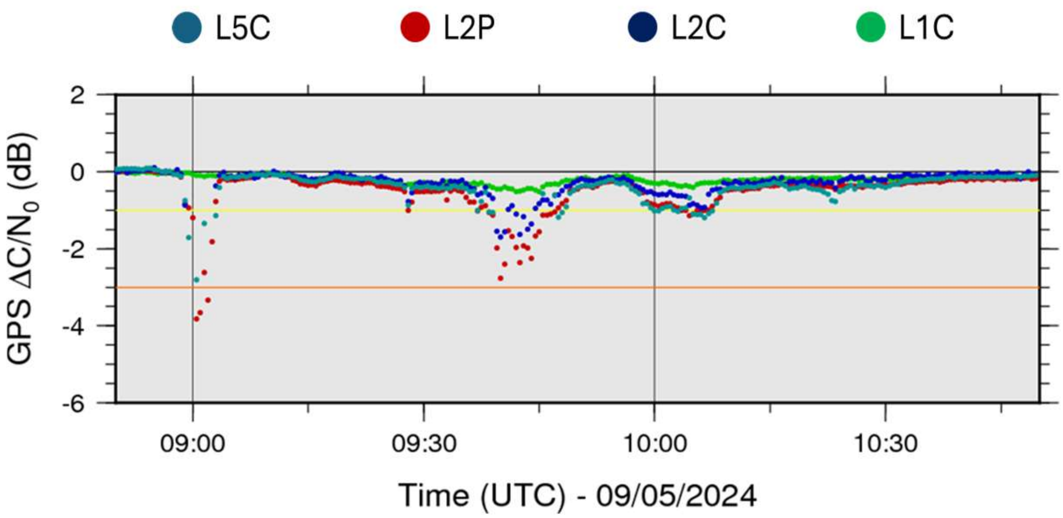
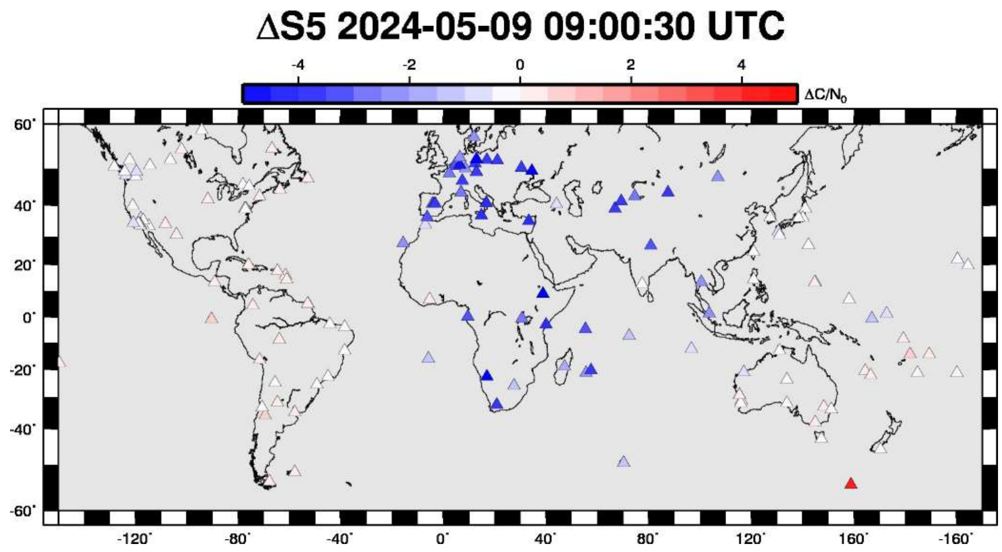


MONITORING SRB IMPACT ON GPS SIGNAL RECEPTION





GPS abnormal variation of the L1C, L2C, L2P and L5C signal receptions
from the EUREF Permanent GNSS Network
due to the solar radio burst of 9 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 are monitored **using large GNSS networks**