World-wide Ionospheric Scintillation Monitoring in real time using non-specialized receivers.

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The focus of this tutorial

- ✓ Introduce scintillation and how to monitor the effects on the signals from Global Navigation Satellite Systems (GNSS).
- ✓ Description of the different elements to be taken into account in the monitoring of scintillation based on the GNSS receivers used for geodetic or mass-market applications.
- ✓ Introduce an example of real-time worldwide monitoring of ionospheric scintillation (the RT-WMIS tool), based on geodetic receivers and recently developed under an European Space Agency (ESA) contract.

Scintillation: general introduction from GNSS perspective.

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Scintillation, what is it?

The effects produced by the fast fluctuations of the ionospheric electron density and total electron content (TEC) on the radio signals crossing the ionosphere. In particular, affecting the radio signals from GNSS satellites. Normally, it has quite local impact.

Physical phenomena producing ionospheric scintillation.

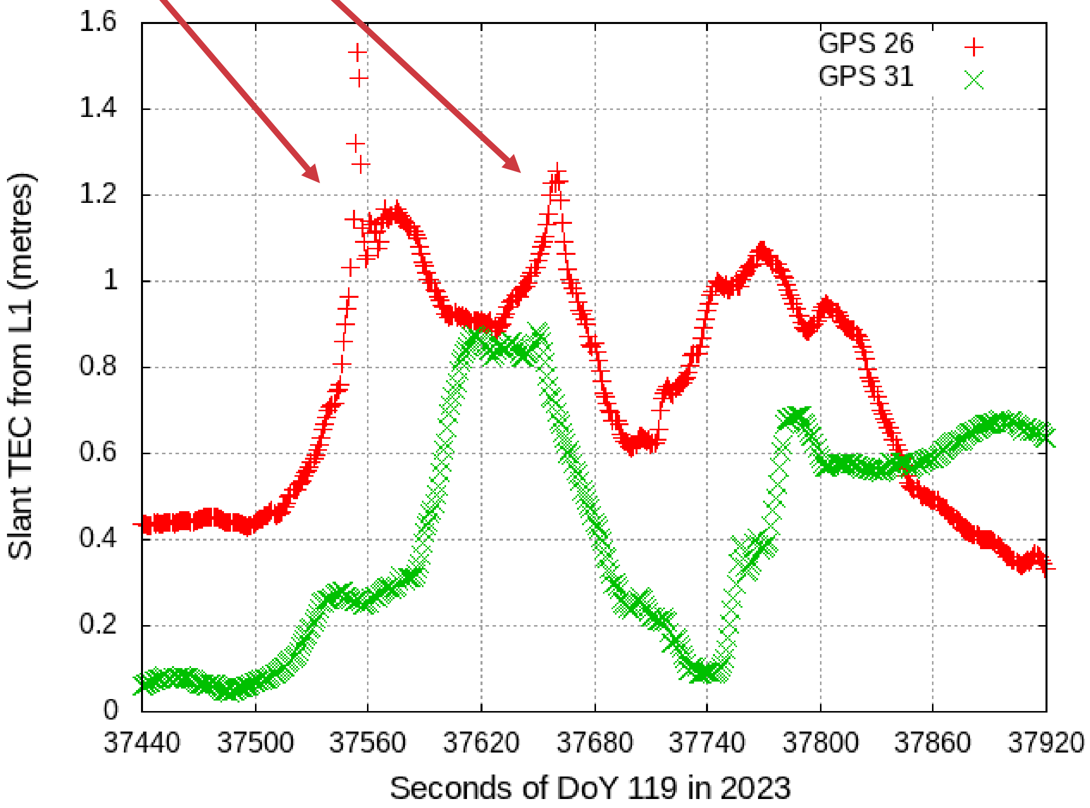
- Anyone giving rise to sudden gradients in the electron content:
  - ✓ plasma depletions (plasma bubbles), fast moving irregularities and, in the high latitudes, polar cap/auroral phenomena and geomagnetic storm effects.

When and Where?

- **Low latitudes:** Increses with solar activity. Maximazes from October to March and from sunset to midnight local times.
- **High latitudes:** All times and all the year. Even in solar minima.
- Middle latitudes: no source of scintillation other than side impact from low and high latitudes.

TEC fluctuations from L1.
Receiver in North Canada

G 26: Azimuth 80° Elevation 54°
G 31: Azimuth 87° Elevation 30°



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How can we classify the type of scintillation? (GNSS users!)

Model for the carrier-phase measurement at frequency f (L_f):

$$L_f = [Geodetically\ modelable\ terms] + \underbrace{\delta t_{rec}}_{Rx\ clock} + \underbrace{B_f}_{const} + \lambda_f \underbrace{N_f}_{int\ bias} - \left(\underbrace{I_f^r}_{refraction} + \underbrace{I_f^d}_{diffraction} \right)$$

Refractive scintillation: ionospheric irregularities of size larger than Fresnel length (300-400 m for L1), and moving at high speed (up to a few km/s).

- **Usual in the high latitudes**: caused by fast changes in the refraction index.
- Large fluctuations of carrier phases, but signal intensity/amplitude remains unaffected.
- The refraction term cancels out in the **Ionosphere-Free (IF) combination**

because: $\boxed{\dfrac{I_1^r}{I_2^r} = \dfrac{f_2^2}{f_1^2}}$

$$\boxed{L_{IF} = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2}}$$

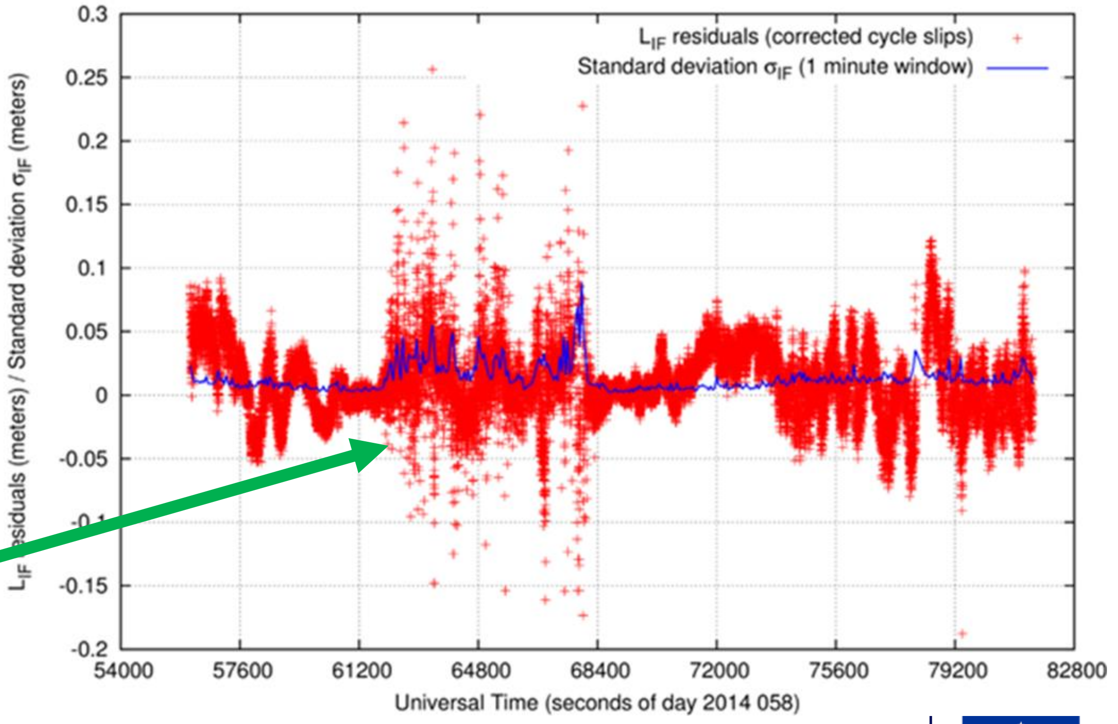
How can we classify the type of scintillation? (GNSS users!)

- **Diffractive scintillation:** signal is scattered when crossing ionospheric irregularities of size smaller than the Fresnel length.
  - **Mostly in the low latitudes:** diffraction causes signal amplitude fading.
  - Due to the low signal intensity => jumps in carrier phase tracking (cycle slips) or loss of lock of the signal.
  - Increases the *noise of the ionosphere-free* (IF) combination used in PPP.

$$L_{IF} = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2}$$

I_f^d is not removed

Diffractive scintillation. Example in a low latitude receiver in Seychelles (SEY1, Javad)



IF residuals (red) in meters after PPP and correcting the cycle slips.

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How can we detect and quantify scintillation? (GNSS signals!)

Specialized scintillation indexes.

- **Need observations at high sampling frequency (at least 1 Hz).**
- **Associated to individual satellites, signals and receivers.**

✓ **Amplitude scintillation index (S4):** standard deviation of signal intensity (SI) divided by the mean value over 60-sec intervals (dimensionless). Mostly related with **diffractive** scintillation.

✓ **Phase scintillation index (σ_φ):** standard deviation (over 60-sec) of the carrier phase observations after detrending. It is measured in radians. Related with **any type** of scintillation.

Detrending means removing any signal fluctuation not due to scintillation.

- Low-frequency (slow) variations: satellite motion, regular daily variations of troposphere, ionosphere …
- But also the high-frequency (fast) fluctuations: clocks and cycle slips (CS).

QUESTION: How to detrend GNSS signals to isolate the high-frequency (> 0.1 Hz) carrier-phase fluctuations caused by ionospheric scintillation?

✓ **Rate of total electron content index (ROTI):** the standard deviation (over 60-sec) of the temporal derivative of the TEC. Where TEC is estimated using a *combination* of carrier phase observations.

EXAMPLE: Amplitude Scintillation (S4)

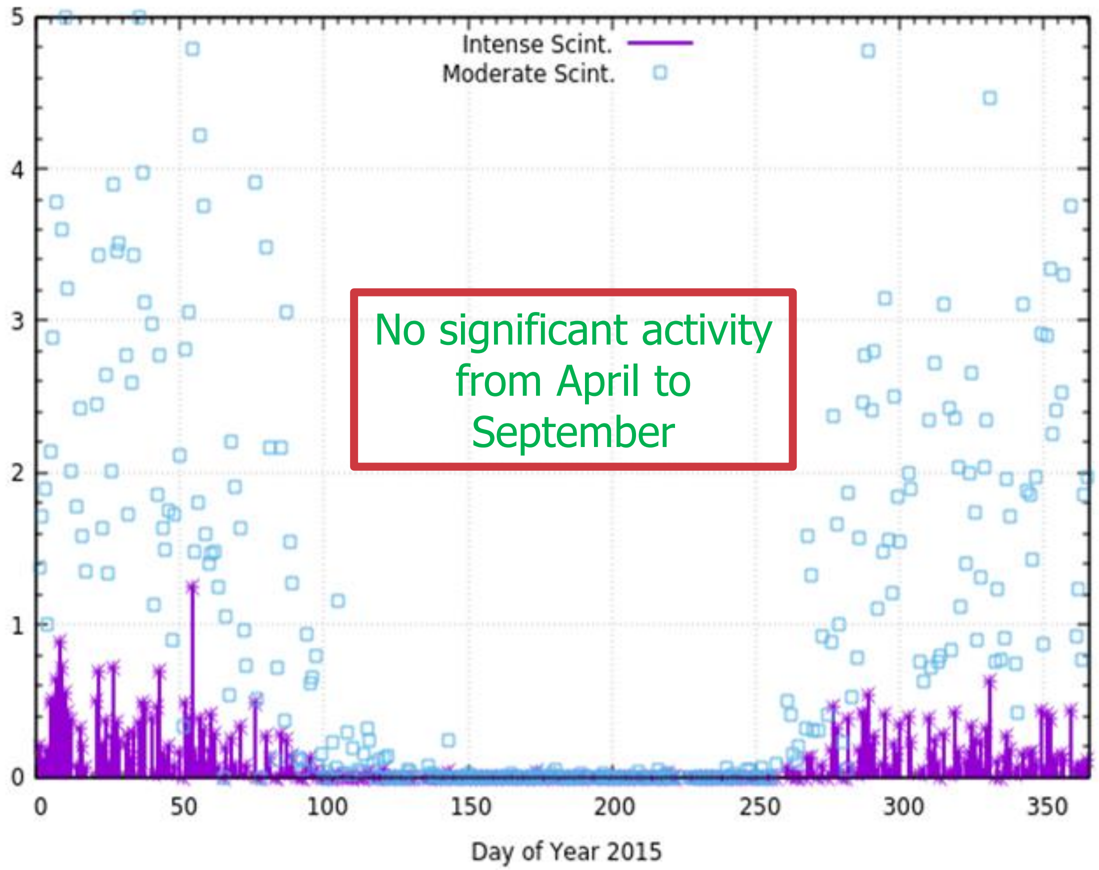
Thresholds from 2015, all year observations in low latitudes
Solar maximum was in 2014

- Moderate amplitude scintillation: **0.3< S4 < 0.5**
- Intense amplitude scintillation: **S4 > 0.5**

Daily frequency (% time) of moderate and intense amplitude scintillation from S4 in 2015.

- Scintillation concentrates from September to March Equinoxes.
- **All the scintillation activity occurs in the local times going from 19:00 to 3:00.**

Low latitude receiver KOUR in French Guyana (53° E, 5° N)



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Scintillation monitoring based on GNSS receivers

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Scintillation Monitoring with GNSS receivers

- **SPECIALIZED DEVICES.** Ionospheric Scintillation Monitoring receivers (ISMR)

- High frequency measurements (> 50 Hz) + very stable clock: normally avoid clock fluctuations but not the Cycle Slips.
- A high-pass filter (HPF), with cut-off 0.1 Hz, for detrending raw signal intensity and carrier phase. Output: S4 and σ_φ
  - Note: Detrended measurements at low elevations can be affected by large errors. Hence, a minimum elevation threshold of 30° is used in the scintillation studies.

✓ **BUT …**

- They are expensive.
- Deployed in a limited number and in limited regions.
- Not always accessible to the public.
- Existing public networks normally do not provide real-time information.

Scintillation Monitoring with GNSS receivers

- **CONVENTIONAL GNSS RECEIVERS**. Geodetic and high-grade receivers (e.g., EUREF, IGS …), but also mass-market receivers of low cost.
    - Large data sets from permanent networks of ground receivers deployed worldwide.
    - Could be enlarged at a low economic cost using commercial-grade receivers.
    - Existing RT products and data streams (e.g., IGS real time service). ***Measurements @ 1 Hz.***

✓ **But a detrending of GNSS signals must be performed:**

1. Using precise products (RCX position, orbits, clocks, tropo). It is advisable to check **satellite clocks.**
2. Then perform a precise and frequent **(every 1 sec)** estimate of the **receiver clock** offset and apply an accurate **CS detector.**
3. Characterize the residual noise remaining after the detrending (during null scintillation) to know the **minimum resolution achieved**.

➢ **Proposed methodology:** Geodetic Detrending (GD)
- Early introduced in Juan et al. 2017, JoGE
- Fully developed and tested against ISMR products in Nguyen et al. 2019 JoGE

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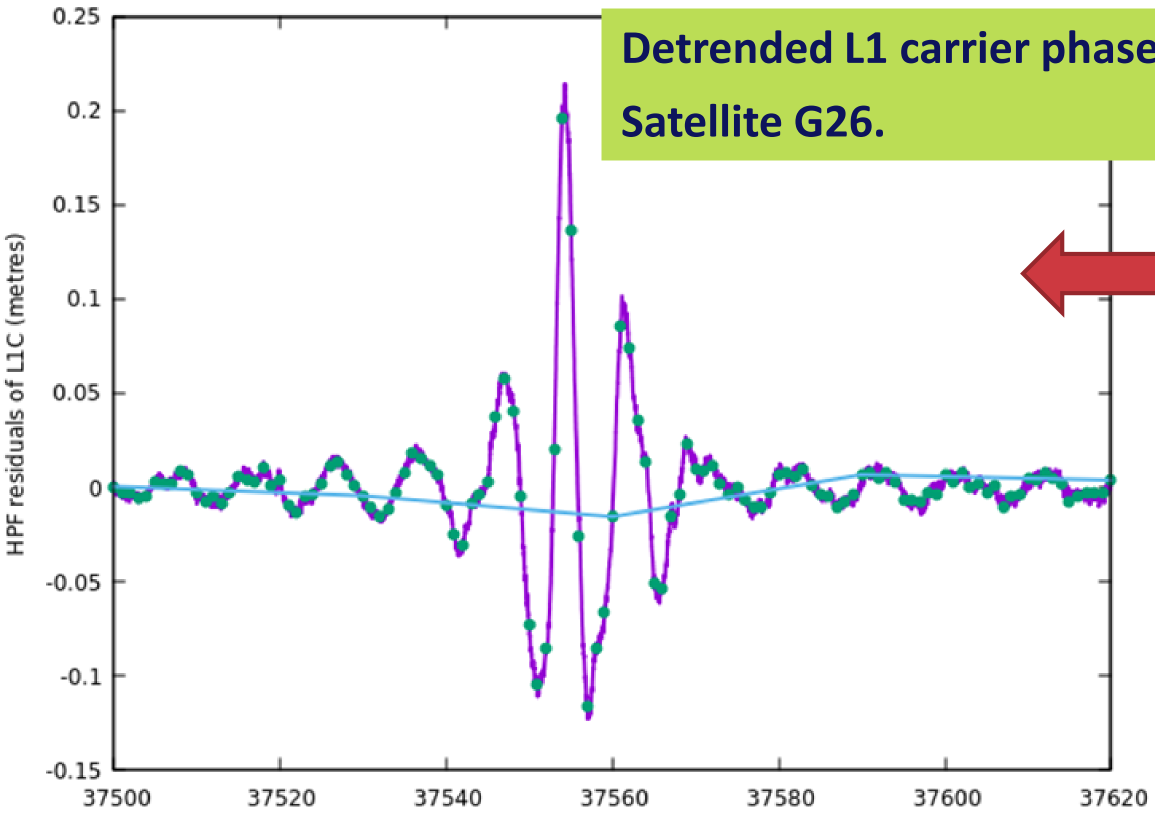
Scintillation Monitoring with conventional GNSS receivers

Can we trace high frequency fluctuations from scintillation with the 1 Hz (1 sec) observations?

- ✓ **YES if the fluctuations last at least a few seconds, which is very frequent.**
- ✓ **But NO with 1/30 Hz (30 sec) sampling.**



Detrended L1 carrier phase.

Satellite G26.

Seconds of DoY 119 in 2023

Two high latitude receivers (north Canada).

- **CHUC: ISMR operating @ 100 Hz (Septentrio)**
- **CHUR: Geodetic operating @ 1Hz**

  or **@ 1/30 Hz (TPS)**

Baseline distance 100 m.

- GNSS measurements every 30 sec were originally used to measure TEC fluctuations with the ROTI.
- In order to use the ROTI for scintillation monitoring, measurements at 1 Hz are mandatory.

Scintillation Monitoring with conventional GNSS receivers

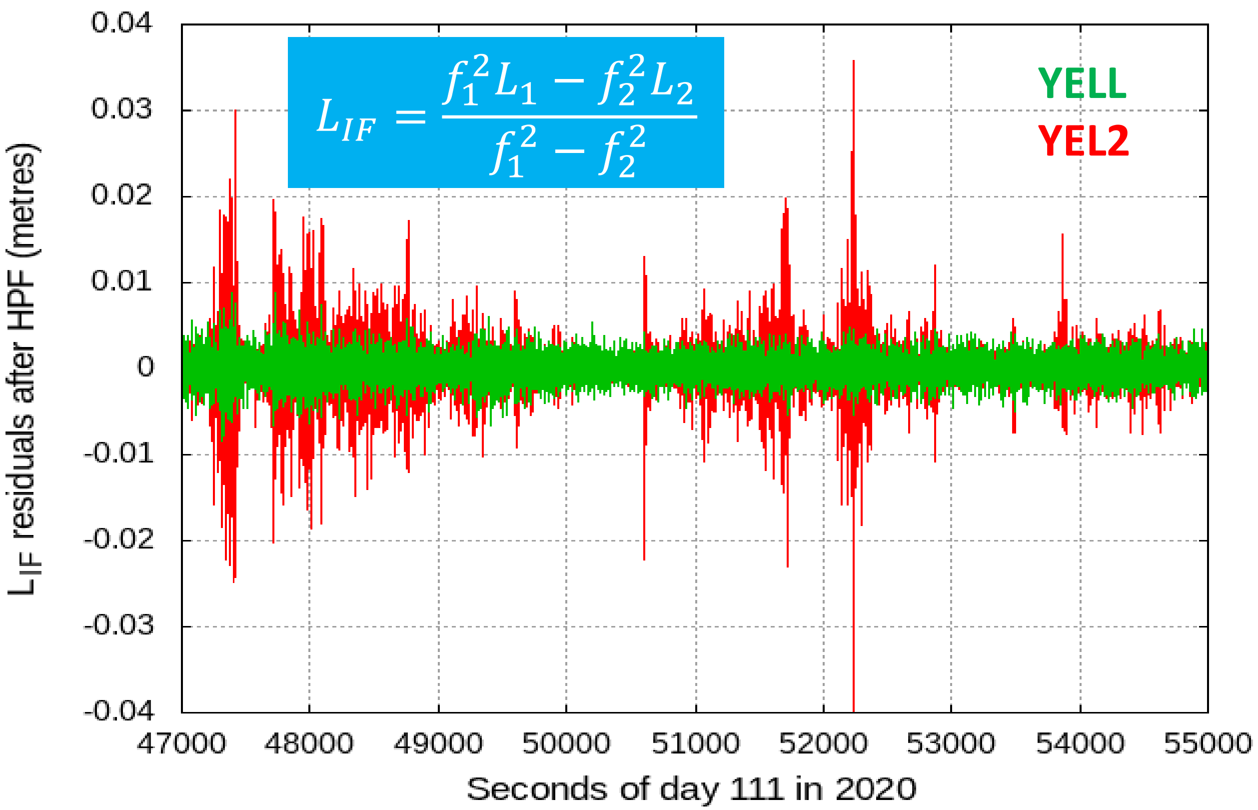
Do all receivers and all carrier-phase observations perform similarly for scintillation control?

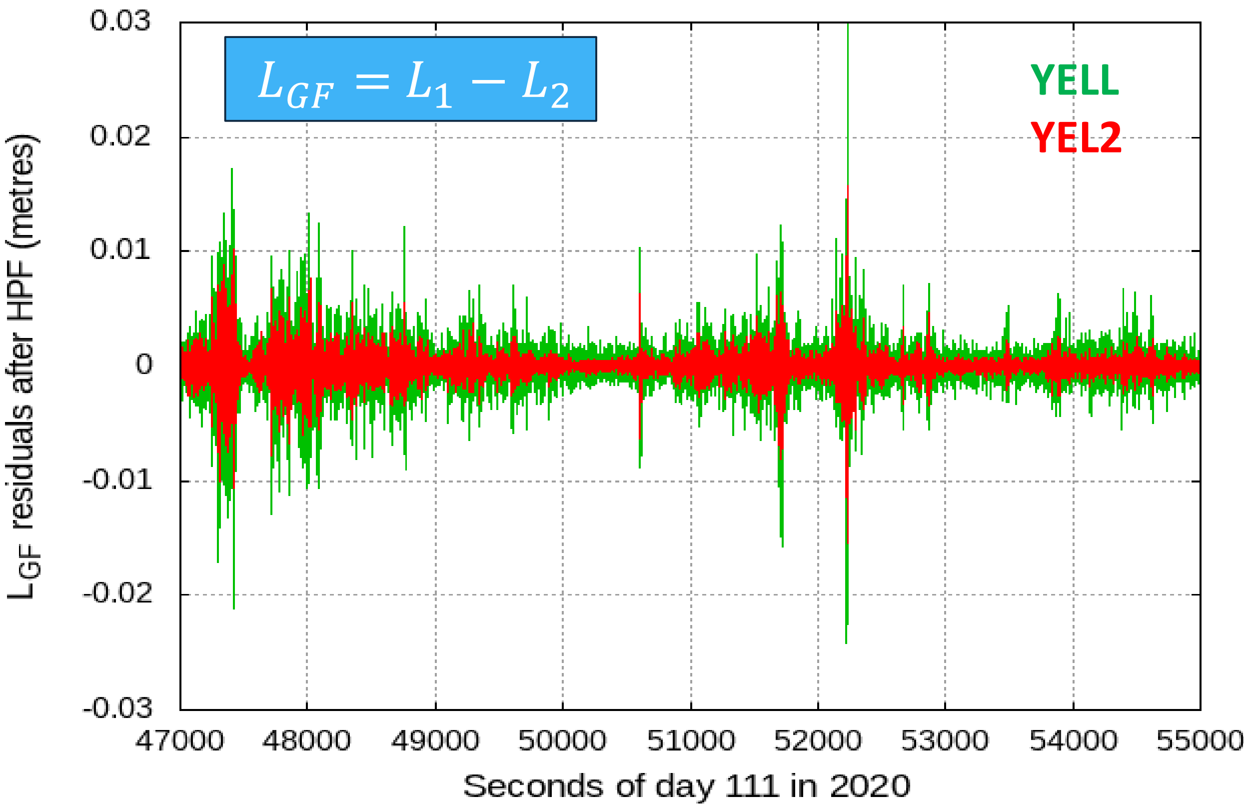
- ✓ **NOT always. One example are the GPS L2W observations.**
- ➢ L2W strongly depends on the tracking technique used by the receiver to acquire the L2 carrier.

High latitude receivers in North Canada.
Refractive scintillation.

YELL (Javad)
YEL2 (Septentrio)
Baseline distance 50 m

Detrended IF and GF combinations formed with L1C and L2W GPS carrier phases.





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Scintillation Monitoring with conventional GNSS receivers

Do all receivers and all carrier-phase observations perform similarly for scintillation control?

✓ **NOT always. One example are the GPS L2W observations.**

➢ L2W strongly depends on the tracking technique used by the receiver to acquire the L2 carrier.

✓ The L2 tracking in the Javad (YELL) avoids correlations between L2 and L1 observations.

✓ **Instead, the L2 tracking in Septentrio (YEL2)** is aided by L1 and clearly introduces a correlation between both signals.

- Hence the IF combination is not really free of the ionospheric fluctuations.
- While the GF combination does not reproduce the true ionospheric fluctuations.

A problem for the ROTI based on the GF combination of L1C and L2W !!

✓ The alternative proposed by the GD is to use ROTI based on uncombined signals (e.g. L1 only).

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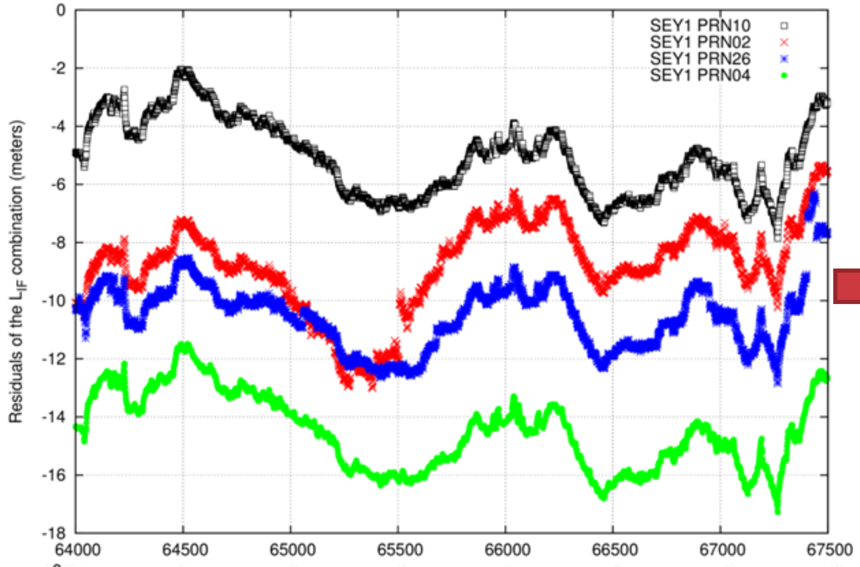
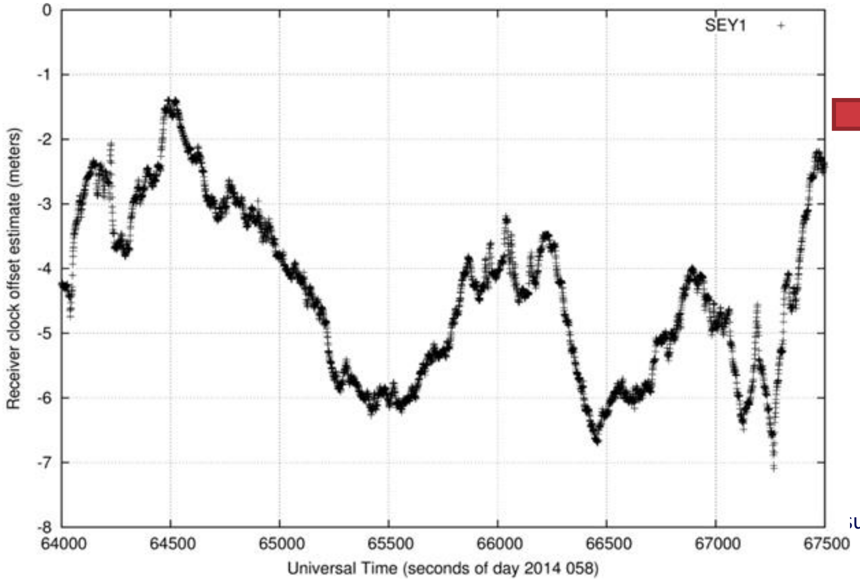
Receiver clock fluctuations

Example from SEY1 Seychelles Island (55º E, 5º S)

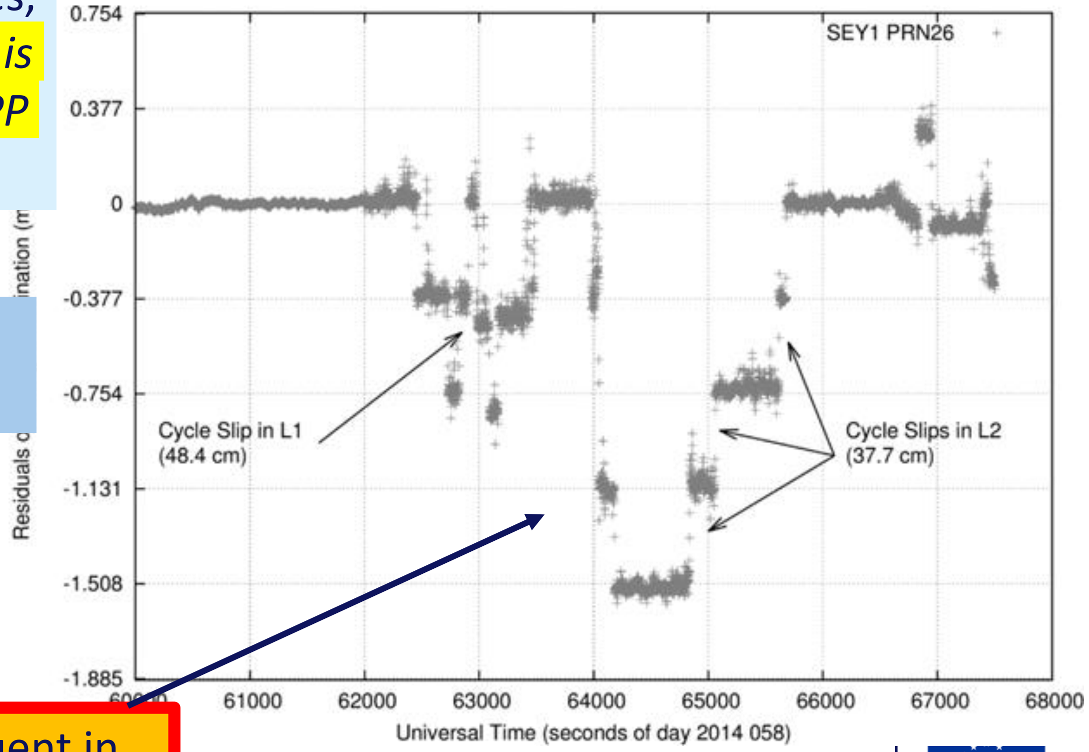


The IF combination after first part of GD : using precise products and models (satellite orbit and clock, tropo, wind-up, tides, rcv coordinates, etc). *This is similar to conventional PPP modelling*.



Receiver clock estimate every 1 second from GD

IF residuals after removing the receiver clock: **Cycle Slips can be observed in each individual signal.**
1 cycle L1 = 48,4 cm in the IF
1 cycle L2 = 37,7 cm in the IF



Cycle slips are more frequent in the L2 than in the L1 carrier phase.

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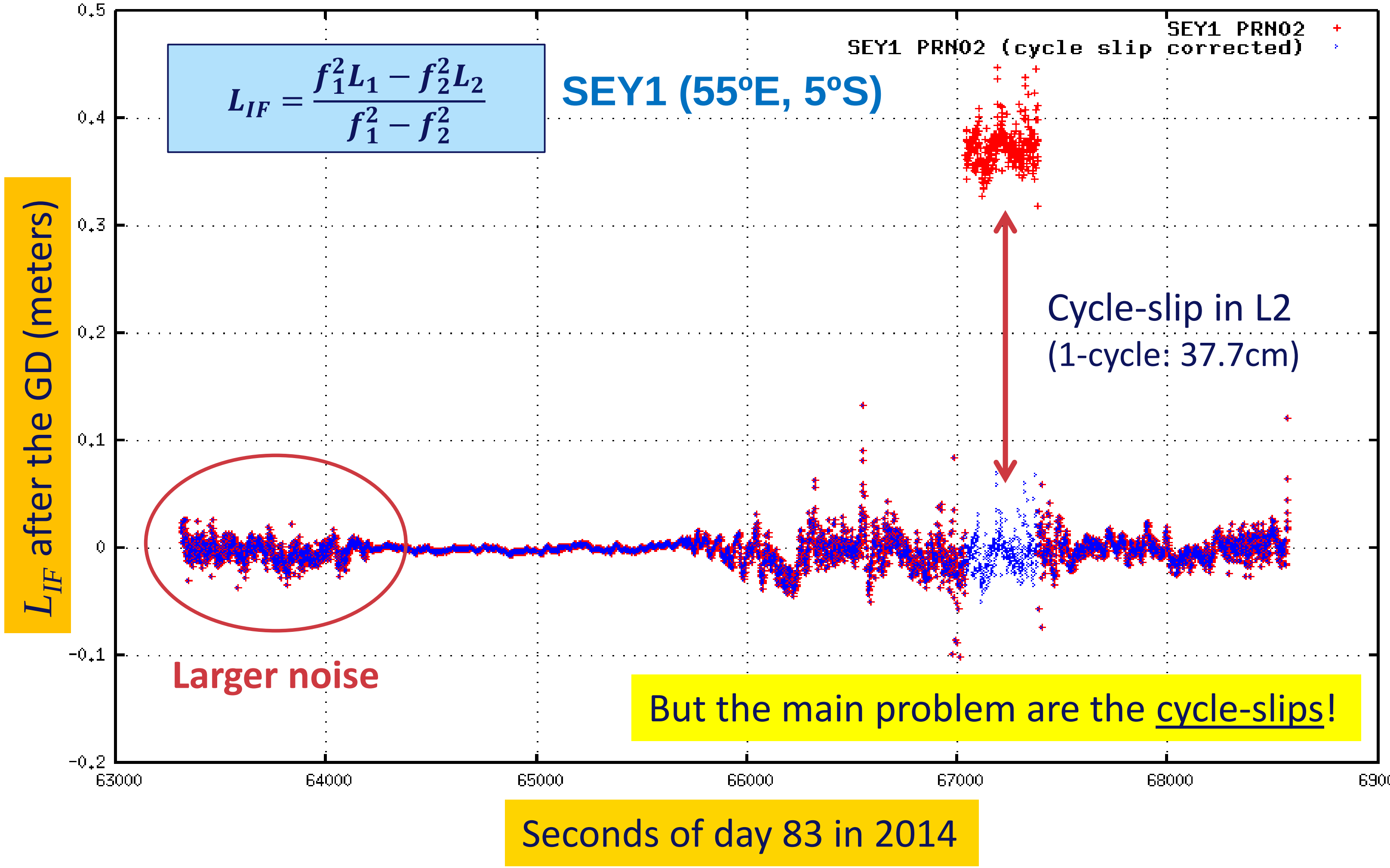
Detection of elemental cycle slips

Diffractive Scintillation in the low latitudes degrades the IF combination: Noise increases and cycle-slips occur.



Effects of undetected Cycle Slips:

- Introduce **misleading fluctuations** in the carrier phases NOT reflecting **true** ionospheric fluctuations. Impact on scintillation monitoring.
- But also impact on precise navigation.

However, if the Cycle-slips can be detected and then corrected:

- ✓ Scintillation can be reliably quantified.
- ✓ Precise navigation under scintillation conditions is feasible, with decimetre level accuracy in the positioning.

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Assessment of satellite clocks

Clocks in some satellites can suffer fast fluctuations. When not properly corrected from the carrier phases they will produce large σ_φ NOT related with scintillation.

GPS, satellite clock fluctuations:

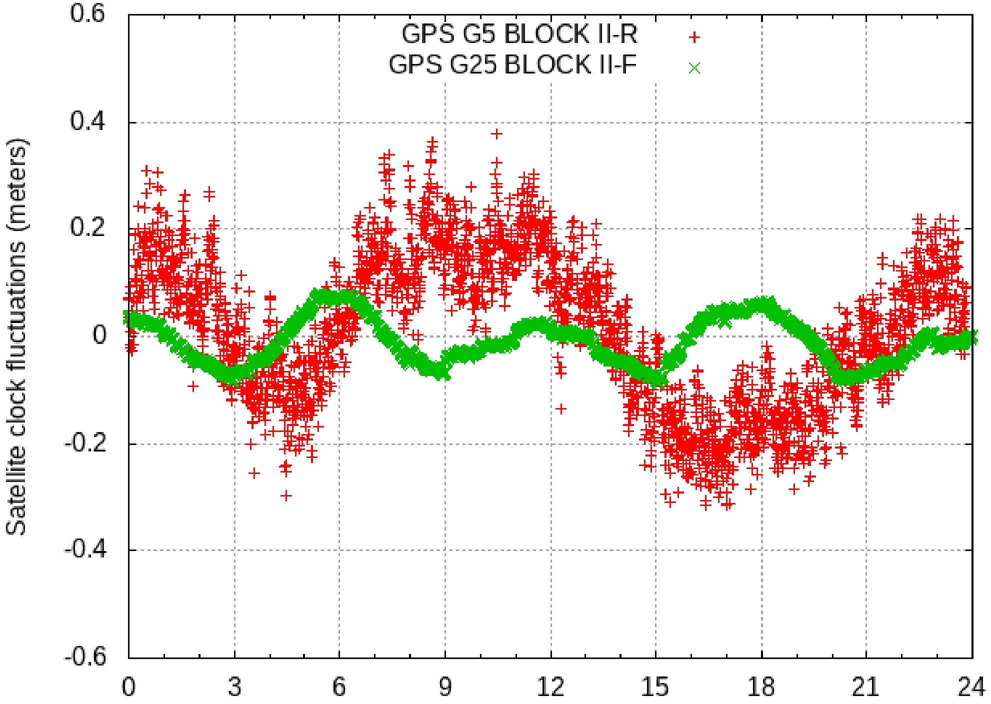
- Block II-R satellite G5, launched in August 2009.
- Block II-F satellite G25, launched in May 2010.

Fluctuations in G5 are tens of cm, but a few cm in G25

Galileo, satellite clock fluctuations:

- In Orbit Vehicle satellite E19, launched in October 2012.
- FOC satellite E30, launched in September 2015.

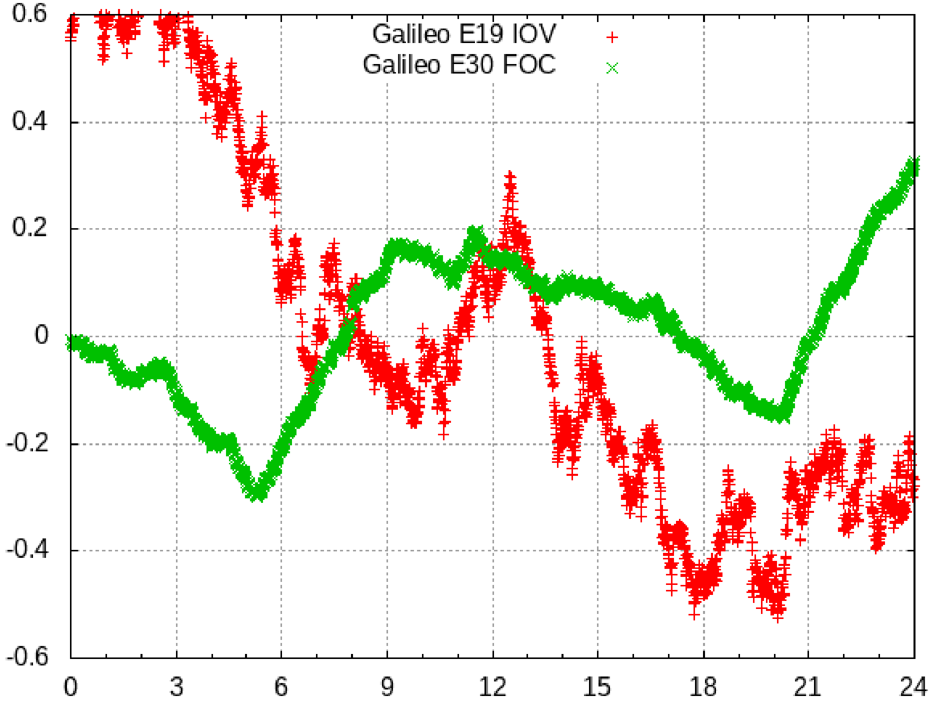
Fluctuations in E19 very large compared to E30.



Hours of day 74 of 2024 (UTC)

The fast (short-time) clock fluctuations cannot be modelled when the satellite clocks are given with 30-sec sampling intervals.

IGS post-process and RT clock products are USUALLY sampled @ 30 sec



Hours of day 74 of 2024 (UTC)

Minimum resolution achieved with scintillation indexes

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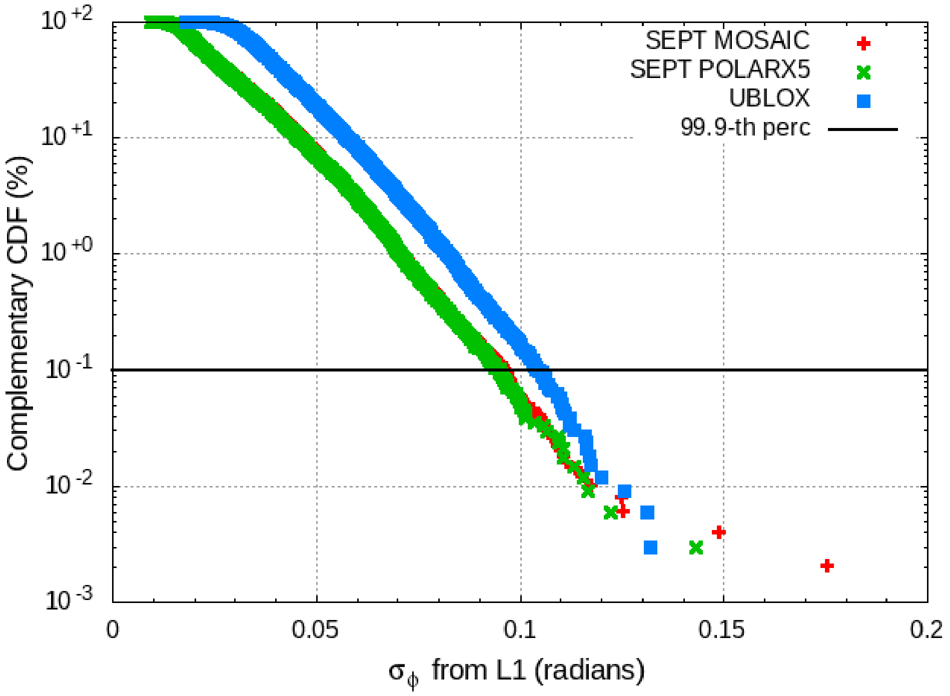
Experiment in Barcelona. UPC campus.

- Single antenna (2.1° E, 41.4° N) connected to *3 receivers*.
- Time Period: DoY 192 to 200, July 2023
- Mid-latitude, summer → Quiet iono & **Null scintillation**

Device	Septentrio PolaRx5e	Septentrio Mosaic X5	Ublox ZED-F9P-04B
Type	Geodetic	Middle-cost	Low-cost
99% S4	0.12	0.12	0.14
99.9% σ_φ	0.09 rad	0.09 rad	0.105 rad

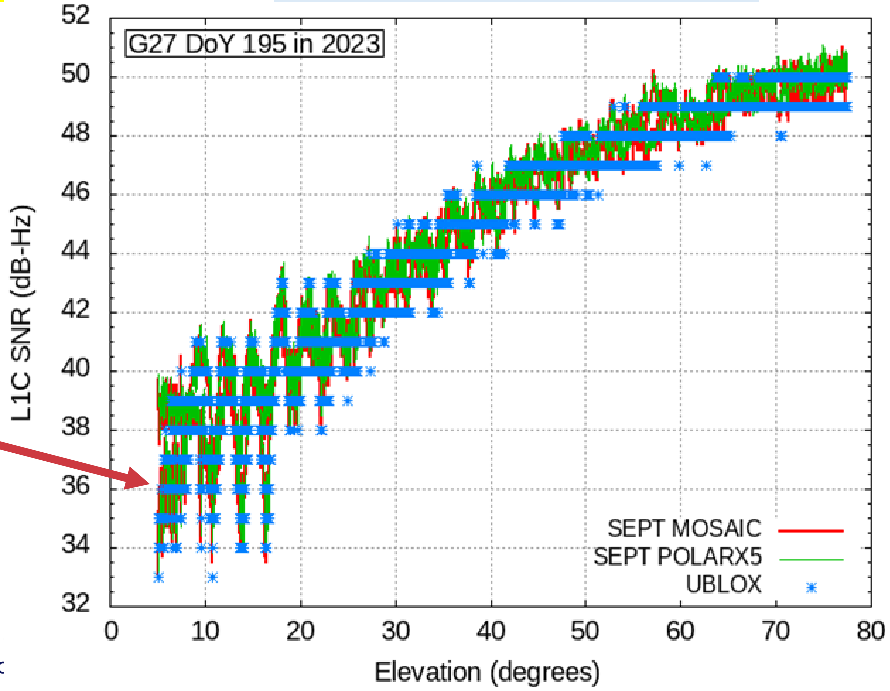
Minimum resolution from the Highest percentiles



Frequency Distribution (1 - CDF) of σ_φ values

- The two Septentrio devices (Mosaic and PolaRx5e) show highly consistent values.
- Ublox shows only slightly less resolution in S4 and σ_φ indexes.
- SNR used to estimate the S4 has **less resolution in the Ublox** compared to the other receivers.

$$SNR = 10^{0.1\left(\frac{C}{N_0}\right)}$$



Real Time Worlwide Monitoring of Ionospheric Scintilation (RT-WMIS)

with conventional GNSS receivers

RT-WMIS Methodology: Geodetic Detrending (GD)

RT implementation in 2023 after an initiative proposed by gAGE/UPC to the ESA Open Space Innovation Platform.

It is based on:

- Currently deployed networks of geodetic GNSS receivers.
- NTRIP to collect data from different casters providing RT carrier phase observations @ 1 Hz.
- RT precise orbits (5 min), clocks (30 sec) and troposphere (5 min) from the worldwide ionosphere caster for Galileo HAS (IONO4HAS).
  - ➢ It can be adapted to use the RT orbits and clocks transmitted by the RT IGS service, and the RT PPP software from BNC to compute troposphere.
- Detrending of individual (uncombined) GNSS signals: RT receiver clock estimate and CS detection.
- Determination of scintillation parameters every 60 sec: **S4, σ_φ, ROTI**, … for each receiver-satellite line of sight.

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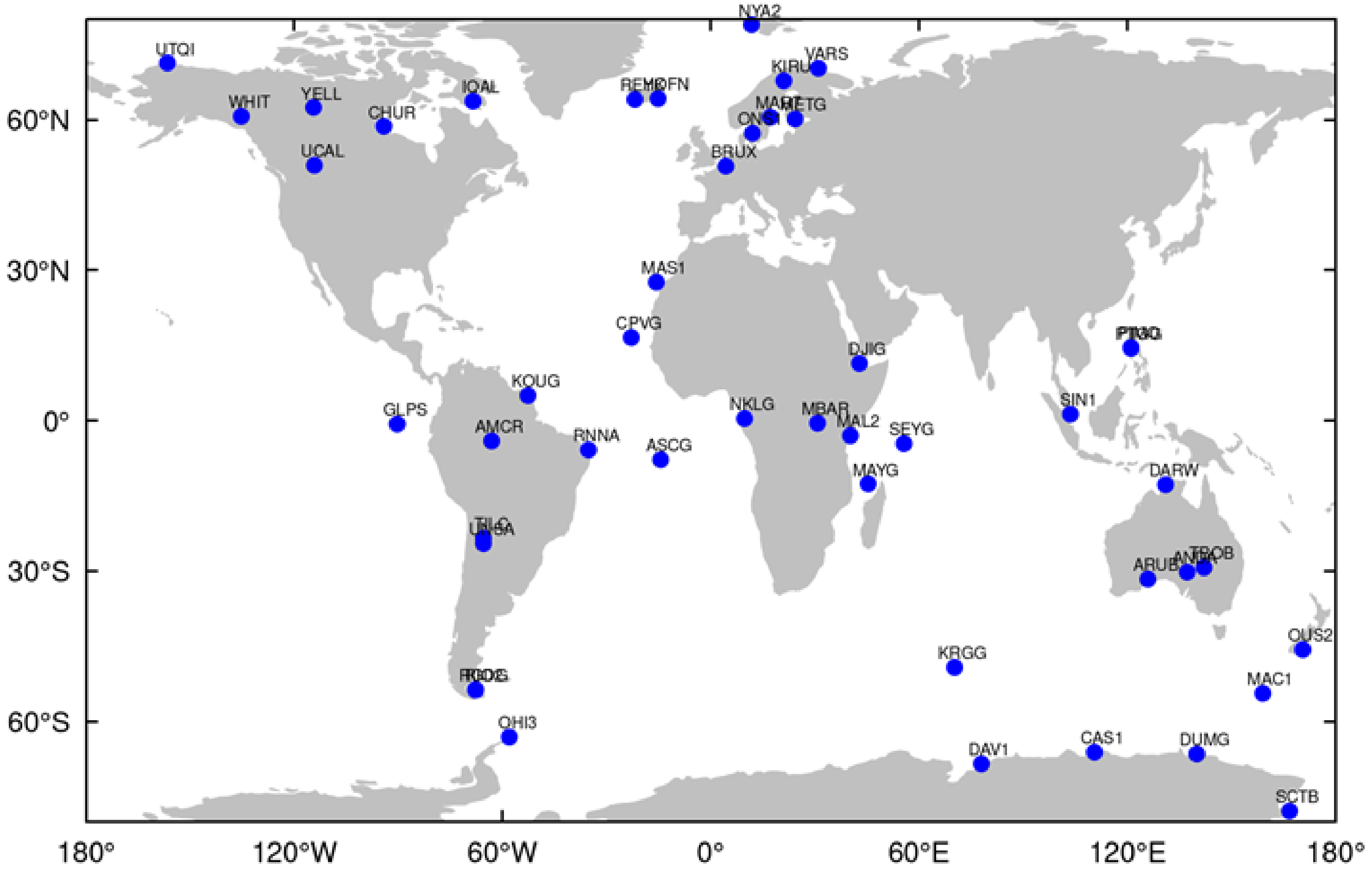
RT-WMIS: Global Observation Network

- 47 GNSS real-time stations, including 3 pairs of nearby receivers.
- Satellite systems: GPS + Galileo
- GNSS signals:
  - ➢ GPS: L1, L2C/W
  - ➢ Galileo: E1, E5a

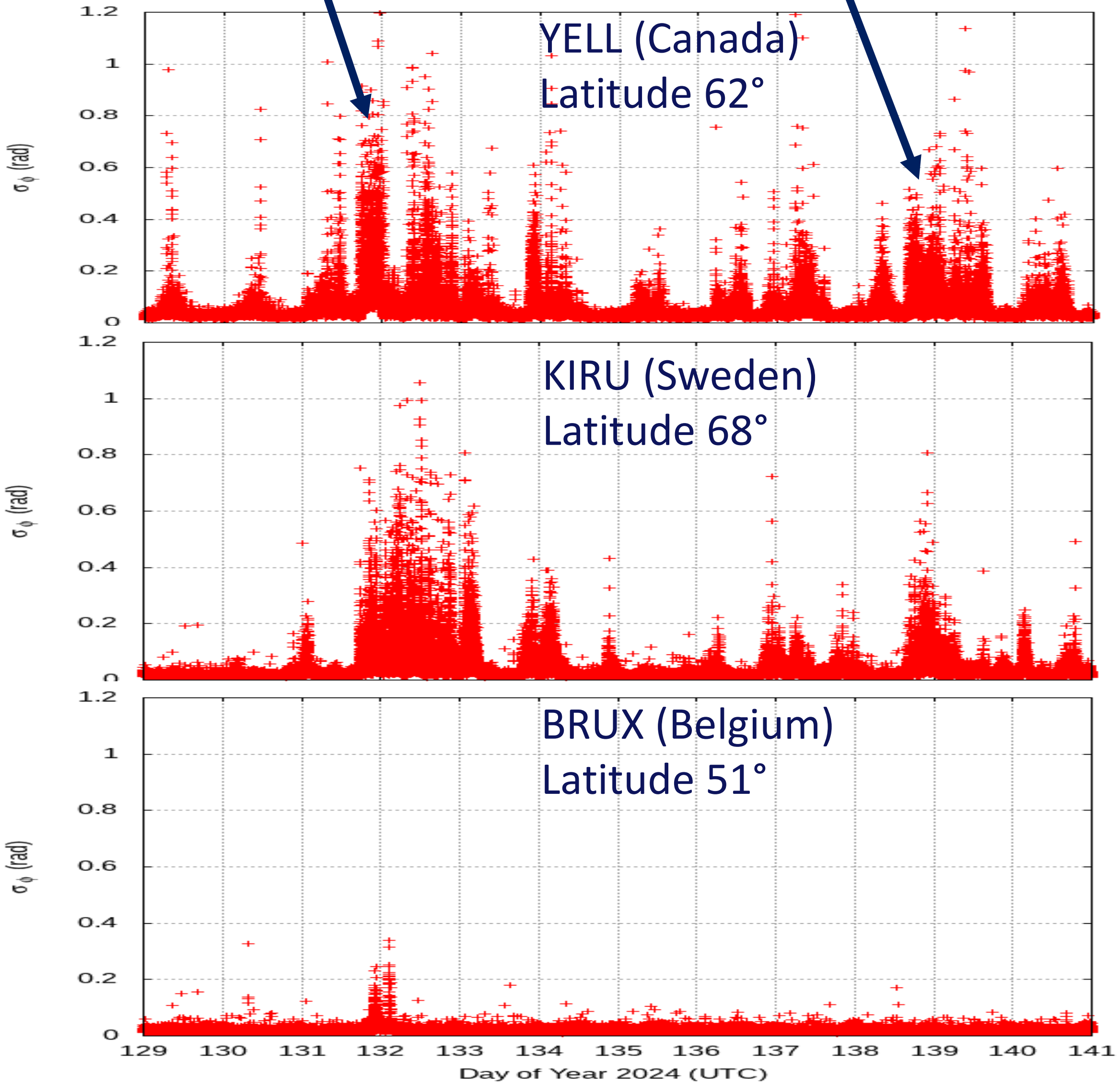


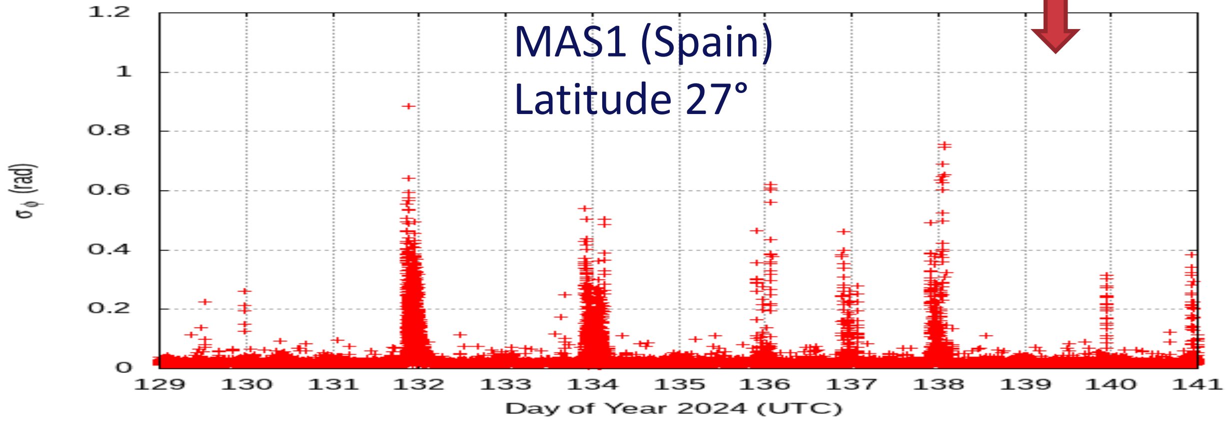
A recent example: σ_φ in geomagnetic storm period May 8 to 19, 2024

G4 NOAA class geomagnetic storm on May 10-11, 2024, Day of Year (DoY) 131-132

G2 NOAA class geomagnetic storm on May 17, 2024. DoY 138

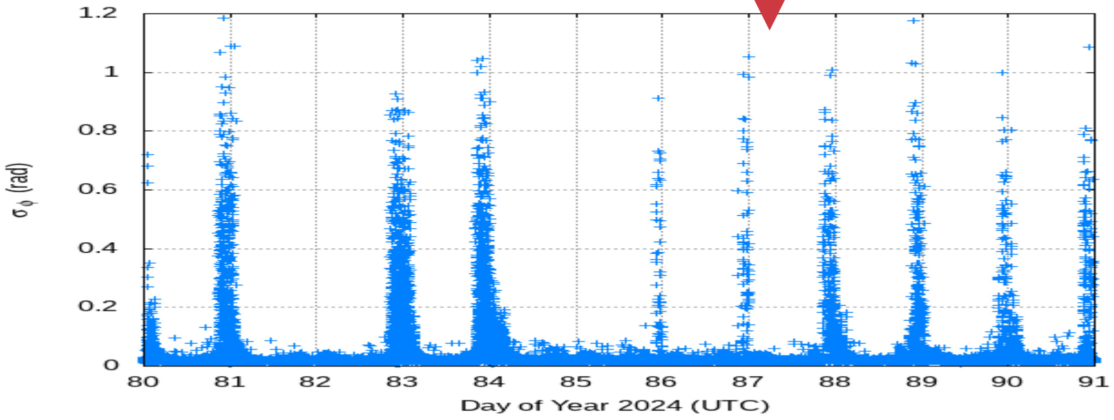
Low latitude in **Gran Canaria Island**





But in **low latitudes** scintillation activity is higher in the equinox **(20 to 30 March 2024)** than during geomagnetic storm period.

MAS1 (Spain)
Latitude 27°



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ESA–OSIP contract:
"RT-WMIS from high-end to low-cost receivers"

Spanish Government & FEDER EU:
"Improved methods for an instantaneous, precise & reliable GNSS-based positioning"

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