Solar radio burst interference index dedicated to GNSS single and double frequency users

Jean-Marie Chevalier [1,2] *(jean-marie.chevalier@oma.be), Nicolas Bergeot* [1,2]*, Pascale Defraigne* [1]*, Christophe Marqué* [1,2] *and Elisa Pinat* [1]

Royal Observatory of Belgium, Space Geodesy and Geodymanics, Brussels, Belgium

Solar Terrestrial Centre of Excellence, Brussels, Belgium

Abstract

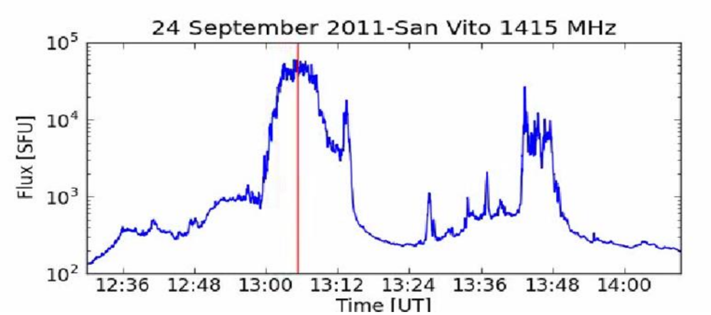
Intense **Solar Radio Bursts (SRBs)** emitted at **L-band frequencies** are a source of **radio frequency interference** for Global Navigation Satellite Systems (**GNSS**) by inducing a noise increase in GNSS measurements, and hence **degrading the carrier-to-noise density (C/N_0)**. Such **space weather events are critical for GNSS-based applications** requiring real-time high-precision positioning.

Since 2015, the Royal Observatory of Belgium (**ROB**) **monitors in near real-time the C/N_0 observations** from the European Permanent Network (**EPN**). The monitoring allows to **detect accurately** the general fades of C/N_0 due to SRB over Europe **as from 1 dB-Hz**. It provides in **near real-time a quantification of the GNSS signal reception fade** for the **L1 C/A** and **L2 P(Y)** signals and **notifies** civilian **single and double frequency users** with **a 4-level index** corresponding to the potential **impact on their applications**. This service is part of the real-time monitoring service of the **PECASUS** project of the **International Civil Aviation Organization (ICAO)** which started end of 2019.

Results of this 5-year monitoring will be discussed, including the **3 SRBs of 2015 and 2017**, together with the new developments toward a **global index** using the International GNSS Service (**IGS**) network. In addition, we will show how the SRB monitoring is sometimes interfered by **GPS flex power campaigns** on the satellites from blocks IIR-M and IIF, and how it is mitigated. The routine and transient GPS flex power campaigns will be presented in terms of C/N_0 variations for the EPN and IGS networks.

1. Solar Radio Burst and GNSS

Intense **Solar Radio Bursts** (SRBs) emitted at L-band frequencies are a source of **Radio Frequency Interferences** (RFI) for Global Navigation Satellite Systems (GNSS) (Klobuchar et al. 1999). During such events, the GNSS **signal reception is degraded** (Cerruti et al. 2006) and fades of **carrier to noise density (C/N0)** can be observed at the GNSS receiver level for all satellite tracks (Figure 1).



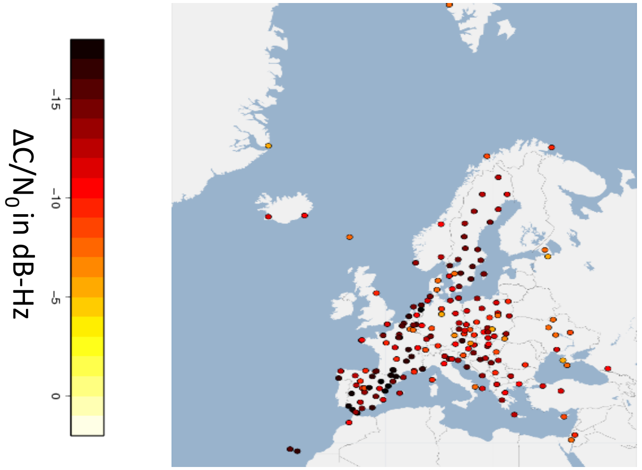


Figure 1: GPS signal reception fade at L2 for the EPN stations during the Solar Radio Burst of the 24th September 2011

It generates large GNSS **positioning errors** on horizontal and vertical components (*Carrano et al. 2009, Sreeja et al. 2014, Muhammad et al. 2015*) (Figure 2). Such **space weather events are critical for GNSS-based applications** requiring real-time high-precision positioning.

Muhammad et al. 2015

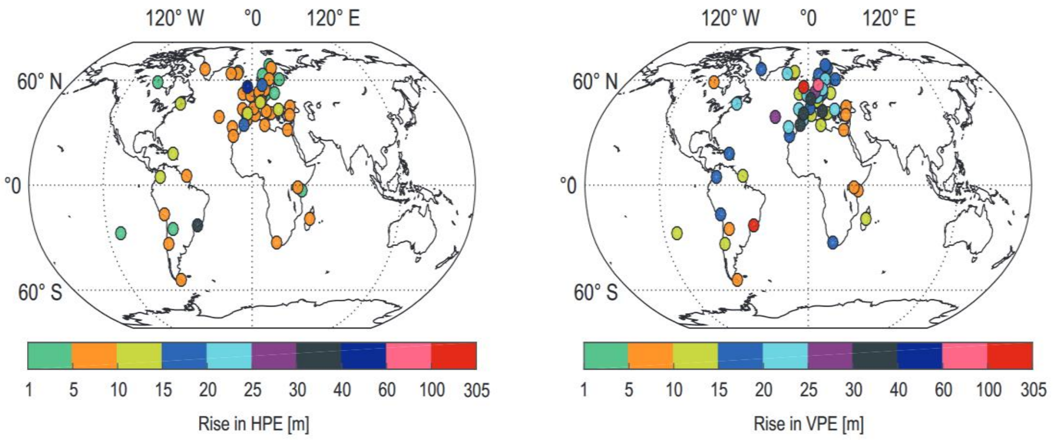
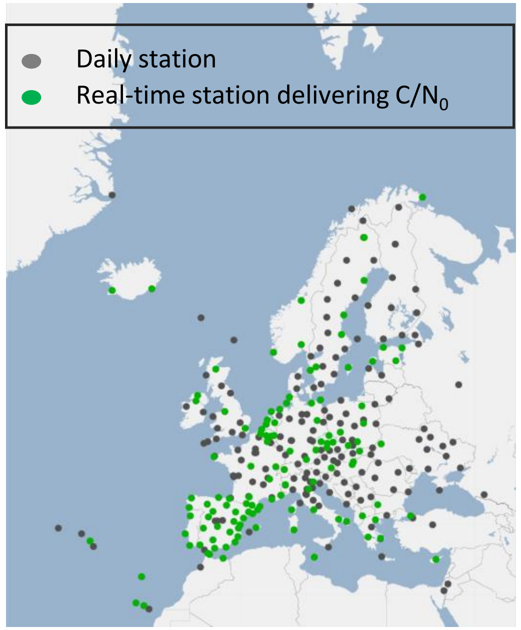


Figure 2: Rise in positioning error during the 24/09/2011 SRB (error during the SRB – error on quiet day)

It is thus important to **nowcast SRB impacting the GNSS applications**. The warning system presented here is **operational since 2015 in near-real time** to detect SRB at the GNSS frequency bands.

2. Data and Method



- Real-time GPS observations **S1** and **S2** corresponding to **L1 C/A** and **L2 P(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) by comparing with **the C/N_0 quiet normal behaviour**, i.e. the median $\langle C/N_0(t, rec, sat) \rangle$ of the 7 previous ground track repeat cycles.

$$\Delta C/N_{0\,(t,\,rec,\,sat)} = C/N_{0\,(t,\,rec,\,sat)} - \langle C/N_{0\,(t,\,rec,\,sat)} \rangle$$

- Estimation of a **$\langle \Delta C/N_0 \rangle_{L1,L2}$ 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.

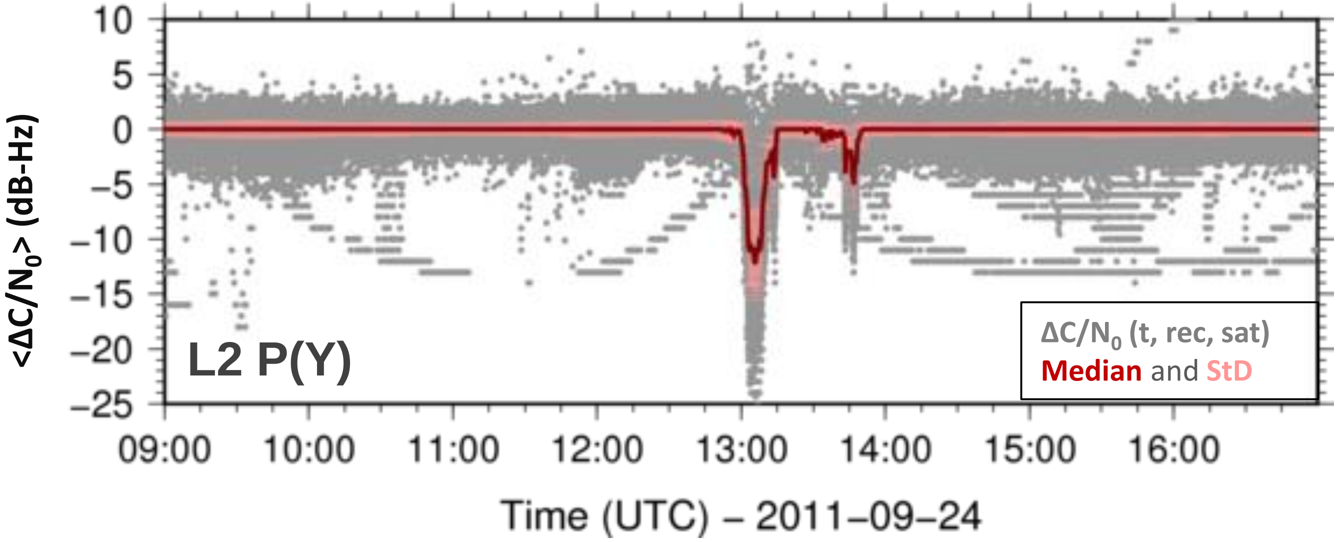
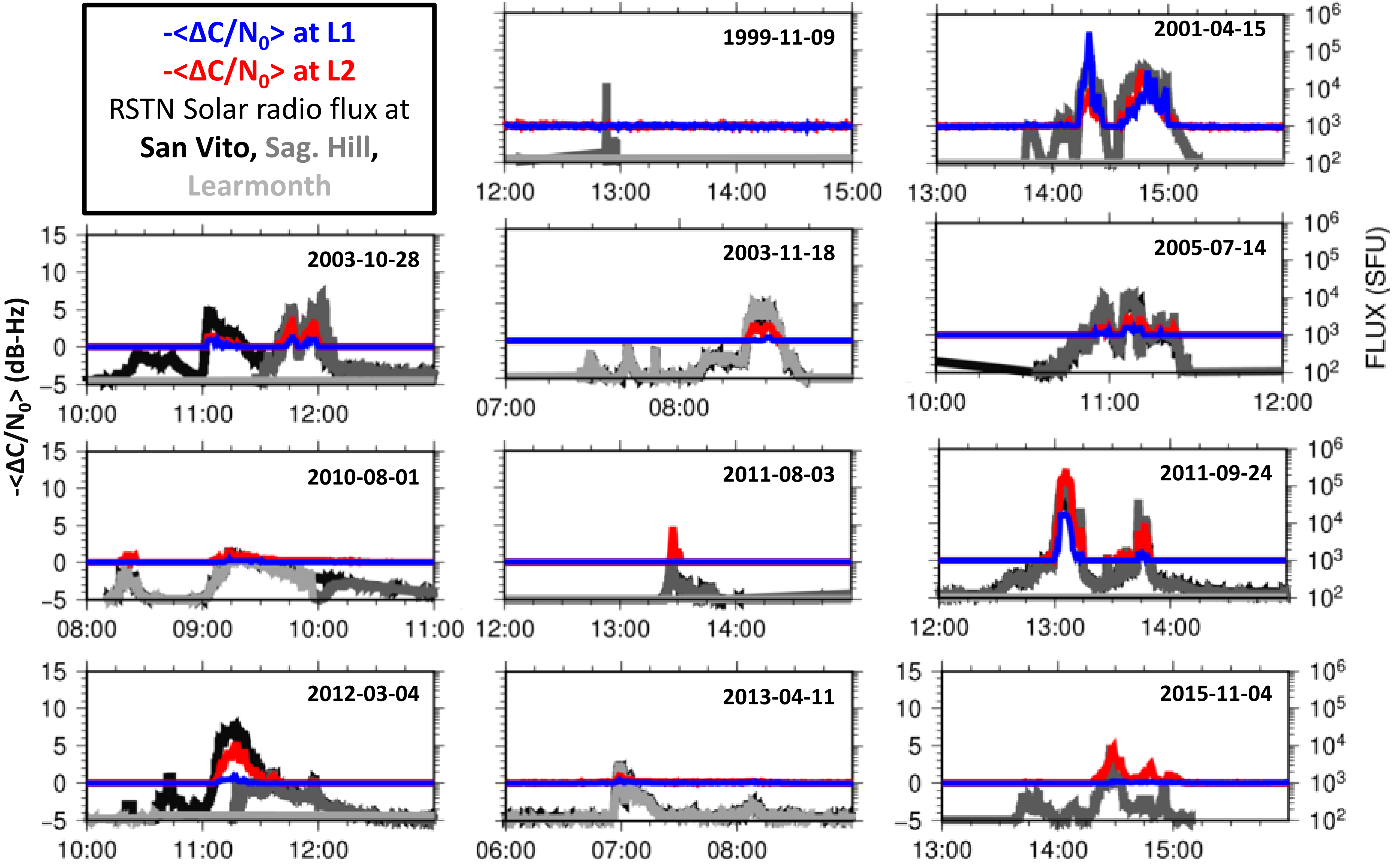


Figure 3: abnormal GPS L2 P(Y) $\Delta C/N_0$ fade for each observations of the EPN (grey) and the median $\langle \Delta C/N_0 \rangle_{L2}$ (in red) over the EPN during the SRB 24/09/2011

3. Validated with SRBs occurring in the sunlit of Europe from 1999 – 2015



- Comparison with **solar radio flux** data **at 1415MHz** from the **Radio Solar Telescope Network (NOAA)**
- The estimated $<\Delta C/N_0>_{L1,L2}$ are **in agreement** with the solar radio flux data above 10^3 SFU (apart in 1999).
- Accurate detection of SRB as from **1 dB-Hz $<\Delta C/N_0>$ fade**, thanks to the large number of stations.
- **GLONASS** data **agrees at 0.1±0.2 dB-Hz with GPS**, apart during the 24/09/2011 at the L2 frequency, with a difference of 4.75 dB-Hz.

4. Near-Real Time SRB Alert System for GNSS Users at www.gnss.be

These estimated $<\Delta C/N_0>_{L1,L2}$ from the GNSS network is used to provide **scaled level warnings** for the GNSS users as **from 1 dB-Hz degradation**.

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

Email alerts, register at iono@oma.be

From iono@oma.be

Subject **SRB Alert: LEVEL 2 STRONG**

To Jean-Marie Chevalier

```
GNSS signal reception over Europe is affected by an ongoing Solar Radio Burst

A general fade of the Carrier to Noise density (C/N0) is observed on GNSS stations in Europe due to an ongoing SRB.
- At the L1 frequency band, the alert level is 1 (MODERATE) with a max fade of -1.11 dB-Hz at 12:01:30(UTC).
- At the L2 frequency band, the alert level is 2 (STRONG) with a max fade of -6.29 dB-Hz at 12:02:30(UTC).
```

***Web page updated every 15mins** : example of the last SRB of the 06/09/2017*

SRB WARNING SYSTEM FOR GNSS APPLICATIONS IN EUROPE

Contact: *iono@oma.be*

To receive real-time alert emails, please contact us to be added to the mailing list.

Last update : 2017-09-06 13:30:00 UTC	L1	L2
Last 15min		
Last 24h		
Last week		

Events of the last 30 days:

Frequency	Date of the maximum fade	Maximum fade (in dB-Hz)	Beginning of the event (fade<-1dB-Hz)	End of the event (fade>-1dB-Hz)
L1	2017-09-06 13:07:30	-1±0.5	2017-09-06 13:07:30	2017-09-06 13:08:00
L1	2017-09-06 13:05:00	-1±0.52	2017-09-06 13:05:00	2017-09-06 13:05:30
L2	2017-09-06 13:03:30	-2.75±0.91	2017-09-06 12:56:30	2017-09-06 13:20:00
L2	2017-09-06 12:20:30	-1±0.52	2017-09-06 12:20:30	2017-09-06 12:21:00
L2	2017-09-06 12:08:30	-2±1.08	2017-09-06 12:08:30	2017-09-06 12:10:00
L2	2017-09-06 12:02:30	-6.25±1.6	2017-09-06 12:01:00	2017-09-06 12:04:30
L1	2017-09-06 12:01:30	-1±0.61	2017-09-06 12:01:30	2017-09-06 12:02:30

5. Online Event Summaries

SOLAR RADIO BURST EVENT 2015-11-04

The signal reception of the GNSS L2 frequency was affected by a solar radio burst on 4th November 2015 between 14:20 and 15:02 (UTC). The maximum peak was observed at 14:29 UTC with a median fade of **-5.8±2.2 dB-Hz** over all EPN stations and a maximum fade of **-10 dB-Hz**.

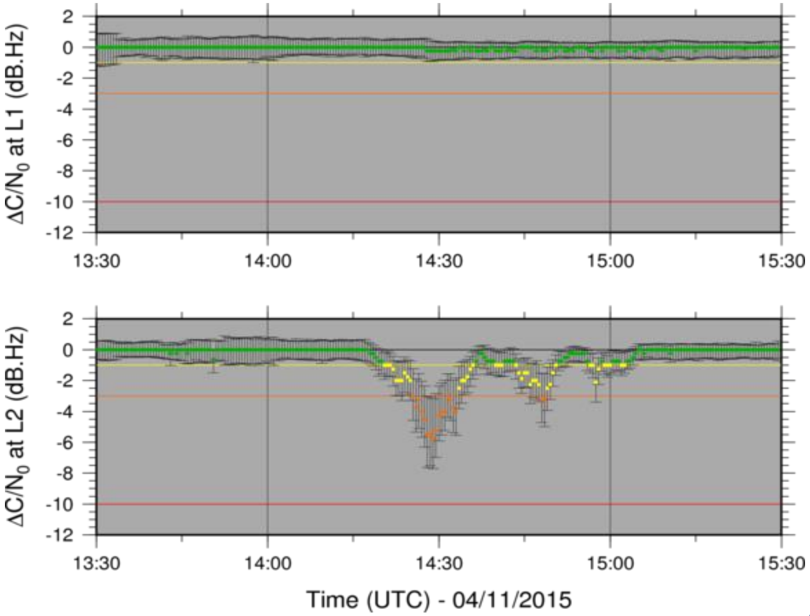


Figure 5: $\langle \Delta C/N_0 \rangle_{L1,L2}$ over the EPN

SOLAR RADIO BURST EVENT 2017-09-06

The SRB impacted the GPS signal reception on both L1 C/A and L2 P(Y) signals. On L1, two fades above 1dB-Hz were detected at 12h01 and 12h05 (UTC). On L2, a first fade above 3dB-Hz which could potentially affect the GNSS application, occurred for 3 min with a maximum of **-6.25±1.6dB-Hz** at 12h02. It was followed by a 2^{nd} fade above 1dB-Hz at 13h03.

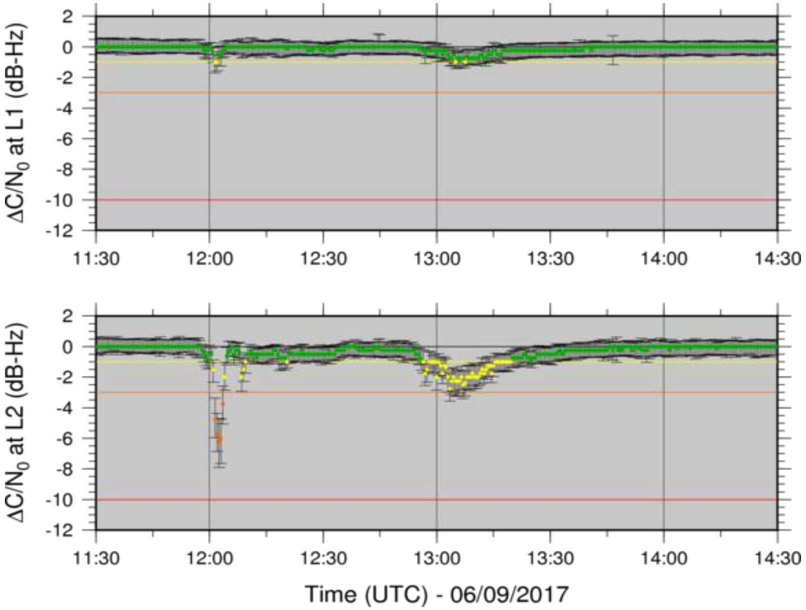


Figure 6: $\langle \Delta C/N_0 \rangle_{L1,L2}$ over the EPN

SOLAR RADIO BURST EVENT 2017-09-07

Two small SRB detected by the GNSS EPN stations but should not impact GNSS applications. The first one was at 10:16 in the L2 frequency band with a maximum fade of signal reception of **-1.00±0.59dB-Hz**. The 2^{nd} one at 14:36, for the 2 frequency bands L1 and L2 with a maximum fade of **-1.75±0.86dB-Hz** at L1 and **-1.25±0.97dB-Hz** at L2.

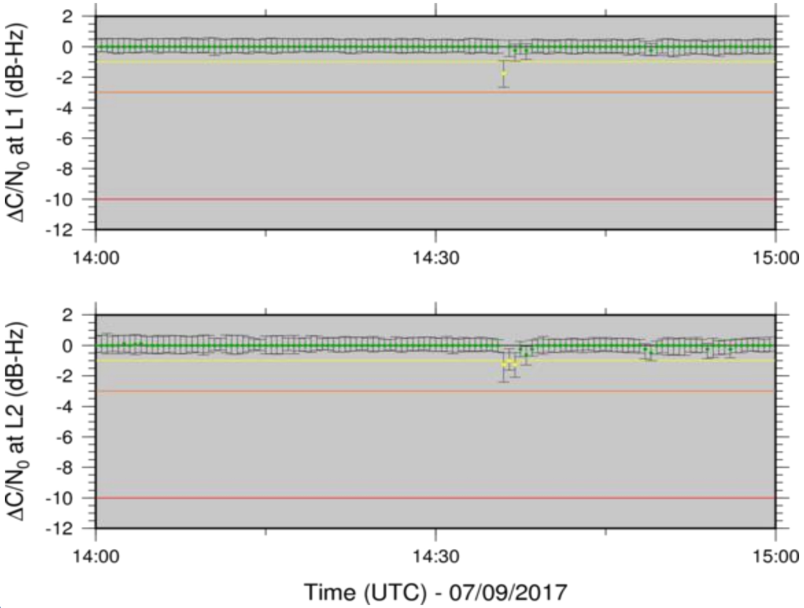


Figure 7: $\langle \Delta C/N_0 \rangle_{L1,L2}$ over the EPN

7. Alerts integrated into PECASUS

FMI | Solar-Terrestrial Centre of Excellence | Met Office | DLR | INGV | CBK PAN | SEIBERSDORF LABORATORIES | FREDERICK UNIVERSITY | Royal Netherlands Meteorological Institute, Ministry of Infrastructure and Water Management | sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Alerts as from 3dB-Hz C/N0 fade, supported with time series of GNSS-based SRB index, and regional TEC maps.
24/7 Operational since November 2019.

8. Toward a Global Index

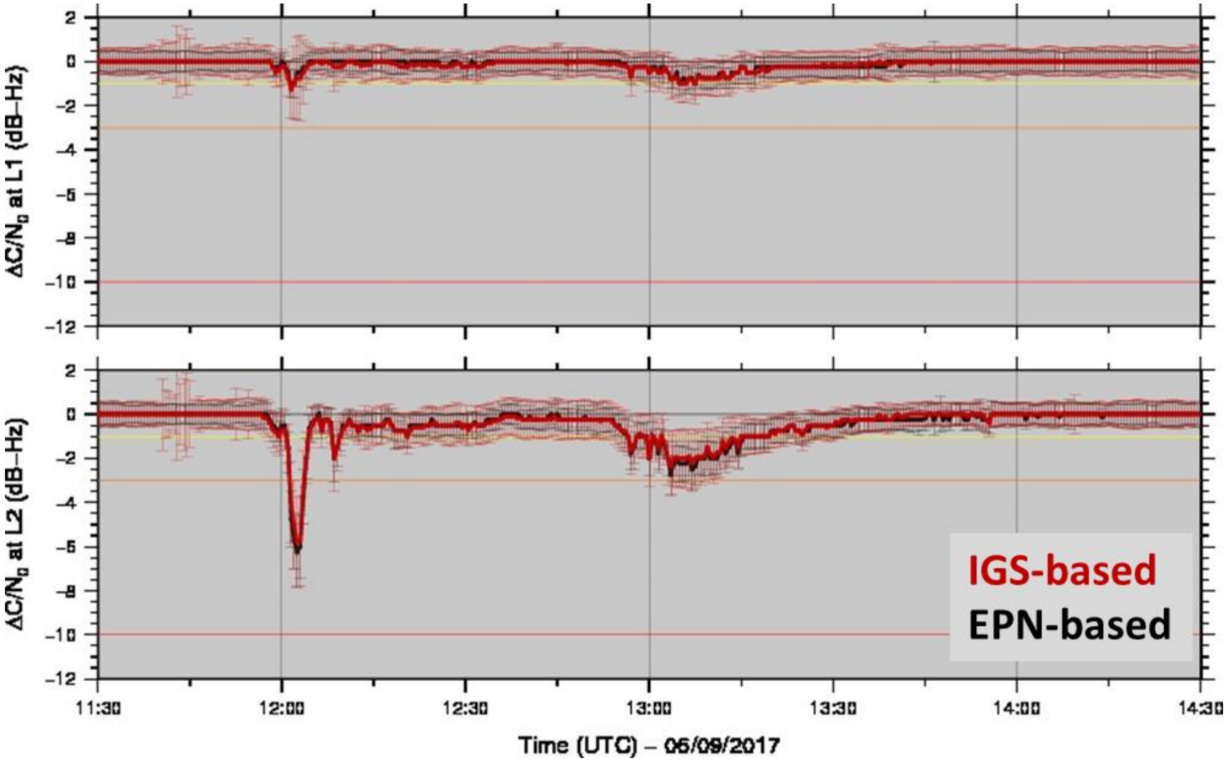


Figure 8: Carrier to noise density variations $<\Delta C/N_0>_{L1,L2}$ over the IGS (in red) at daylight (sun elevation>30°) and over the real-time EPN during the SRB of the 6th September 2017

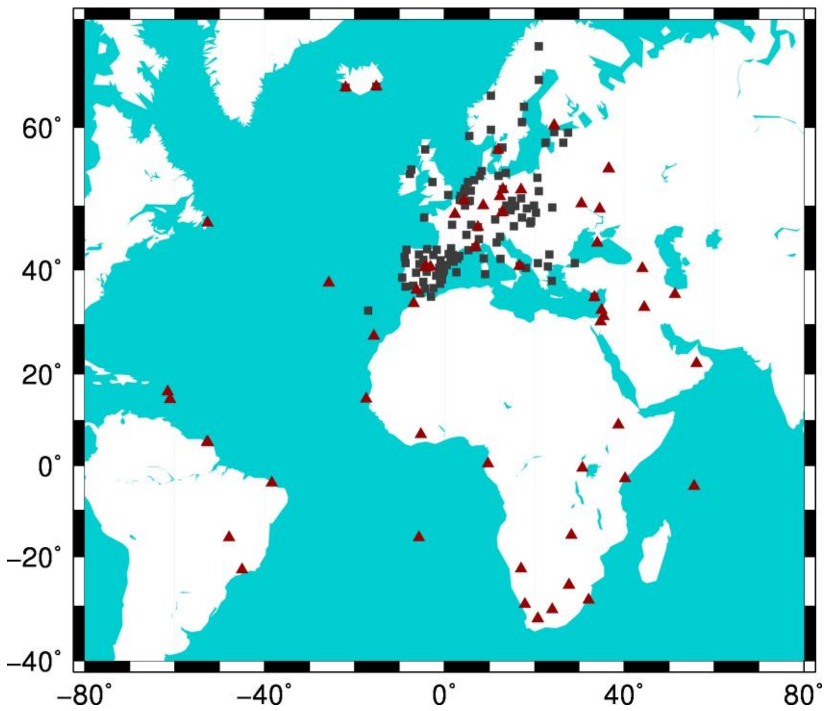


Figure 9: EPN (black) and IGS (red) stations used for the estimation of the European and Global $<\Delta C/N_0>_{L1,L2}$ indexes during the SRB of the 6th September 2017

For the SRB of the 6th September 2017, a **global $<\Delta C/N_0>_{L1,L2}$ index** based on the **IGS network** was estimated (in red) and compared to the **EPN-based** index (black) (Figure 8). The two indexes fits very well, even with different sets of stations (Figure 9): only 10 common stations (68 IGS stations and 116 EPN stations). These first results also allows a **cross-validation** for estimating signal reception fades due to SRB. This global index will be run on a daily basis in June 2020, and in near-real time by the end of the year.

9. False SRB alerts, real signal reception changes

Since 2015, 5 false SRB alerts were issued:

- 1 due to a loss of internet connection (*solved*)
- 4 due to the **GPS "(Anti-jam) Flex Power" :** 2018-04-13, 2019-06-20, 2020-02-14, 2020-04-06

The GPS Anti-jam Flex Power is a modulation of power between the signal components (L1 C/A, L1 P(Y), L2 P(Y)) and can be operated on **block IIF and IIR-M GPS satellites.** When applied, **increase or decrease of C/N_0** on the concerned satellites are observed by the ground stations, interfering with our SRB detection method (Figure 10).

To mitigate these interference effects, SRB hypothesis is discarded when :

- ✓ only couple of satellites are impacted
- ✓ $<C/N_0>$ is increasing on the other signal components
- ✓ $<C/N_0>$ variation occurs at night-time

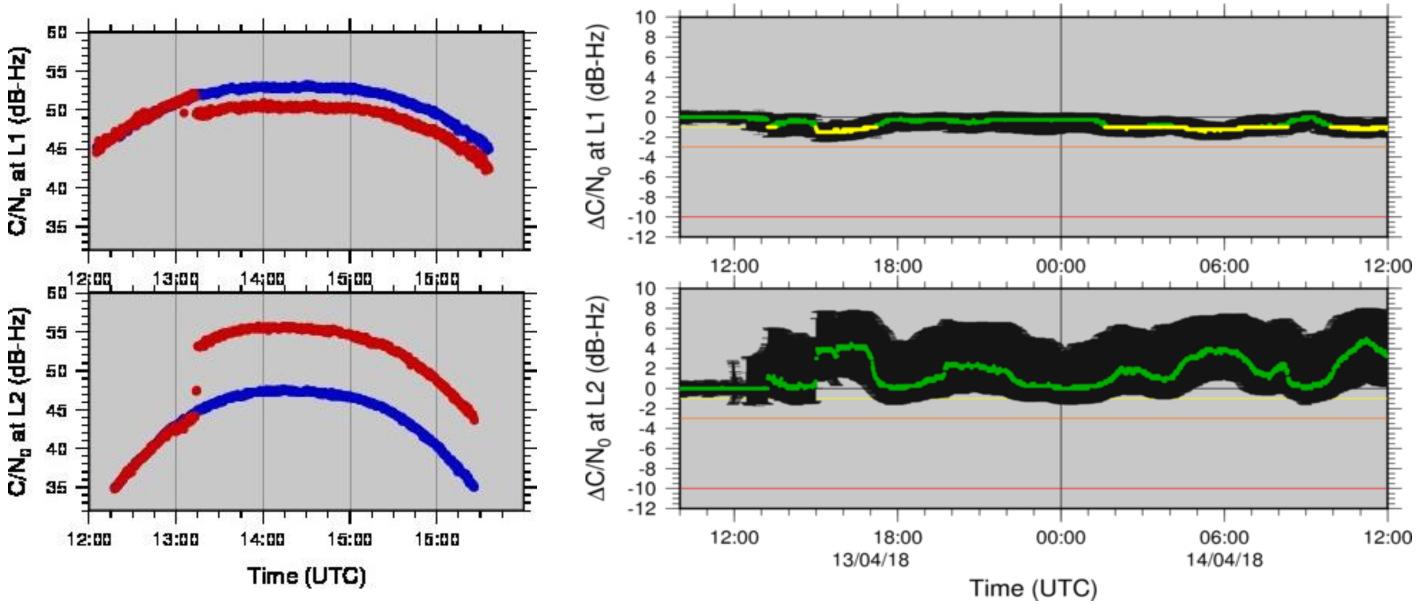


Figure 10: Flex power campaign of the 13th April 2018 operated on the block IIF and IIR-M satellites.
Left plot: C/N_0 (in red) and its expected behaviour (in blue) for the track of PRN25 by BRUX
Right plot: impact on the $<\Delta C/N_0>_{L1,L2}$ indexes estimated with the EPN, variations are due to the IIF and IIR-M satellites in view

10. GPS Flex Power Campaigns

Since 2017, we identified several flex power campaigns:

Starting Date	Ending Date	Zone	Satellites	Signal	$\Delta C/N_0$
Long-Term Campaigns					
27th Jan. 2017 (Figure 12)	14th Feb. 2020	Eu-Afr-As	Block IIF (G10 and G32 excluded)	L1 C/A (S1) L2 P(Y) (S2)	+2 dB-Hz +1 dB-Hz
14th Feb. 2020 (Figure 11, 13)	On-going	Eu-Afr-As	IIR-M and IIF	L1 C/A (S1) L2 P(Y) (S2)	-2 dB-Hz +9 dB-Hz
Short-Term Campaigns					
13th Apr. 2018 (Figure 10) 20th Jun. 2019	17th Apr. 2018 21st Jun. 2019	Global	Block IIF and IIR-M	L1 C/A (S1) L2 P(Y) (S2)	-1.5 dB-Hz +6 dB-Hz
6th Apr. 2020	7th Apr. 2020		G17, G31 (IIR-M)	L2 P(Y) (S2)	-10 dB-Hz

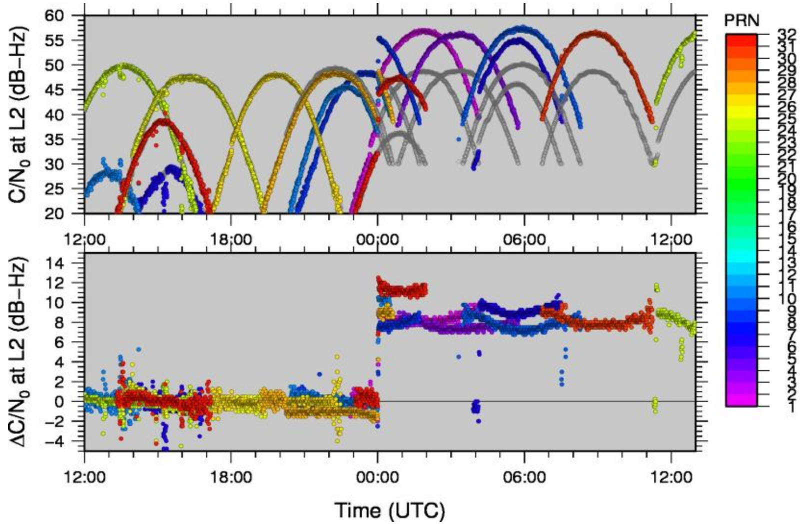


Figure 11: Flex power of the 14th Feb. 2020. Top plot: C/N_0 observations from BRUX of the block IIF and IIR-M satellites (one colour per satellite) and their expected behaviour (in grey). Bottom plot: estimated $\Delta C/N_0$ w.r.t. to the previous days

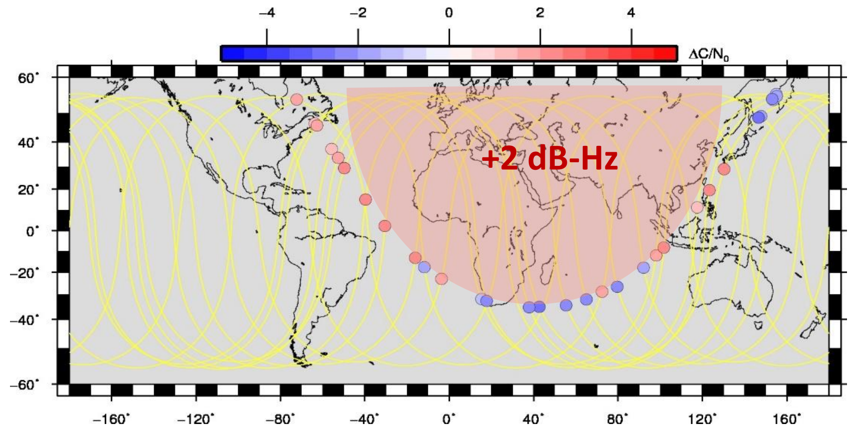


Figure 12: C/N_0 variations of L1 C/A signals along the orbit of the Block IIF satellites using the IGS. It highlights the satellite locations of the flex power **activation and deactivation** on a typical day between the 27th Jan. 2017 and 14th of Feb. 2020

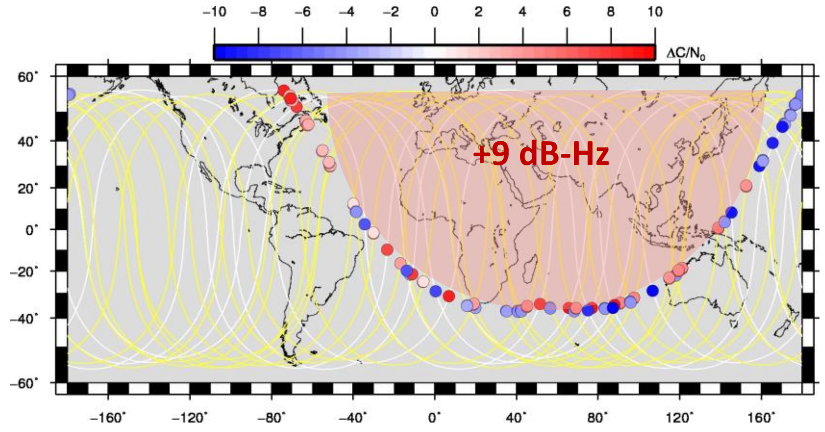


Figure 13: C/N_0 variations of L2 P(Y) signals along the orbit of the Block IIF and IIR-M satellites using the IGS on a typical day since the 14th of Feb. 2020.

CONCLUSIONS

The signal reception of the EPN is monitored in near-real time to detect Solar Radio Bursts as a source of interference for GNSS users (here).

Warnings and potential impact on applications are provided to the users with a scaled-level index for the tracking of the L1 C/A and L2 P(Y) signals.

During the last 5 years of monitoring, the 3 SRBs occurring at the GNSS frequencies were detected in near-real time.

Only 5 false alerts were transmitted, for which 4 of them revealed a change of the GPS signal reception due to the "Anti-jam Flex Power" capabilities of the GPS block IIF and IIR-M satellites.

The monitoring is now being set at global scale with the IGS.