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

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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/N₀). 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/N₀ observations from the European Permanent Network (EPN). The monitoring allows to detect accurately the general fades of C/N₀ 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/N₀ 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).

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.

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.

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

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

- Real-time GPS observations $S_1$ and $S_2$ corresponding to $L_1$ C/A and $L_2$ 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 $<C/N_0(t, rec, sat)>$ of the 7 previous ground track repeat cycles.

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

- Estimation of a $<\Delta C/N_0>_{L1,L2}$ 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) $\Delta C/N_0$ fade for each observations of the EPN (grey) and the median $<\Delta C/N_0>_{L1,L2}$ (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 $\langle \Delta C/N_0 \rangle_{L1,L2}$ 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 $\langle \Delta C/N_0 \rangle$ 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](http://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.

![Web page updated every 15mins: example of the last SRB of the 06/09/2017](image)

**Table:**

<table>
<thead>
<tr>
<th>Level</th>
<th>GNSS $\Delta C/N_0$ Fade</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>&gt;1 dB-Hz</td>
<td>none</td>
</tr>
<tr>
<td>Moderate</td>
<td>-1 dB-Hz</td>
<td>SRB detected but should not impact GNSS applications</td>
</tr>
<tr>
<td>Strong</td>
<td>-3 dB-Hz</td>
<td>Potential impact on GNSS applications</td>
</tr>
<tr>
<td>Severe</td>
<td>-10 dB-Hz</td>
<td>Potential failure of the GNSS receivers</td>
</tr>
</tbody>
</table>

**Email alerts, register at iono@oma.be**

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**From iono@oma.be**

**Subject:** SRB Alert: LEVEL 2 STRONG

To Jean-Marie Chevalier

A general fade of the Carrier to Noise density (C/No) 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 -6.20 dB-Hz at 12:02:30(UTC).
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 $-5.8 \pm 2.2 \text{ dB-Hz}$ over all EPN stations and a maximum fade of $-10 \text{ dB-Hz}$.

**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 $-6.25 \pm 1.6 \text{ dB-Hz}$ at 12h02. It was followed by a 2nd fade above 1dB-Hz at 13h03.

**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 $-1.00 \pm 0.59 \text{ dB-Hz}$. The 2nd one at 14:36, for the 2 frequency bands L1 and L2 with a maximum fade of $-1.75 \pm 0.86 \text{ dB-Hz}$ at L1 and $-1.25 \pm 0.97 \text{ dB-Hz}$ at L2.

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7. Alerts integrated into PECASUS

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.
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.](image-url)
10. GPS Flex Power Campaigns

Since 2017, we identified several flex power campaigns:

<table>
<thead>
<tr>
<th>Starting Date</th>
<th>Ending Date</th>
<th>Zone</th>
<th>Satellites</th>
<th>Signal</th>
<th>(\Delta C/N_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Long-Term Campaigns</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>27\textsuperscript{th} Jan. 2017 (Figure 12)</td>
<td>14\textsuperscript{th} Feb. 2020</td>
<td>Eu-Afr-As</td>
<td>Block IIF (G10 and G32 excluded)</td>
<td>L1 C/A (S1) L2 P(Y) (S2)</td>
<td>+2 dB-Hz +1 dB-Hz</td>
</tr>
<tr>
<td>14\textsuperscript{th} Feb. 2020 (Figure 11, 13)</td>
<td></td>
<td>On-going</td>
<td>Eu-Afr-As</td>
<td>IIR-M and IIF</td>
<td>L1 C/A (S1) L2 P(Y) (S2)</td>
</tr>
</tbody>
</table>

| **Short-Term Campaigns** |                   |        |                                 |                 |                        |
| 13\textsuperscript{th} Apr. 2018 (Figure 10) | 17\textsuperscript{th} Apr. 2018 | Global | Block IIF and IIR-M | L1 C/A (S1) L2 P(Y) (S2) | -1.5 dB-Hz +6 dB-Hz |
| 20\textsuperscript{th} Jun. 2019 |                   |        |                                 |                 |                        |
| 6\textsuperscript{th} Apr. 2020 | 7\textsuperscript{th} Apr. 2020 | G17, G31 (IIR-M) | L2 P(Y) (S2) |                 | -10 dB-Hz          |

Figure 11: Flex power of the 14\textsuperscript{th} Feb. 2020. Top plot: \(\text{C/N}_0\) observations from BRUX of the block IIF and IIR-M satellites (one colour per satellite) and their expected behaviour (in grey). Bottom plot: estimated \(\Delta \text{C/N}_0\) w.r.t. to the previous days.

Figure 12: \(\text{C/N}_0\) 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 27\textsuperscript{th} Jan. 2017 and 14\textsuperscript{th} of Feb. 2020.

Figure 13: \(\text{C/N}_0\) 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 14\textsuperscript{th} 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.