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Solar radio bursts impact on the International GNSS Service Network during Solar Cycle 24

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Abstract—Solar radio bursts (SRB) are a known source of noise for Global Navigation Satellite Systems (GNSS) such as GPS or Galileo. They can degrade the carrier-to-noise ratio of satellite signals, thereby diminishing system performance and, in severe cases, causing total service outages. Although a small amount of particularly intense events have already been studied in detail, the commonness and intensity of SRBs that could potentially impair GNSS performance remain uncertain. This study broadens the scope beyond merely extreme SRBs, studying the impact of SRBs on GNSS throughout Solar Cycle 24. Solar 1.4 GHz observations from the Radio Solar Telescope Network are used to find the 20 most intense SRBs at that frequency. The impact of each SRB is then evaluated in terms of GNSS signal strength decrease, reduction in the number of available satellites, and precision degradation. The results show that at the GPS L1 frequency only one event presented extended service degradation, while at the L2 frequency, minimum operational requirements were not met by at least one station during seven of the SRBs. Only a modest correlation between performance degradation and SRB intensity is found. In particular, it is reported how some mild SRBs affected satellite signals while others almost ten times more intense went unnoticed. The fundamental role that the SRB circular polarization plays in these discrepancies is shown with new 1.4 GHz circular polarization observations from the SMOS satellite. The different responses of GNSS receivers to SRBs depending on the receiver manufacturer are also explored.

Keywords: Solar radio bursts / GNSS / GPS / Navigation

1 Introduction

Global navigation satellite systems (GNSS) usually require a minimum carrier-to-noise ratio (C/N_0) of around 30 dBHz for good tracking, or, equivalently, a value of 5 in the standardized 0-to-9 signal strength indicator scale (e.g., [IGS/RCTM RINEX WG, 2020](#)). Under normal conditions, satellites at a not-too-low elevation angle over the horizon can easily reach more than 40 dBHz. However, under especial conditions, the C/N_0 can degrade to the point where system performance is affected. This can happen, for example, by variations in the signal power C during ionospheric scintillation triggered during solar flares or geomagnetic storms, or by increasing the amount of background noise N_0 during solar radio bursts (SRB). GNSS systems are, however, polarization sensitive and will only react to the right-hand circularly polarized (RHCP, following the IEEE polarization convention) component of the SRB.

The potential effects of solar radio bursts on GPS were first suggested by [Klobuchar et al. \(1999\)](#). Assuming randomly

polarized solar radio bursts, they estimated the amount of flux density required to produce a “just noticeable” 3 dB decrease in GPS signal-to-noise and a potentially more serious 10 dB decrease, finding values of 4×10^4 sfu (solar flux unit, where $1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$) and 2×10^5 sfu, respectively. Comparing their thresholds with the intensity of historical events they found that only 14 SRBs from the three previous solar activity cycles could have produced a slight decrease in signal-to-noise, and found no SRB able to produce a significant effect on GPS receiver operations.

[Chen et al. \(2005\)](#) reported the first observation of an SRB-induced GPS signal degradation. They found severe signal corruption at dayside International GNSS Service (IGS) stations during the “Halloween” event from 28 October 2003, including a 100% loss of lock during 30 s at one station. By comparing the rate of loss and the solar radio flux at the frequency bands observed by the Radio Solar Telescope Network (RSTN) they found a maximum correlation with the flux at 1.415 GHz, which is located between the GPS L2 signal at 1.228 GHz and L1 at 1.575 GHz. The reported solar flux densities were in the range 4×10^3 to 1.2×10^4 sfu at that frequency, which is one order of

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magnitude lower than the proposed threshold in Klobuchar et al. (1999) for a significant impact on GPS. Their study also concludes that the ionospheric perturbations produced by the X-ray and extreme ultraviolet radiation of the flare played only a secondary role.

The 28 October 2003 event was also studied by Cerruti et al. (2006), addressing the sensitivity of GPS systems to SRB polarization with RHCP observations from the Owens Valley Solar Array. They measured a maximum degradation of 3.0 dB at L1 and 10.0 dB at L2. For the event that occurred on 7 September 2005 they measured a C/N_0 decrease of about 2.3 dB and a RHCP flux density of 8×10^3 sfu for the associated SRB. A theoretical estimation by Cerruti et al. (2006) also found that an SRB with RHCP flux density of 10300 sfu would produce a 3 dB signal fade at L1 and 5.2 dB at L2, for an added semicodeless L2 fade of 8.2 dB.

A series of four intense solar flares took place near solar activity minimum in December 2006, the days 5, 6, 13 and 14. All but the first presented solar radio bursts associated with GPS signal fades (e.g., Carrano et al., 2009). The most intense event at 1.4 GHz occurred on December 6 with an estimated power of 10^6 sfu RHCP, and lesser values of 6.5×10^5 and 5×10^5 sfu at 1.2 and 1.6 GHz, respectively (Cerruti et al., 2008). The reported decreases in C/N_0 of 17 dB at L1 and 18–20 dB at L2 were intense enough so that many sunlit IGS receivers did not meet operational requirements as they were tracking fewer than four satellites (Cerruti et al., 2008). Carrano et al. (2009) reported somewhat deeper fades and positioning errors up to 20 m horizontally and 60 m vertically. Clear but milder effects were also reported for the events that occurred on December 13 and 14 (e.g., Cerruti et al., 2008; Afraimovich et al., 2008; Carrano et al., 2009). Interestingly, the event on December 5 did not produce any detectable fade in L1 or L2 signals despite being the most intense of the four December 2006 flares in terms of its X-ray emission (Carrano et al., 2009).

On 24 September 2011, an SRB associated with an M7.1 X-ray flare produced the most intense radio emissions at GNSS frequencies registered during Solar Cycle 24. At 1.4 GHz, the peak intensity of this SRB has been reported to be around 1.1×10^5 sfu based on observations from the Sagamore Hill RSTN station (e.g., Sreeja et al., 2013, 2014; Muhammad et al., 2015) (however, another RSTN station in San Vito and ESA's SMOS satellite measured a weaker intensity of around 6×10^4 sfu). Despite being one order of magnitude weaker than the SRB from 6 December 2006, several authors found substantial performance degradation. Sreeja et al. (2013) and Muhammad et al. (2015) reported C/N_0 reductions of around 10 dBHz for GPS L1 and more than 20 dBHz for GPS L2. They also found an increase in position errors and several receivers not meeting minimum operational requirements as they were tracking fewer than four satellites. Sreeja et al. (2014) studied the impact of this same SRB over a real-time precise point positioning service. They found a reduction in the number of tracked satellites and an increase in the positioning errors from the usual 10–20 cm up to 2.2 m.

Sato et al. (2019) reported a maximum signal strength degradation of 10 dB during the event on 6 September 2017, at a time when the solar flux density was pulsating around 2×10^3 sfu. The authors also detected an increase in positioning error and loss of lock for all GNSS satellites from a possible combined flare and SRB impact.

By means of theoretical analysis, Demyanov et al. (2012) found that solar radio emissions of 10^3 sfu or higher could cause GPS or GLONASS signal tracking failures, especially at the L2 frequency. Huang et al. (2018) conducted a statistical study of GNSS L-band SRBs to evaluate their probability of exceeding a series of five intensity thresholds. Based on 20 years of 1.4 GHz RSTN observations they found 141 SRBs with flux density of at least 10^3 sfu and 21 SRBs with flux density of at least 10^4 sfu. However, as the authors pointed out, RSTN radio flux observations lack polarization information.

The literature reviewed in this introduction shows that the current understanding of how SRBs influence GNSS comes primarily from two types of studies: those that analyze in great detail the most extreme events, and those more theoretical or statistical in nature that, for lack of more concrete observational inputs, have to rely on certain assumptions such as impact thresholds or polarization degrees. This paper aims to help bridge the gap between these two approaches by providing GPS impact statistics that rely on observations rather than on theoretical expectations. By including not only extreme events but also moderate intensity radio bursts, this work can aid in determining intensity thresholds, finding milder events so far overlooked by the community, and better understanding the role that factors such as SRBs polarization or receiver type play on GNSS degradation.

The paper is structured as follows. Section 2 describes the GNSS and solar radio observations used. Section 3 defines the metrics applied to characterize the GNSS service degradation. Section 4 presents the results, which are discussed in Section 5 in terms of SRB intensity, polarization, frequency dependence and receiver manufacturer. Section 6 summarizes and concludes the paper.

2 Data

2.1 Solar radio observations

The reference solar radio observations used for this work are the 1.4 GHz solar flux density measurements from the RSTN. The RSTN is a global network of solar radio observatories operated by the US Air Force. It has a total of four stations located in Sagamore Hill, USA (station code K7OL); Palehua, USA (PHFF); Learmonth, Australia (APLM); and San Vito, Italy (LISS). The observations are made available by NOAA at <ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-radio/rstn-1-second/>. The frequency of 1.4 GHz was selected for its proximity to the 1.2 GHz of the GPS L2 signal and the 1.6 GHz of the GPS L1 signal.

The events studied in this work are the 20 most intense 1.4 GHz SRBs detected by the RSTN during Solar Cycle 24. The selection of events has been made by automatically searching the highest fluxes in the available data and manually rejecting false positives such as radio frequency interferences. The peak intensity of the SRB ($F_{\max}$), the instant of maximum intensity ($t_{F_{\max}}$), the RSTN stations that observed the SRB and the classification of the associated GOES X-ray flare are shown in Table 1. For SRBs observed by more than one RSTN station, the reported $F_{\max}$ value is the average of the maximum intensities measured by each station, while the $\pm$ sign covers the range of $F_{\max}$ values observed by all available stations. A larger

Table 1. List of the 20 most intense 1.4 GHz SRBs from Solar Cycle 24 observed by the RSTN.

Event ID	$F_{\max}$ (10^3 sfu)	$t_{F_{\max}}$ (UTC)	RSTN station	GOES flare
01	50.63	15 February 2011, 02:35	APLM	X2.2
02	29.76	7 March 2011, 20:17	K7OL	M3.7
03	86.94 ± 27.21	24 September 2011, 13:05	K7OL, LISS	M7.1
04	3.87 ± 0.13	25 September 2011, 05:41	APLM, LISS	M7.4
05	1.91	23 January 2012, 04:05	APLM	M8.8
06	34.85	4 March 2012, 11:17	LISS	M2.0
07	24.61	5 March 2012, 04:27	PHFF	X1.1
08	5.41	7 March 2012, 01:28	PHFF	X5.4
09	2.56 ± 0.17	17 May 2012, 02:04	APLM, PHFF	M5.1
10	2.08 ± 0.16	14 June 2012, 14:09	K7OL, LISS	M1.9
11	5.46	21 November 2012, 16:12	K7OL	M3.5
12	3.31 ± 0.11	11 April 2013, 06:59	APLM, LISS	M6.5
13	7.53 ± 0.30	4 January 2014, 19:31	K7OL, PHFF	M4.1
14	3.89 ± 0.07	25 February 2014, 00:46	APLM, PHFF	X5.0
15	4.19 ± 0.17	2 April 2014, 13:58	K7OL, LISS	M6.5
16	14.28	25 June 2015, 09:20	APLM	M7.9
17	5.89	4 November 2015, 14:27	K7OL	M3.7
18	19.60	6 September 2017, 12:03	LISS	X9.3
19	3.97	7 September 2017, 10:16	LISS	M7.3
20	8.32	7 September 2017, 14:36	LISS	X1.3

selection of events is considered unnecessary for the purpose of this work as the weakest selected SRBs already show no large impact on GPS observations.

2.2 GNSS observations

The GNSS performance during SRBs is analyzed using data from the IGS (Johnston et al., 2017). The IGS is a federation of over 200 institutions that provides, among other products, GNSS data from a network of over 500 worldwide stations. Only GPS L1 and L2 signals are used here, as they have the best data availability during Solar Cycle 24. The data were obtained from the Crustal Dynamics Data Information System (CDDIS; Noll, 2010) via ftp-ssl at gdsc.cddis.eosdis.nasa.gov/pub/gps/data/daily. IGS stations with Sun elevation angles of less than 20 degrees at the time of the peak SRB intensity are not used for this work. Stations with evident problems unrelated to the SRB, such as data gaps, high levels of noise or a too-low number of tracked satellites in undisturbed conditions, are also discarded.

Certain limitations have to be taken into consideration when comparing 1.4 GHz RSTN observations and GNSS signal degradations from IGS data. The first and most important limitation is the lack of polarimetric information in the RSTN data. GNSS antennas are only sensitive to the RHCP of SRBs, therefore, the RSTN can only provide an upper limit to the RHCP intensity affecting the GNSS receivers. The second limitation is that the 1.4 GHz frequency is not exactly the same as the 1.2 GHz of the GPS L2 signal or the 1.6 GHz of GPS L1. Although the exact implications of this limitation are still not fully known because of the lack of observational input, SRBs can occasionally show sharp transitions in this frequency range (see, e.g., Marqué et al., 2018). Finally, the one-second sampling rate of the RSTN observations is faster than the 30-second rate used here for the GNSS observations. This difference in sampling rates could result in occasional mismatches between the peak SRB intensities and the peak GNSS signal degradation

if the burst exhibits a rapid evolution. A resampling of the RSTN observations is discarded because of their frequent clock desynchronizations.

3 Characterization of the GPS degradation

The impact of the 20 selected SRBs on the sunlit IGS GPS stations is characterized here in terms of three parameters: the degradation of the satellite's signal strength, the reduction in the number of available satellites and the degradation of the satellite's geometry as measured by the geometric dilution of precision (GDOP). These three parameters are chosen because they are directly accessible from the IGS data (signal strength) or because they are used by final navigation systems users to assess the service integrity (number of available satellites and geometry degradation). More processed parameters, such as position errors, are discarded as they strongly depend on the processing algorithm. Only stations that provide the signal strength in physical units (dBHz) are considered.

The reduction of the satellite's signal strength is the direct effect of SRBs over the satellite's signal. In order to isolate the degradation produced by the SRB from other factors affecting the signal strength, such as the elevation angle of the satellite, a quiescent background is used. The quiescent background is obtained by calculating the median signal strength of each satellite using data from three days before and three days after the SRB. The signal fade of each satellite is then calculated by removing the quiescent background from the signal strength during the SRB. The final signal fade is calculated for each IGS station and expressed as the median fade of all observed satellites.

Intense SRBs can cause signal degradation to the point where one or more satellites become unusable. Typically, a minimum of four valid satellites is required for a GNSS receiver to operate. The number of available satellites is therefore an easy and widely used parameter to assess the operational

performance of a GNSS system. In practice, satellites with signals weaker than a given threshold are often discarded by GNSS receivers. The exact value of this threshold depends on the particular performance requirements of each user, but for real-time applications, they are typically in the 20–35 dBHz range (e.g., Wang, 2019; Everett et al., 2022). For this work, a threshold of 24 dBHz is used, which corresponds to level 4 in the standardized signal strength indicator scale. The effect of a given SRB on the number of available GPS satellites is classified here according to two categories: moderate, if the signal strength of at least four satellites drops below 24 dBHz relative to the quiescent reference; and severe, if the signal strength of at least seven satellites drops below this 24 dBHz threshold. The final value is expressed as the percentage of affected IGS stations in each category. The reason to use the decrease in the number of satellites as an indicator, rather than the absolute number of available satellites, is that the latter is highly station-dependent. Even under undisturbed conditions, the number of accessible satellites can vary from 7–8 to about 10–12 depending on the station. The thresholds were selected so that they are meaningful regardless of this variability.

As the SRB reduces the number of available GPS satellites, those that remain tend to be found nearer to the zenith. This leads to a degradation in their geometry that results in larger errors, even in situations where there are enough available satellites with good signal quality. The multiplicative increase in the error produced by geometric factors is given in terms of the geometric dilution of precision or GDOP (see, e.g., Langley, 1999). In a similar way as for the reduction in the number of available satellites, the effect that SRBs had on the increase of the GDOP is provided here as the percentage of IGS stations that experienced GDOP degradation. Three categories are used: moderate increase, if the GDOP rises by at least five relative to the quiescent reference; severe, if the GDOP increases by at least 20; and a “loss of service” category for the stations with less than four satellites available. As before, a signal strength mask of 24 dBHz is used. To mitigate the role of eventual overreactions of the GDOP to small changes in the number of satellites, two additional conditions are imposed: first, GDOP degradations produced by the loss of only one satellite are ignored; second, the degradation must have a minimum total duration of at least 150 s.

Figure 1 shows, as an example, the effects that the SRB on 24 September 2011 had on the GPS L2 service frequency at the IGS MAS1 station, in terms of signal strength degradation, reduction in the number of satellites with signals above 24 dBHz and GDOP degradation.

4 Results

Figures 2 and 3 show the impact of the 20 SRBs from Table 1 on the GPS L1 and L2 frequencies, respectively. In both figures, the upper panel illustrates the maximum decrease in signal strength at each IGS station. This is represented using a statistical box plot, where each SRB is depicted by one box. These boxes are arranged in descending order based on the intensity of the SRBs. As in any standard box plot (see, e.g., Smith, 2011), the boxes extend from the lower to the upper quartile, the orange line indicates the median signal fade, and

the whiskers enclose the signal fades that fall between these quartiles and 1.5 times the interquartile distance. Values outside this range are shown as circles and considered statistical outliers in their response to the SRB.

It can be noted from Figure 2 that the signal fades at the GPS L1 frequency were in general mild during Solar Cycle 24. Seven SRBs produced signal fades of at least 5 dBHz, but they affected in most cases just a handful of stations during each event. The only SRB that produced an extended impact in terms of a decrease in the satellite’s signal strength was the already well-studied event on 24 September 2011 (Event 03 in Table 1, see Sect. 1 for references). For it, approximately 75% of IGS stations presented signal fades exceeding 5 dBHz, with a median of 6.6 dBHz and a maximum of 25.7 dBHz. During this event, all seven stations that were equipped with an Allen Osborne Associates (AOA) receiver reported signal fades exceeding 13 dBHz. This occurred despite the Sun elevation angles being relatively low at these stations, ranging from 20° at station ALGO in Canada, to 42° at station SUTM in South Africa. They appear as statistical outliers in the box-plot of this event. The relationship between SRB impact and receiver manufacturer will be addressed in Section 5.

During the SRB on 24 September 2011, twelve out of 74 IGS stations experienced a decrease in the number of available satellites at the L1 frequency by at least four. Three of these stations lost seven satellites and one lost nine. This translated into a total of five stations performing below the minimum operation requirements specified in the previous section. At the GPS L1 frequency, no other event experienced a significant GDOP degradation, despite some of them undergoing a moderate reduction in the number of satellites (bottom and middle panels in Fig. 2, respectively).

As shown in the Introduction, the GPS L2 frequency tends to be more susceptible to SRBs than L1. This effect is also evident by comparing Figures 2 and 3. Seven SRBs were able to degrade the signal strength by at least 5 dBHz at L1. In contrast, ten of them exceeded this threshold at L2, half of which degraded the signal by at least 15 dBHz at one or more stations. The five SRBs that produced signal degradations beyond 15 dBHz are the burst on 15 February 2011 (Event 01 in Table 1), 24 September 2011, (Event 03), 4 March 2012 (Event 06), 4 November 2015 (Event 17) and 6 September 2017 (Event 18). In the course of these five bursts, a minimum of 10% of the IGS stations experienced a decrease in the number of available satellites by four or more (middle panel in Fig. 3). Specifically, during Events 01 and 06 more than 30% of the stations were affected. The impact was even more significant during Events 17 and 03, with more than 40% and nearly 60% of the stations experiencing this reduction, respectively. The problem was also observed during other SRBs but with only a few stations affected.

At the L2 frequency, seven out of the 20 selected radio bursts resulted in a service degradation that fell below the minimum operational requirements in at least one station (bottom panel in Fig. 3). As for the L1 frequency, the largest effects were observed during the SRB on 24 September 2011 (Event 03). During this event, nearly 40% of the IGS station had less than four satellites with signal strength above 24 dBHz for at least 150 s. Events 01, 06 and 17 produced service degradation at 27%, 17% and 21% of the stations, respectively. For Events 01 and 06 the most common problem was a moderate surge in

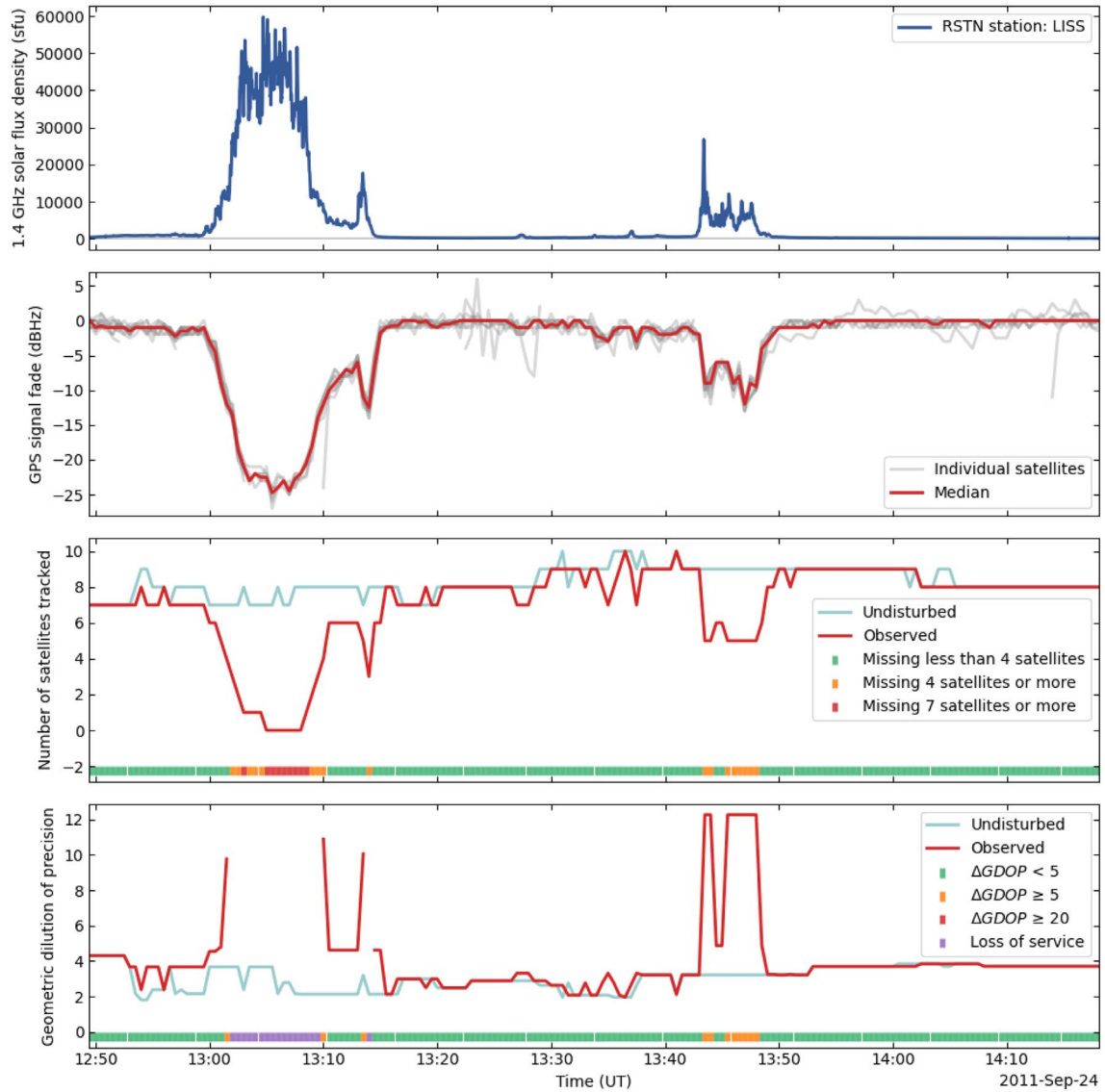


Figure 1. Example of a solar radio burst impacting the GPS service at the L2 frequency. *Top panel:* Solar radio burst on 24 September 2011 observed at 1.4 GHz by the RSTN station LISS. *Second panel from the top:* Signal strength degradation at the IGS station MAS1. The figure is the result of subtracting undisturbed reference observations from the reported signal strength of the satellites during the solar radio burst. *Third panel from the top:* Reduction in the number of available satellites at station MAS1 compared to undisturbed conditions. The severity of the reduction at each instant is color-coded and indicated at the bottom of the panel. The classification in levels of degradation is the same as in Figures 2 and 3, as detailed in the text. A signal strength mask of 24 dBHz is used. *Bottom panel:* Same as the third panel but for the geometric dilution of precision. The gaps indicate a period of time when the system failed to meet minimum operational requirements.

errors caused by GDOP degradation, with three stations falling short of the minimum operational requirements during each burst. Event 17, on the other hand, had ten stations below minimum operational requirements and four with larger GDOP-related errors.

The GDOP degradation at L2 during Events 18, 11 and 08 was less widespread, impacting only 6–8% of the stations. Although this percentage is lower than during the above-mentioned Events 03, 01, 06 and 17, it is similar to that affecting the L1 frequency during Event 03. Event 08 only produced

a moderate error increase, while during Events 18 and 11 two stations each did not meet minimum operational requirements. Despite Event 18 producing somewhat deeper signal fades than Event 11, these two events presented similar service degradation. This is probably because of the short duration of Event 18, which is near the 150 s threshold used for this work. Events 07, 04 and 10 only produced significant service degradation at one or two stations each. These are usually stations that were not operating far from minimum operational requirements in undisturbed conditions.

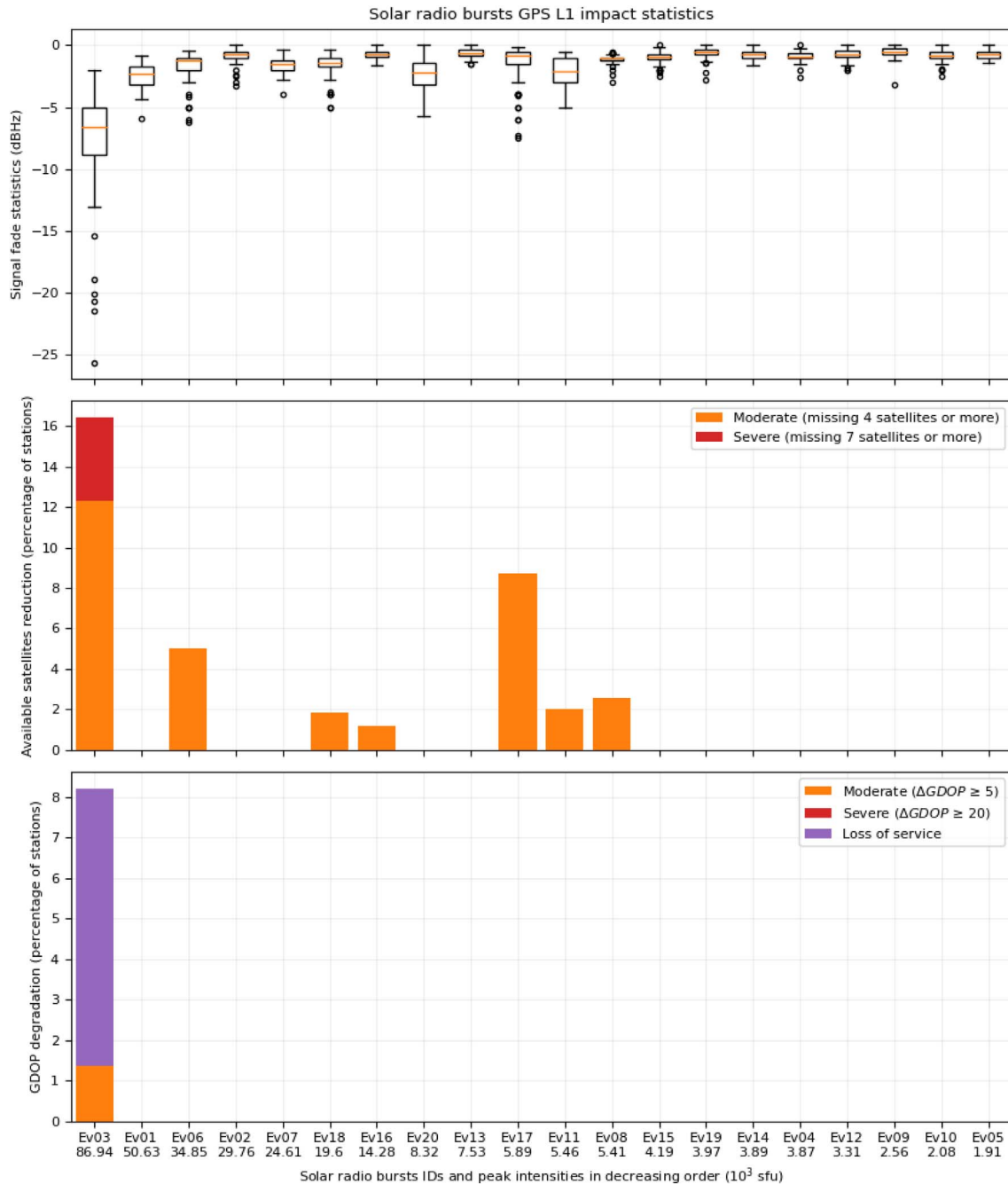


Figure 2. SRB impact statistics at the GPS L1 frequency in terms of signal fading (top panel), reduction in the number of available satellites (middle panel), and GDOP degradation (bottom panel). The signal fade statistics are shown as a box plot for each SRB (see text for details). The reduction in the number of available satellites and the GDOP degradation are presented as stacked bar plots showing the percentage of stations affected at different degradation levels. The SRBs are sorted with decreasing intensity on the x-axis (see Table 1 for SRB details).

5 Discussion

5.1 Correlation between GPS signal fades and SRB intensity

Figure 2, and particularly Figure 3, show that the intensity of solar radio bursts and the resulting GPS service degradation do not consistently align. Although it is true that a more intense SRB generally leads to a greater GPS signal disruption, the

exceptions to this rule are numerous. For example, Events 02, 16 and 13 went practically unnoticed in the GPS L2 signal despite being the fourth, seventh and ninth most intense bursts, respectively. On the other hand, comparably weaker events, such as Event 17 (tenth most intense), or even Event 12 (17th most intense), resulted in disturbances of different degrees. Although this modest correlation is not unexpected considering that GNSS receivers only respond to the RHCP of SRBs, it proves that the relation between the total and RHCP intensities

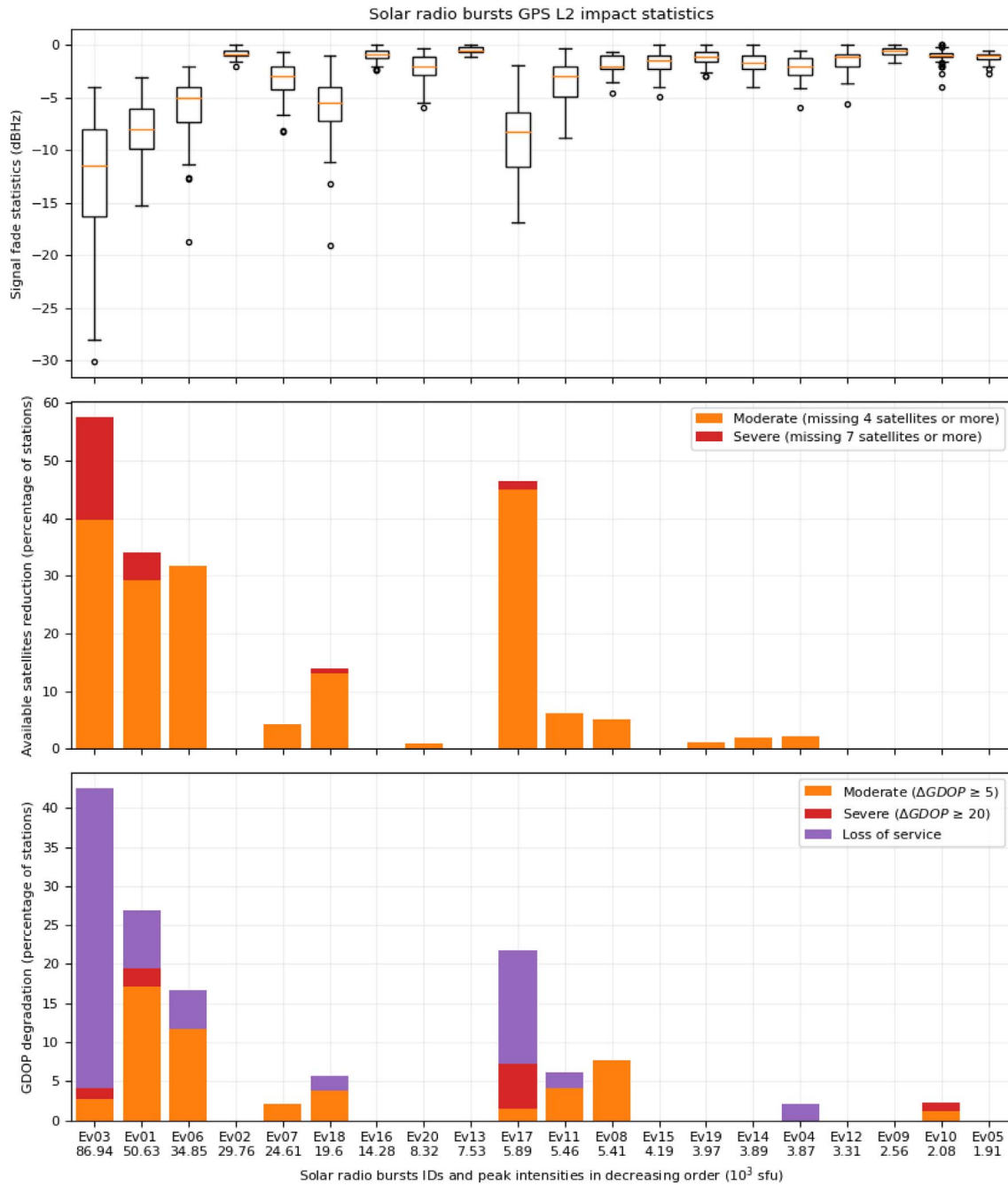


Figure 3. Same as Figure 2 but for the GPS L2 frequency.

is not as direct as often assumed. RHCP observations of SRBs at GNSS frequencies are, however, not as easily available as the total intensity observations used here, which greatly complicates the execution of a similar analysis based on polarization instead of total intensity. The same problem appears when trying to address the limitations of using SRB observations at 1.4 GHz instead of at the 1.575 GHz of L1 or the 1.228 GHz of L2. This subsection discusses the role of polarization and frequency dependencies in the limited correlation between RSTN observations and GPS service degradation.

5.1.1 Polarization dependencies

Two frequent assumptions made in the literature are that SRBs are either fully polarized or totally unpolarized. Figures 2 and 3 suggest that neither of these assumptions is correct. If SRBs were normally unpolarized, then, the RHCP of the bursts would correspond to half the value of their total intensity, making the total intensity a perfectly valid proxy of the RHCP. Conversely, if SRBs were mostly fully polarized, then at least the service degradation produced by the RHCP bursts should show

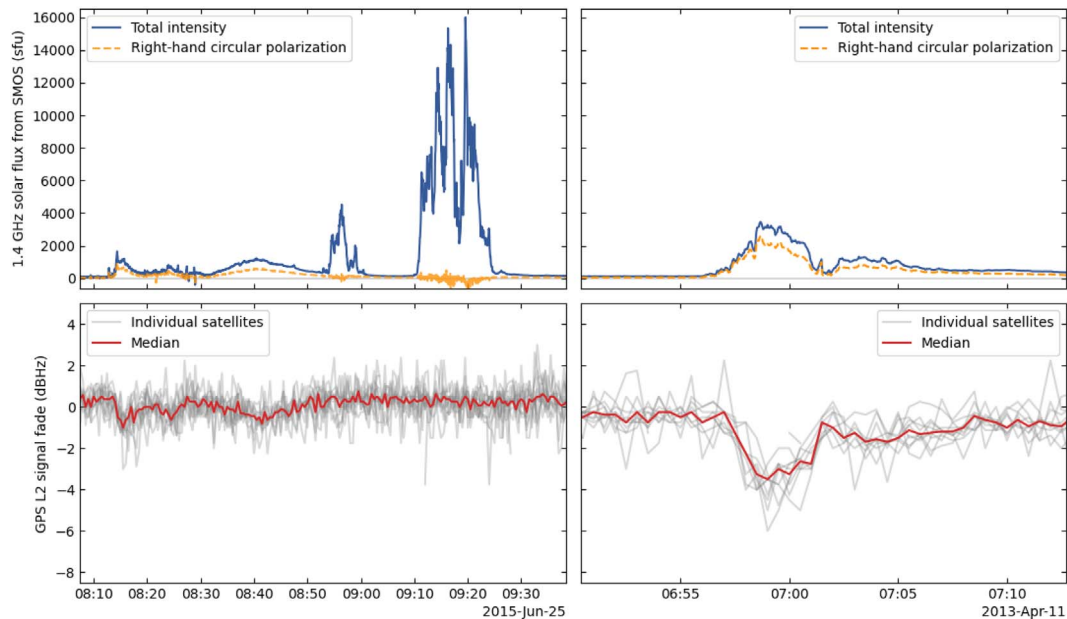


Figure 4. GPS L2 signal fades during the solar radio bursts on 25 June 2015 (left) and on 11 April 2013 (right). It can be noted how the signal fades (bottom panels) correlate well with the right-hand circular polarization of the bursts, but not with their total intensity. The solar radio observations (top panels) are from ESA’s SMOS mission. The GPS L2 data (bottom panels) are from the IGS CHUM station and were recorded with a local solar elevation angle of approximately 55° .

a correlation. None of these two scenarios is observed in the results from Figures 2 and 3.

Given the shortage of circular polarization observations at GNSS frequencies, the European Space Agency (ESA) has considered the possibility of adding this functionality to its SMOS mission. SMOS is an Earth Explorer satellite originally conceived to perform observations of soil moisture over land and salinity over the oceans using radio interferometry at 1.4 GHz (Mecklenburg et al., 2012). As part of its normal operations, SMOS needs to correct the impact of the Sun in its field of view, which is in fact its strongest source of interference (see, e.g., Camps et al., 2004; Khazâal et al., 2020). The estimated Sun brightness temperature is annotated in the SMOS L1B user product and has been found to show a promising good correspondence with ground-based solar radio observations (Crapolicchio et al., 2018; Flores-Soriano et al., 2021). In view of the potential, but also limitations, of these SMOS data (Flores-Soriano et al., 2021), a new prototype algorithm dedicated specifically to obtaining solar radio observations with SMOS has been developed within the framework of an ESA project. Observations of two solar radio bursts extracted with this prototype algorithm are used here to test the role of the circular polarization in the above-mentioned discrepancies between the SRB total intensity and the depth of the GPS signal fades.

The top panels of Figure 4 show the total intensity and circular polarization of the SRBs on 25 June 2015 (Event 16, left in Fig. 4) and on 11 April 2013 (Event 12, right in Fig. 4), as seen by SMOS. These are, respectively, the seventh and 17th most intense of the SRBs selected for this work. The bottom panels show the associated GPS L2 signal fades. To make the GPS signal fades comparable with each other, both were recorded by the same IGS station (CHUM), with a local solar

elevation angle close to 55° at the time of peak total radio burst intensity in both cases. The station was equipped with a Trimble NetRS receiver and an AOAD/M_T antenna. The main burst of Event 16 (09:10–09:25) is approximately four times more intense than Event 12. However, the main burst of Event 16 is LHCP, whereas Event 12 has an RHCP of between 70% and 80% of its total intensity. As a result, despite being weaker in terms of total intensity, Event 12 produced a clear decrease in GPS signal strength, unlike the main burst of Event 16. The importance of the circular polarization is also evident when comparing the effects that the different bursts forming Event 16 had on the GPS signal. During Event 16, three minor bursts occurred between 08:10 and 08:50. These bursts were roughly one order of magnitude less intense than the main burst, but in a similar way as Event 12, they were partially RCHP. Once again, the weak RHCP bursts managed to degrade the GPS signal, while the more intense LHCP bursts between 08:50 and 09:25 did not.

Figure 4, while merely an example, clearly demonstrates the limitations of using total intensity observations of SRBs for analyzing GNSS signal degradation. The broad range of polarization states exhibited by these SRBs is such that any attempt to infer RHCP intensities based purely on total intensity observations are bound to be highly uncertain. Establishing a correlation between the depth of GNSS signal fades and the intensity of SRBs requires therefore observations of circular polarization.

5.1.2 Frequency dependence

Addressing the drawbacks of using SRB observations at 1.4 GHz instead of at the GPS L1 and L2 frequencies is hindered by the lack of calibrated solar radio observations at those

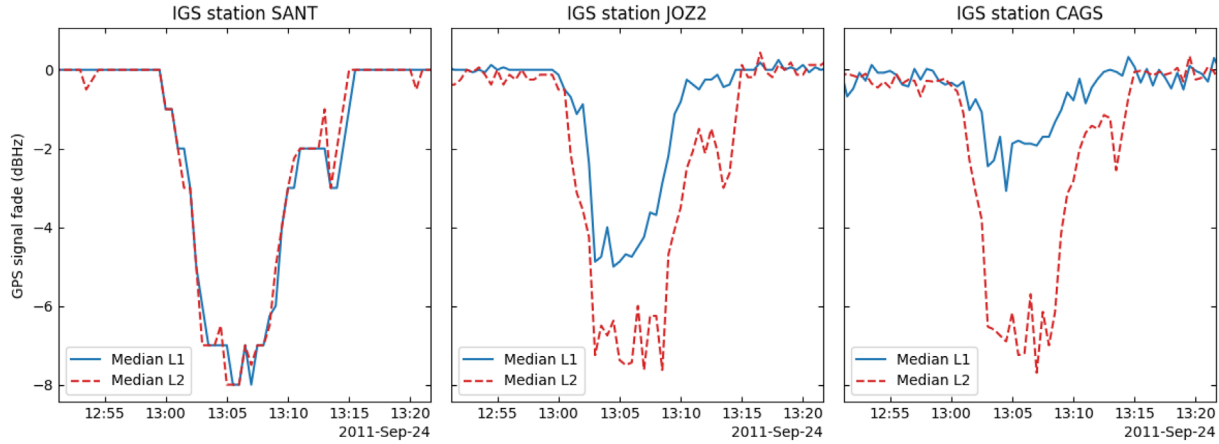


Figure 5. GPS signal fades at the L1 and L2 frequencies measured by three different IGS stations during the main burst of Event 03. To facilitate the comparison, the stations were selected for having similar signal fades at GPS L2. The fades at L1 were, however, different, proving that the relative impact at L1 and L2 does not only depend on the spectral properties of the bursts but also on the station used. From left to right their receivers are Ashtech UZ-12, Leica GRX1200GGPro and Trimble NetR8.

frequencies. This problem is further exacerbated by the absence of polarization information. One could, in principle, try to correlate the GPS signal fades at L1 and L2 with the SRB intensities at those frequencies (e.g., [Sato et al., 2019](#)). Nonetheless, this method is generally incorrect because of differences in how each GPS signal is processed. Furthermore, the processing differs among manufacturers, which could lead to contradictory conclusions depending on the GNSS station used (see also [Sect. 5.2](#)). [Figure 5](#) shows, as an example, the differences between the L1 and L2 signal fades at IGS stations SANT, JOZ2 and CAGS during Event 03. Their receivers were, respectively, an Ashtech UZ-12, a Leica GRX1200GGPro and a Trimble NetR8. They were chosen for this example because of their similar signal fades at L2, which facilitates the comparison. The fades at L1 were, however, different by up to almost 6 dBHz, proving that their difference relative to L2 is not simply a matter of different SRB intensities at each GPS frequency.

In terms of morphology, it is not uncommon that GPS signal fades have a close resemblance to their associated 1.4 GHz SRB. [Figures 1 and 4](#) are examples of this. Although this similarity in shape does not provide information about the intensity of the SRB at GPS frequencies, it does suggest that any difference between the SRB at 1.4 GHz and at GPS frequencies was small enough as to maintain the morphology. This is, however, not always the case. [Marqué et al. \(2018\)](#) observed Event 17 across the spectral range from 610 MHz to 1.427 GHz. They reported a peak flux at 1.0 GHz that was 30 times more intense than at 1.4 GHz. If this is interpolated to L2, it results in an approximate difference of a factor of 15 between L2 and 1.4 GHz. The resultant discrepancy in morphology between the signal fades and the associated 1.4 GHz SRB is shown in [Figure 6](#). This difference in frequency could also partially explain why Event 17 appears somewhat misplaced in [Figure 3](#). If the intensity of Event 17 were tentatively corrected by multiplying it by the aforementioned factor of 15, it would rank as the most or second most intense, which is likely an overestimation based on its impact. This does not apply, however, to [Figure 2](#). There, at the L1 frequency, Event 17 also exhibits anomalously high signal degradation for its comparatively mild intensity at 1.4 GHz.

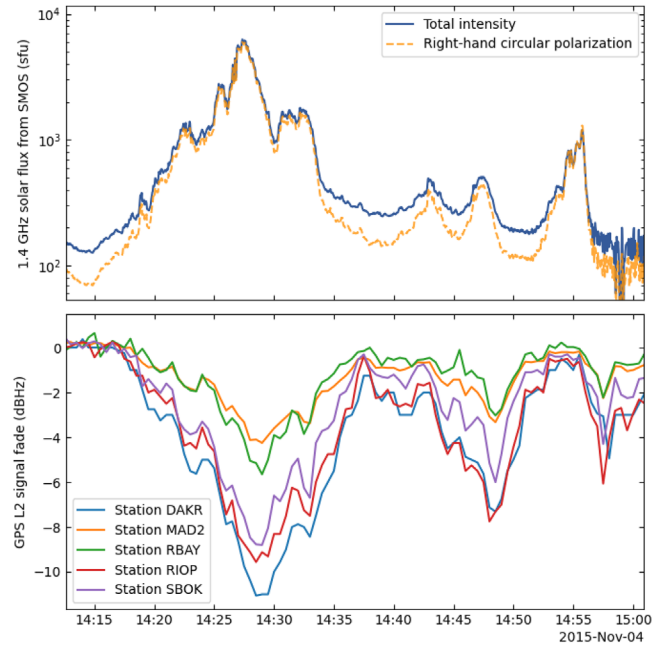


Figure 6. Example of GPS L2 signal fades (bottom panel) whose temporal profile exhibits morphological inconsistencies with the RHCP of the 1.4 GHz SRB (top panel). These inconsistencies are exacerbated by the sharp transition in intensity that the bursts had in the 1.0–1.4 GHz frequency range (see [Marqué et al., 2018](#)). The burst corresponds to Event 17 in [Table 1](#). The GPS data are from five random IGS stations and the SRB observations are from SMOS.

Yet, according to the data from [Marqué et al. \(2018\)](#), the peak flux of the burst at L1 should have been slightly lower than at 1.4 GHz, not higher. The reason behind this anomaly is probably related to the signal processing, as all affected stations were equipped with an Ashtech receiver (see also the bottom left panel in [Figure 7](#) and the discussion in the next subsection).

A more quantitative strategy for estimating the differences in SRB flux densities between 1.4 GHz, and the GPS L1 and

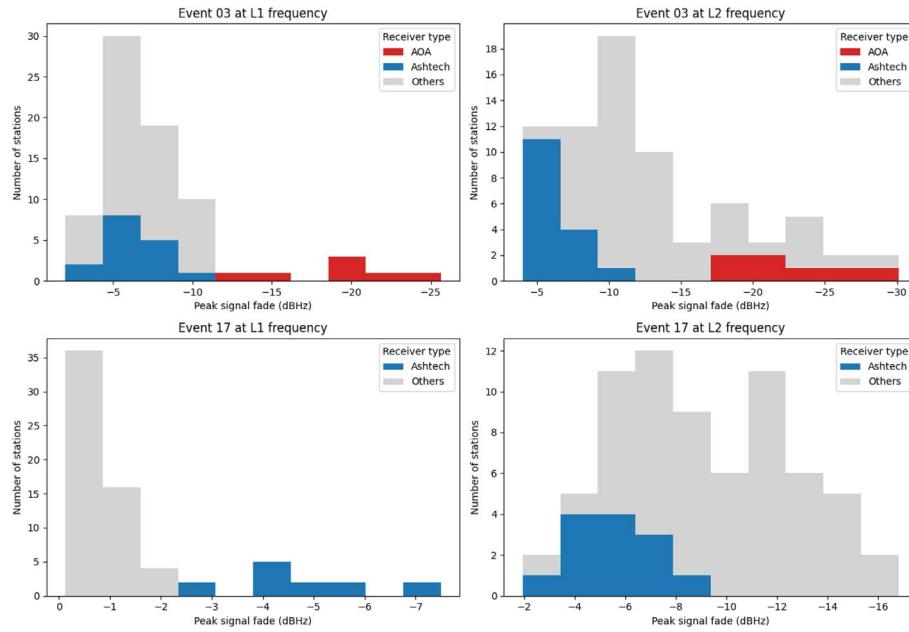


Figure 7. Comparison between the signal fades measured by IGS stations during the SRBs on 24 September 2011 (Event 03 in Table 1, shown in the top panels) and on 4 November 2015 (Event 17, bottom panels), at the L1 and L2 frequencies (left and right panels, respectively), depending on the station's receiver.

L2 frequencies is by interpolating the polarization observations at 1.0 and 2.0 GHz from the Nobeyama Radio Polarimeters (NoRP). This method has, however, several limitations. SRBs are usually significantly different at these two frequencies, their formation mechanisms and wave modes are not necessarily the same, and the relationship between frequency and flux density is generally non-linear. Six SRBs from Table 1 have NoRP observations available at 1.0 and 2.0 GHz. They are Events 01, 05, 07, 08, 09 and 14. Only data with flux densities above 150 sfu at 1.0 GHz are considered here to avoid comparing background signals. Out of these six radio bursts, one (Event 08) shows a mean difference between the estimated intensities at 1.4 GHz and GPS frequencies of around 5%. Three radio bursts (Events 05, 07, 09) show mean differences of around 15%, while two (Events 01 and 14) show mean differences in the 20–25% range.

5.2 GPS service degradation depending on receiver manufacturer

The statistical outliers in the box plots from Figure 2 suggest that not all GNSS receivers respond to SRBs in the same way. To further explore this dependency, the signal fades at different stations have been compared based on their receiver's manufacturer. Nine different brands have been identified: AOA, Ashtech, JAVAD, JPS, Leica, NovAtel, Septentrio, TPS and Trimble. However, not all brands were present during every event. Figure 7 shows as an example the distribution of the peak signal fades during the SRBs on 24 September 2011 and on 4 November 2015, at the L1 and L2 frequencies. They correspond to Events 03 and 17 in Table 1, respectively. AOA and Ashtech receivers have been highlighted in colour while all the other manufacturers are represented in grey to avoid cluttering. No AOA receiver is depicted for Event 17 as they were not

available during this SRB. While AOA and Ashtech were selected for this example because of their clear differences from other receivers, they are not the only brands that display discrepancies (see below).

Figure 7 shows that the response of GNSS receivers to SRBs can vary significantly depending on the manufacturer. During Event 03, AOA receivers exhibited deeper signal fades at the L1 frequency than any of the other available manufacturers. At L2, AOA shows again among the deepest signal fades but with other manufacturers registering similar values. These other stations were, however, more exposed to solar radio noise because of their comparatively higher solar elevation angles (see, e.g., Carrano et al., 2009, for an estimation of the GPS signal fading as a function of the solar incidence angle). During Event 03 Ashtech receivers behaved similarly to other manufacturers at the L1 frequency but showed shallower signal fades at L2. This behaviour of shallower fades at L2 by Ashtech receivers was also observed during Event 17. However, during Event 17 at the L1 frequency, Ashtech receivers showed the deepest signal fades, contrary to their behaviour during Event 03 at the same frequency. Interestingly, Ashtech receivers displayed similar fades at L1 than at L2 during both events, contrary to the other receivers, which show deeper fades at L2. Another unusual behaviour is displayed by the AOA receivers during the radio burst on 7 March 2011 (not shown here), where the signal fades were deeper at L1 than at L2.

GNSS stations with different equipment, but situated close to each other, offer a good opportunity to compare how they react to SRBs under similar solar elevation angles. Figure 8 shows the fading of the GPS L2 signal during the main burst of Event 03 in three geographical areas: mainland Spain, the northeast of North America (USA and Canada) and the northwest of Europe (United Kingdom, France, Belgium and the Netherlands). In the Spanish group (left panel in Figure 8), there

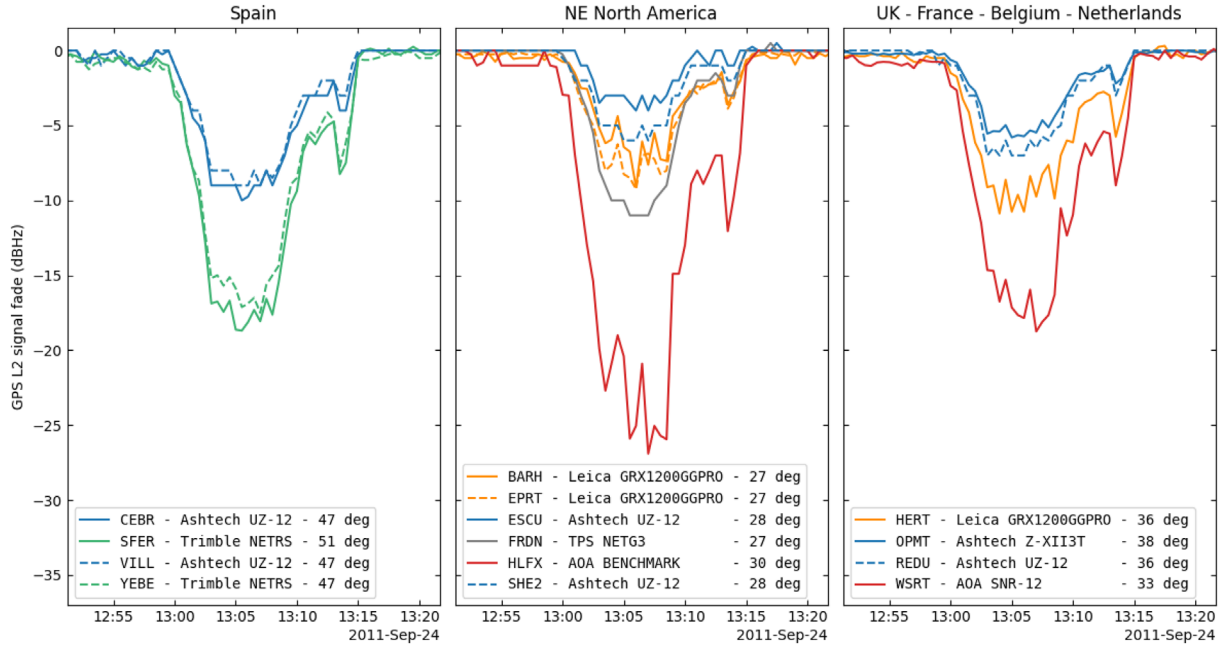


Figure 8. Comparison between the GPS L2 signal fades of GNSS stations situated in the same geographical area depending on their receiver. There are four stations from Spain (left panel), six from the northeast of North America (middle panel) and four stations from the northwest of Europe (right panel). GNSS receivers from the same brand are represented in the same colour. The legend indicates the name of the station, the model of its receiver and the solar elevation angle at the time of maximum SRB emission. It can be noticed how receivers from the same brand tend to behave similarly. The SRB corresponds to Event 03 in Table 1.

are two stations with an Ashtech receiver and two other stations with a Trimble receiver. The stations with the same type of receiver show similar signal fades, but those from stations with a Trimble receiver are almost 10 dBHz deeper than those from stations with an Ashtech receiver. Similar to the Spanish group, in the groups from the northeast of North America (middle panel) and the northwest of Europe (right panel), the stations with the least deep signal fades are those with an Ashtech receiver. Moreover, in both groups, the station with the deepest signal fades had an AOA receiver (although a different model), while Leica receivers present signal fades intermediate to those of Ashtech and AOA. The repetition of these patterns across different locations permits discarding local factors such as the local noise environment as the primary cause behind these discrepancies.

Even though the differences in their behaviour highlight the importance of considering the specific characteristics of GNSS receivers when assessing the impact of solar radio bursts, a direct comparison between different receivers is not trivial. Their response to SRBs depends on proprietary or semi-proprietary information and is susceptible to changing through firmware upgrades. Although differences between receivers could make some more resilient against SRB interference than others, it is also plausible that the signal strengths reported by different manufacturers, even though expressed in dBHz units, may not be entirely comparable.

Figures 9 and 10 take a closer look at the comparability between the signal strengths measured by receivers from different manufacturers. The data correspond to stations VILL and YEBE during the SRB on 24 September 2011. These stations are located in central Spain and are separated by an approximate

distance of 74 km. YEBE was equipped with a Trimble NetRS receiver and VILL with an Ashtech UZ-12 receiver. The solar elevation angle at the instant of maximum SRB emission was 47°. The top panels of Figure 9 indicate that in normal conditions, both stations should have been tracking nine satellites each, although with significantly higher signal strengths at VILL. Although the signal strength can be conditioned by several factors other than the receiver, a similar scenario is observed at nearby stations CEBR (Ashtech UZ-12 receiver) and SFER (Trimble NetRS). During the SRB (bottom panels in Figure 9), YEBE was tracking at L2 only three satellites, none of them with a signal strength above 20 dBHz. On the other hand, VILL never tracked fewer than six satellites, all of them with signal strengths above 32 dBHz. This indicates that, regardless of signal intensity masks and internal signal strength calculations, YEBE operated during a few minutes below minimum operational conditions, as it was tracking fewer than four satellites in total. VILL, on the other hand, did not encounter this problem. A second difference is that VILL stopped tracking satellites at reported signal strengths significantly higher than YEBE. Figure 10 shows the evolution of the signal strength of four GPS satellites at both stations. It can be noticed how YEBE continued to track satellites until their signal strength fell to approximately 17 dBHz, which is considerably lower than VILL's 32 dBHz. This happens not only during SRB, but also for low-elevation satellites (bottom panels of Fig. 10). These disparities between stations indicate that different receivers may not only respond differently to SRBs, but also that their reported signal strength may not always be directly comparable, not even when they are provided in physical units.

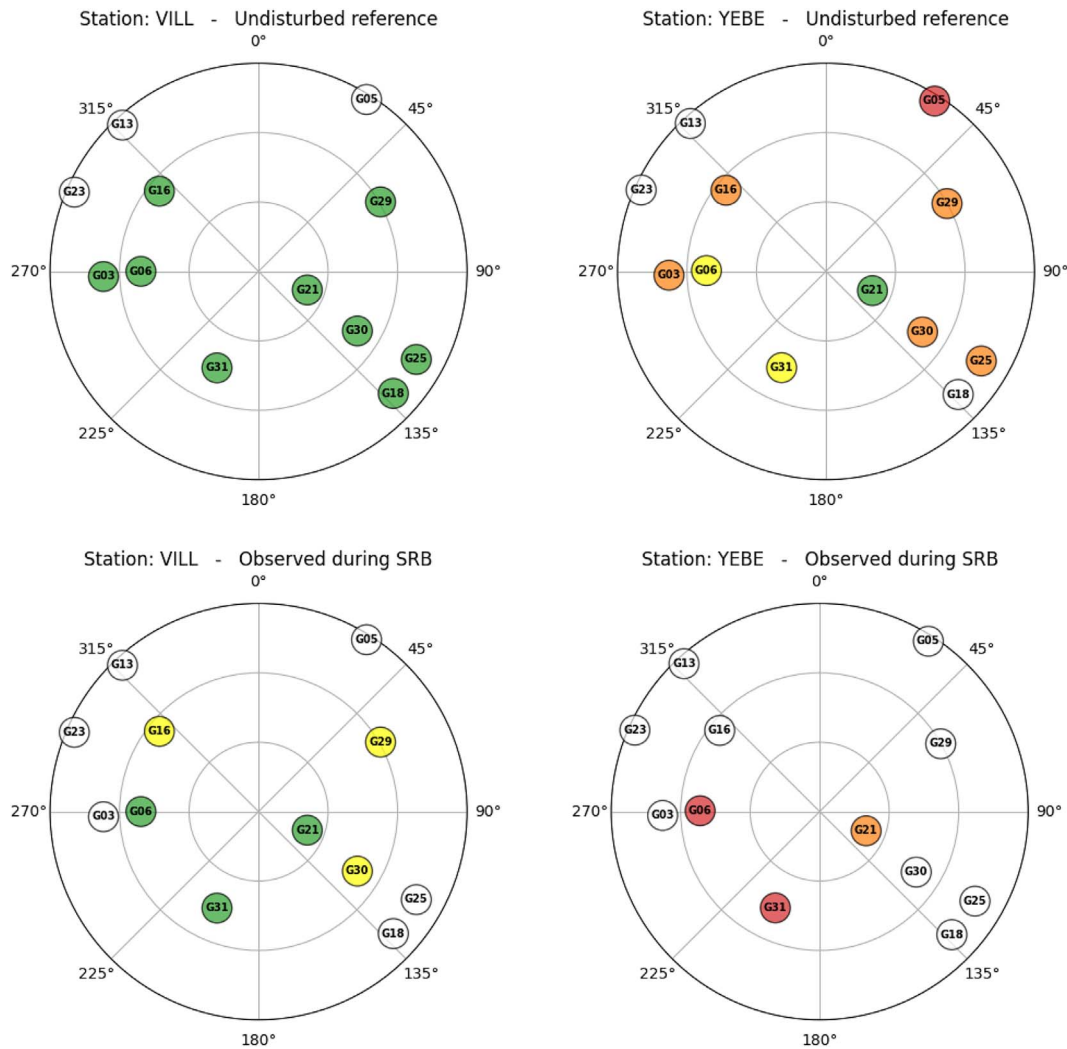


Figure 9. Skyplots with the distribution of GPS satellites and colour-coded L2 signal strength during the SRB on 24 September 2011 at 13:05:30 UTC for IGS stations VILL (left panels) and YEBE (right panels). The colour code is: green (for signal strengths higher than 36 dBHz), yellow (in the range 30–36 dBHz), orange (18–30 dBHz), red (lower than 18 dBHz) and white if the satellite is not available. The thresholds follow the standardized signal strength indicators scale. The top panels indicate the expected undisturbed conditions, while the bottom panels show the conditions observed during the SRB.

Although the primary focus of the analyses above was on the influence of GNSS receivers on the different responses of GNSS stations to SRBs, GNSS antennas could, in principle, also play a role. Approximately 72% of the receivers used in this study were connected to antennas from the same brand as the receiver. The amount of stations with other receiver-antenna combinations is therefore too small to conduct an analysis similar to those performed for the receivers. However, here again, one can examine stations in close proximity to each other, equipped with the same receiver but different antennas, to assess the role of the antenna under otherwise similar conditions. Out of the 12 station pairs used for this test, none of them exhibited a discrepancy in their L2 signal fades persistently exceeding 2 dBHz during SRBs. For example, during the SRB on 24 September 2011 all AOA receivers were connected to AOAD/M_T antennas. Ashtech receivers, on the other hand, were connected to antennas from various manufacturers. IGS stations CEBR and VILL, which are separated by a distance of only

35 km, were both equipped with an Ashtech UZ-12 receiver. The antenna of CEBR was an ASH701945B_M, while the antenna of VILL was an AOAD/M_T (i.e., the same antenna as the AOA receivers.) Despite having different antennas, the behaviour of CEBR and VILL during the radio burst was practically identical (left panel of Fig. 8), with a maximum difference of just 1 dBHz. Although these tests are far from being an exhaustive analysis of the role of antennas during SRBs, they suggest that receivers have a more significant impact than antennas on the discrepancies observed between stations.

6 Summary and conclusions

This paper has presented an investigation into the effects that solar radio bursts had on the GPS receivers of the International GNSS Service Network during Solar Cycle 24. Focusing on the 20 most intense 1.4 GHz solar radio bursts detected by

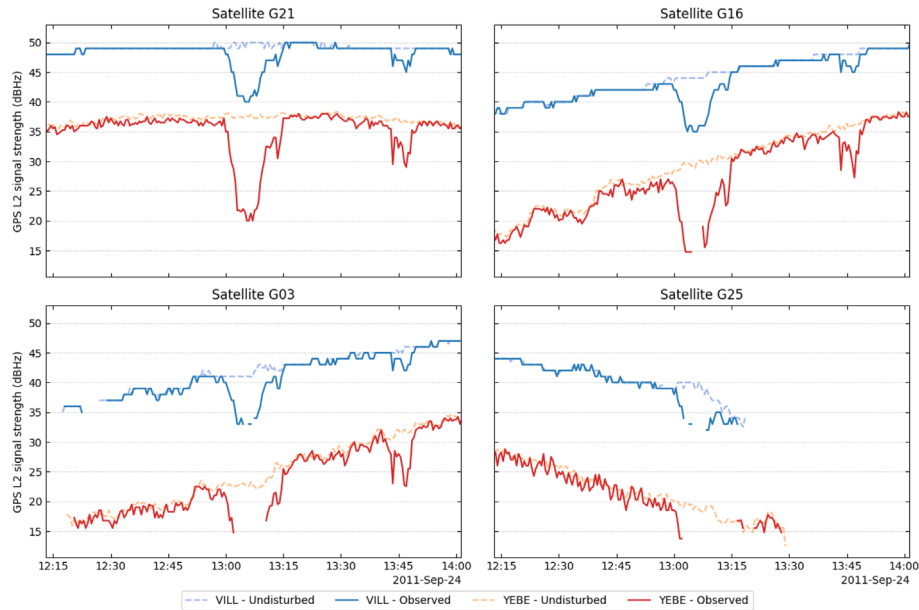


Figure 10. GPS L2 signal strengths of four GPS satellites as measured at IGS station VILL (blue) and YEBE (red) during the SRB on 24 September 2011 (solid line) and according to the undisturbed reference (dashed line). The stations are separated by an approximate distance of 74 km. Their receivers are an Ashtech UZ-12 (VILL) and a Trimble NetRS (YEBE).

the RSTN, the impacts were characterized in terms of the degradation of signal strength, reduction in the number of available satellites, and precision decrease as a result of the satellite geometry deterioration.

At the GPS L1 frequency, only the event on 24 September 2011 presents extended service degradation, with 75% of the stations reporting signal fades exceeding 5 dBHz, and five stations operating below minimum operational requirements. At this frequency, the effects of the other radio bursts were noticed only by a few stations and without significant consequences to service integrity.

The impact of solar radio bursts was more pronounced at the GPS L2 frequency. Out of the twenty selected radio bursts, ten caused a reduction in signal strength by at least 5 dBHz at one or more stations. During five of these radio bursts, the degradation exceeded 15 dBHz. Notably, these five radio bursts reduced the number of available satellites by at least four for between 10% and 60% of the stations. Seven radio bursts produced service degradation below minimum operational requirements, although in three of them, the loss of service was experienced by only one or two stations. To the best of this author's knowledge, the impact on GNSS during several of these events, such as Events 01, 06, 08, 11 and 17, has yet not been studied in detail elsewhere. Particularly in the current situation of insufficient SRB observations with polarization at GPS frequencies, having a diverse set of events is crucial for determining an empirical relationship between burst intensity and GPS service degradation.

Although the degradations of GPS signals shown in this paper are a consequence of the noise introduced by solar radio bursts, their correlation with the burst intensities is found to be modest at best. This can be at least partially explained by the fact that GPS systems are sensitive only to the right-hand circular polarization of the burst and that the available observations of solar radio bursts lack polarization information. Experimental

solar radio observations from the SMOS mission, which include polarization data, show enhanced correlation and a diversity of polarization states that underscores the importance of incorporating polarization when examining the relationship between radio bursts and the disturbances they cause in polarization-sensitive systems such as GNSS. Given these findings, trying to establish solar radio burst intensity thresholds that could be of use to affected GNSS users is only feasible when polarization information is available. Adding to SMOS the capability to provide solar radio observations could help address this issue. Having been in orbit since 2010, SMOS could provide a large enough dataset of SRB observations to help establish intensity thresholds, while also aiding in understanding how subsequent GNSS service upgrades have improved the resilience of GNSS systems against SRBs. Furthermore, adding these solar radio observations as one of the near real-time SMOS products would provide affected users with a monitoring service.

The drawbacks of using SRB observations at 1.4 GHz instead of at GPS frequencies have also been addressed. At least one SRB (Event 17) displays significant discrepancies in both intensity and shape. A tentative analysis using NoRP polarization observations at 1.0 GHz and 2.0 GHz suggests that discrepancies of up to 20–25% between the SRB intensities at GPS frequencies and at 1.4 GHz are probably not uncommon.

This paper has also explored how different receivers respond to the same radio burst. It was observed that receivers from different manufacturers may exhibit different degrees of impact, even when other factors such as the solar elevation angle are held approximately the same. The signal strength of the satellites during the radio bursts was found to be manufacturer-dependent, even when the stations provided the measurement in units of dBHz. A variation in receiver response was also noticed in the relative depths of the signal fades at L1 and L2. These dependencies complicate the task of establishing intensity thresholds, as the impact is receiver-specific. It is however worth noting that

the current situation may differ somewhat from the conditions during Solar Cycle 24, from which the GPS data used in this study were obtained. Since then, some manufacturers have been acquired by other companies, new stations have been added to the IGS Network, and others have been upgraded.

At this point it is probably pertinent to issue some words of caution. Solar flares and solar radio bursts are distinct phenomena and have different impacts on GNSS systems. This fact is well known within the scientific community but it is too often overlooked by final users of space weather services. Users of radio systems affected by space weather conditions often rely on impact scales that use the intensity of solar flares as a threshold, such as NOAA's scale for radio blackouts. These scales are, however, not applicable to disturbances caused by solar radio bursts, as the intensities of flares and radio bursts do not correlate. The results of this paper are a good example of this. Among the four events with the largest impact on GPS, only Event 01 was an X-class flare, while the other three were relatively mild flares with intensities between M2.0 and M7.1 (see Table 1). On the other hand, out of the six X-class flares, only two (Events 01 and 18) had an impact on GPS. This absence of impact during intense flares also suggests that, at least for the metrics and GNSS sampling rates used in this study, the ionospheric perturbations produced by flares have a negligible influence on GNSS impact compared to SRBs.

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