https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae Discussions

Space Weather Study through Analysis of Solar Radio Bursts detected by a Single Station CALLSTO Spectrometer

Theogene Ndacyayisenga[1], Ange Cyanthia Umuhire[1], Jean Uwamahoro[2], and Christian Monstein[3]

[1]University of Rwanda, College of Science and Technology, Kigali, Rwanda.
[2]University of Rwanda, College of Education, P.O. BOX 55, Rwamagana – Rwanda.
[3]Istituto Ricerche Solari (IRSOL), Università della Svizzera italiana (USI), CH-6605 Locarno-Monti, Switzerland.

Correspondence: Theogene Ndacyayisenga (ndacyatheogene@gmail.com)

Abstract. This article summarizes the results of an analysis of solar radio bursts detected by the e-Compound Astronomical Low cost Low-frequency Instrument for spectroscopy and Transportable Observatory (e-CALLISTO) spectrometer hosted by the University of Rwanda, College of Education. The data analysed were detected during the first year (2014–2015) of the instrument operation. The Atmospheric Imaging Assembly (AIA) images on board the Solar Dynamics Observatory (SDO) were used to check the location of propagating waves associated with type III radio bursts detected without solar flares. Using quick plots provided by the e-CALLISTO website, we found a total of 202 solar radio bursts detected by the CALLISTO station located in Rwanda. Among them, 5 are type IIs, 175 are type IIIs, and 22 type IVs radio bursts. It is found that all analysed type IIs and $\sim$ 37% of type III bursts are associated with impulsive solar flares while Type IV radio bursts are poorly associated with flares. Furthermore, all of the analysed type II bursts are associated with CMEs which is consistent with the previous studies, and $\sim$ 44% of type IIIs show association with CMEs. On the other hand it is observed that the majority of type IV radio bursts are believed to be originated from CME-driven shocks. Findings from this study confirms that solar radio bursts (SRBs) from ground observation and analysis constitute a clue to diagnose the space weather phenomena such as solar flare and CMEs and to some extent, they may serve as the advance warning of the related severe space weather hazards.

1 Introduction

About eight decades ago, solar radio bursts (SRBs) were classified into five types based on their morphologies and drift rates (Wild, 1950). From the meter to decimeter range, characteristic burst signatures correspond to well-identified physical processes, such as shock waves (type II bursts, Nelson and Melrose (1985); Cairns et al. (2003); Ganse et al. (2012)), electron beams streaming along open magnetic field lines (type III bursts, Lin et al. (1981, 1986)), or electron populations trapped in eruptive flux ropes and post-flare loops (type IV bursts, Nindos et al. (2008)). Type II radio bursts are the bright radio emissions often associated with CMEs and characterized by a slow frequency drift rate ($\leq -1\ MHz\ s^{-1}$) (McLean and Labrum, 1985; Nelson and Melrose, 1985). They are excited by magneto-hydrodynamics (MHD) shocks in the solar atmosphere (Nelson and Melrose, 1985; Cliver et al., 1999; Nindos et al., 2008, 2011; Vršnak and Cliver, 2008). MHD shocks are driven by both flares and CMEs in the solar atmosphere (Nindos et al., 2008). The type III radio bursts are the intense, frequently observed, and fast drifting bursts from high to low frequencies. These bursts usually come from active regions (Saint-Hilaire et al., 2013)

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

and they are generated when solar flares send electron beams streaming into the heliosphere via plasma mechanism (Ginzburg and Zhelezniakov, 1958). Type III radio bursts typically appear as isolated bursts that last in 1–3 s, in groups that last in 10 minutes and as storms that last few hours. The impulsive flares in X-ray and/or H_α frequencies, exhibit type III radio bursts at their ascending phases (Cane and Reames, 1988). The most detailed and most recent analysis of type III burst properties with their interpretations is given in the article by Reid and Ratcliffe (2014) and more generally on solar radio emission (e.g, Dulk (1985); McLean and Labrum (1985); Bastian (1990); Pick and Vilmer (2008); Gary et al. (2018)). On the other hand, type IV bursts are often accompanied by long-duration events observed at EUV or soft X-ray wavelengths and coronal mass ejections. The diagnosis of the solar atmosphere by a better understanding of the solar radio emissions is sophisticated by ever-increasing instruments technology. With this advancement, several ground and space telescopes have been built to observe solar radio bursts (SRBs) at a global scale. Space based observations detect interplanetary bursts at ≤ 14 MHz using WAVES–WIND (Bougeret et al., 1995), and WAVES–STEREO (Kaiser, 2005; Rucker et al., 2005) instruments. Globally distributed ground-based solar radio spectrographs include: Radio Solar Telescope Network (RSTN) operated by US Airforce (Guidice et al., 1981), Hiraiso Radio Spectrograph (HiRAS) in Japan (Kondo et al., 1994), ARTEMIS-IV in Greece (Caroubalos et al., 2001), IZMIRAN in Russia (Gorgutsa et al., 2001), Gauribidanur Low frequency Solar Spectrograph (GLOSS) in India (Kishore et al., 2014) and many others[1]. The development of the Square Kilometre Array (SKA) (Dewdney et al., 2009; Nindos et al., 2019) will open a new opportunity to understand radio-wave propagation. Despite this technological advancement, gaps in data were highly recognized in developing countries, especially African continent (Guhathakurta et al., 2013). In order to tackle these data gaps, the International Space Weather Initiative (ISWI)[2] has contributed to the observation of space weather phenomena through the deployment of ground-based instruments (Haubold et al., 2010). In this regards, a Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) radio spectrometer (Benz et al., 2005, 2009) has been deployed in different parts of the globe. Through collaboration, Rwanda has been the first country in East Africa that acquired a CALLISTO spectrogram. Our motivation is to use the radio bursts data detected by the CALLISTO station at the University of Rwanda, College of education, to check their correlation with the solar activities. The analysis presented here aims to demonstrate the trend of observation of CALLISTO Rwanda during its first year of operation, that is a period of October 2014 to September 2015. This article is structured as follows. Section 2 describes the observation and methods used to get analysed data. The results and discussions are presented in section 3. Our concluding remarks and summary are in section 4.

2 Observation and methods

The list of radio bursts presented in this article were detected by CALLISTO station in Kigali, Rwanda (1.9441°S, 30.0619°E) during its first year of operation from October 2014 to September 2015. In this study, we used quick plots provided by the network[3] and manual inspection to analyze all the detected bursts. We identified a total of 202 radio bursts comprising 5 type

[1] https://www.astro.gla.ac.uk/users/eduard/cesra/?page_id=187
[2] http://www.iswi-secretariat.org
[3] http://soleil.i4ds.ch/solarradio/callistoQuicklooks/

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae Discussions
Open Access
EGU

IIs, 175 type IIIs, and 22 type IV bursts events. Figure 1 illustrates the spectral overview and the time coverage of the instrument through the year at the station and it is important to mention here that the time varies with the seasons of the Sun. All the burst

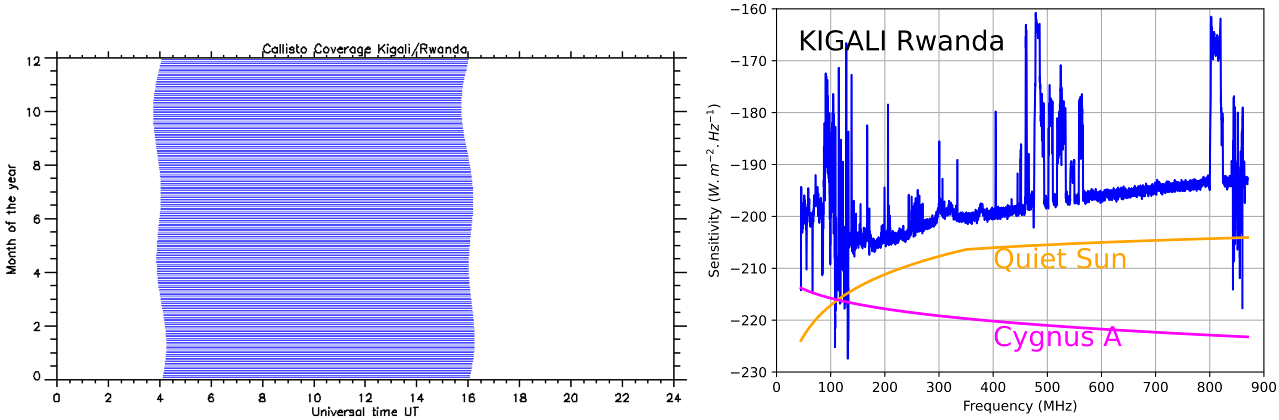

Figure 1. The left panel shows the observation coverage by CALLISTO station at University of Rwanda in Kigali. The right panel displays the spectral overview Kigali/Rwanda. Strong peaks near 100 MHz, 500 MHz and 800 MHz are due to FM-radio, digital video broadcast and mobile phone transmitters. Negative peaks with respect to blue baseline are due to saturation of the spectrometer from strong local transmitters. Best frequencies for solar burst observations are 45 MHz-80 MHz, 150 MHz- 450 MHz and 600 MHz-800 MHz due to low interference.

events were observed through a channel of 80.9 MHz to 45 MHz. Radio bursts are used as diagnostics of the level of solar activity, therefore we carefully examined their association with the solar transients using the database from Heliophysics Event Catalogue[4]. Following that some type III and type IV radio bursts were detected in the absence of solar flares and/or CMEs, the Atmospheric Imaging Assembly (AIA, Lemen et al. (2012)) images on board the Solar Dynamics Observatory (SDO) were checked to see whether there are propagating wave associated to them. SDO/AIA images enable us to observe jets and their source region with a temporal and spatial resolution (Innes et al., 2011).

3 Results and discussions

The observed bursts and the associated flare properties are split into three tables according to their classification. Table 1 presents 5 intense and well-separated type II radio bursts. Similarly, Table 3 presents type IV bursts identified while a detailed table of type III radio bursts can be accessed from http://www.e-callisto.org/GeneralDocuments/Type_III_radio_bursts_2014_2015_kigali.pdf. For each table, the analysed bursts parameters such as the burst date (yy/mm/dd format), the corresponding onset time, and frequency range are listed in the first four columns, respectively. The next five columns list the associated flare properties: the flare onset time, end times, GOES x-ray flare classes, heliographic coordinates, and active regions (ARs) and the

[4]http://hec.helio-vo.eu/hec/hec_gui.php

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

last column shows associated CME onset, respectively. The analysis shows that all type II radio bursts are associated with solar flares, ∼37% of the type III radio bursts detected are flare associated and ∼13% of type IV bursts are flare related. Findings

Table 1. Type II SRBs observed by e-CALLISTO network, Kigali station.

	Type II bursts			Associated Flares					CME
Date	Start	Frequency (MHz)		Time (UT)		Class	ARs	Locations	Onset
	(UT)	Start	Stop	Onset	End				(UT)
2014/11/02	09:50:00	62.0	45	09:20	10:36	C4.5	2192	S12W92	10:00
2014/11/05	09:49:00	65.0	45	09:26	09:55	M7.9	2205	N15E53	10:12
2014/11/05	09:52:15	80.9	64	09:26	09:55	M7.9	2205	N15E53	10:12
2015/08/22	06:52:23	75.0	45	06:39	06:59	M1.2	2403	S14E09	07:12
2015/08/28	06:36:00	67.0	47	06:17	06:38	C4.5	2403	S15W71	06:36

are compared to the results obtained in the previous similar studies using other CALLISTO stations such as Mahender et al. (2020) who found that 426/1531 (∼ 28%) type III bursts were flare associated. The remaining non-flare associated type III and IV bursts may be due to small-scale feature events present in the solar corona. Furthermore, the association of these bursts with coronal mass ejections (CMEs) was traced out. It is observed that all analysed type II radio bursts are associated with CMEs while only ∼44% of all type III radio bursts are accompanied by CMEs. In similar way, it is believed that the majority of type IV radio bursts are triggered by CME-driven shocks. Table 2 gives a summary of these observations. Among type II bursts

Table 2. Summmary of observations

parameters	Type II bursts	Type III bursts	Type IV bursts
Total number	5	175	22
Flare associated	5	66	3
CME associated	5	78	18
Flare associated (%)	100	∼37	∼13
CME associated (%)	100	∼44	∼82

detected by the instrument, the one of August 22, 2015 is chosen based on its geoeffectiveness as displayed in Figure 2. Figure 2(a) illustrates a dynamic spectrum for the August 22, 2015 type II burst event observed by CALLISTO station in RWANDA starting at 06:52 UT and disappears at 06:58 UT with a duration of 6 minutes. The event has a band split fundamental structure with the corresponding frequencies ranging between 46-56 MHz and 46-75 MHz, respectively as estimated from the dynamic spectrum. Figure 2(b) is the processed dynamic spectrum of the August 22, 2015 type II burst. It was smoothed to remove the radio frequency interferences (RFIs) to observe all features for further analysis. The event is associated with a CME that occurred at 07:12 UT. This CME caused a mild storm on August 23, 2015, at 09:00 with Dst=-44 nT. The calculated CME average linear speed of 643 km/s is high enough to produce a shock. Hence, the measured shock height closer to the onset time

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae
Discussions

of the associated type II burst is found to be 1.5 Rs (Figure2(c)). It is also associated with an M1.2 flare class (Figure2(d)) originating in the active region (AR) 2403, that occurred at 06:49 UT and located at S14E09 on the solar disk. Even though all type II radio bursts are associated with both flares and CMEs, it is diificult to confirm the driver of the coronal shocks because the two phenomena often occur simultaneously (Zhang et al., 2001).

A small fraction of type III bursts was associated with impulsive flares. It is believed that radio bursts that have no direct connection with impulsive flares may be originated at H_α ejecta, X-ray footpoints and X-ray or/and extreme-UV (EUV) jets (Alissandrakis et al. (2015), and references therein). The November 3, 2014 is selected among the type III bursts reported in the table maintained at http://www.e-callisto.org/GeneralDocuments/Type_III_radio_bursts_2014_2015_kigali.pdf because a maximum number of type III radio bursts were detected on this day. Out of 12 separate type IIIs reported, only one is triggered by solar flare. With the help of images provided by SDO/AIA, the remaing 11 bursts are associated with outward propagating waves. This observation is consistent with earlier studies that inferred that type III radio bursts are commonly associated with jets in extreme Ultraviolet (EUVI) and x-rays (e.g., (Bain and Fletcher, 2009; Klassen et al., 2011; Krucker et al., 2011; Klassen et al., 2012)) with typical electron beams coinciding the path as the jets. Figure 3 shows a smple of the SDO/AIA images using 171Å bandpass of the Sun on November 3, 2014. The obervation also agrees with Innes et al. (2011) and Alissandrakis and Patsourakos (2013) who found that the jets causing type III radio bursts originate near the umbral brightening.

It is noted that the propagating waves last longer as they look the same for all detected radio emissions from 06:55 UT to 10:05 UT. A similar trend was observed on the 9 type III radio bursts observed in the absence of solar flares on July 9, 2015. Another interesting observation is that 34 cases of CMEs precede type III radio bursts without flares which implies that Type IIIs may originate from the same site where CMEs are launched (Dididze et al., 2019). On the other hand, Figure 4 displays a dynamic spectrum of type III radio burst followed by type II radio burst of November 2, 2014, detected by CALLISTO station in Rwanda. These two types of radio bursts were triggered by the C4.5 flare that starts and ends at 09:20 to 10:36 UT, respectively. The CME associated with these events was off the Sun-Earth line.

Although the small fraction of type III radio bursts, we have plotted the heliographic longitudes and latitudes of the associated solar flares as indicated in Figure 5. It is trustworthy to mention here that most of the flare related to type III radio bursts find their origin near the equator (±30°). This result is consistent with the findings by Mahender et al. (2020) who found that the analysed 426 type III bursts associated with the solar flares originated close to the equator (i.e. heliographic latitudes ±23°). The network has also observed type IV radio burst events.

Unlike type IIIs the majority of type IV radio emissions are believed to originate from the backbone of the CME-driven shocks since they are poorly associated with flares. From Table 3, 18 type IV out of 22 ($\sim$ 82%) are accompanied by CMEs.

Table 3: Type IV SRBs observed by e-CALLISTO network, Kigali station.

	Type IV bursts				Soft X-ray flares					CME
N^0	Date yyyy/mm/dd	Start (UT)	Frequency (MHz) Start	Stop	Start (UT)	End (UT)	Location position	Class	ARs	Onset (UT)
1	2014/10/30	10:11:45	66.0	45	09:54	10:06	S12W92	M1.2	2192	....

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae
Discussions
Open Access

2	2014/11/06	08:27:00	78.0	48	....	....	....	....	....	08:00
3	2014/11/14	08:23:00	73.0	45	....	....	....	....	....	08:12
4	2014/11/25	15:56:35	80.9	45	....	....	....	....	....	....
5	2014/12/05	16:06:00	80.9	45	....	....	....	....	....	15:24
6	2015/01/01	11:00:00	78.0	45	....	....	....	....	....	10:36
7	2015/01/09	09:34:10	80.0	48	....	....	....	....	....	08:24
8	2015/01/12	09:07:32	78.0	45	....	....	....	....	....	....
9	2015/01/12	10:31:00	75.0	45	....	....	....	....	....	....
10	2015/01/13	09:14:00	80.9	45	....	....	....	....	....	09:12
11	2015/01/17	15:20:22	80.9	45	....	....	....	....	....	15:12
12	2015/01/21	11:26:10	80.9	45	....	....	....	....	....	11:24
13	2015/01/27	08:31:30	80.9	45	07:13	08:27	S16W16	C2.1	2275	08:00
14	2015/01/30	14:26:30	80.9	45	....	....	....	....	....	13:48
15	2015/02/06	08:44:00	80.9	45	....	....	....	....	....	08:24
16	2015/02/10	09:27:30	72.0	45	....	....	....	....	....	09:24
17	2015/02/24	10:13:00	78.0	45	09:54	11:53	S21E87	C1.4	....	10:00
18	2015/04/16	06:43:10	80.9	45	....	....	....	....	....	06:36
19	2015/04/24	10:52:25	80.9	45	....	....	....	....	....	10:48
20	2015/04/29	06:11:56	77.0	45	....	....	....	....	....	05:36
21	2015/05/28	12:14:57	73.0	45	....	....	....	....	....	12:00
22	2015/07/08	18:22:50	68.0	45	....	....	....	....	....	12:12

We have chosen January 2015 when many type IV radio bursts were detected and analyse 6 of them out of 9 recorded. Figure 6 presents the SOHO/LASCO C2 images and their corresponding running difference images from SDO/AIA of chosen type IV radio bursts (rows in green of Table 3). The first two type IV bursts are accompanied by CMEs followed by another two without CMEs and then two type IV with CMEs. It seen that type IV radio bursts detected by this instrument are poorly associated with solar flares. These observations are in agreement with Kumari et al. (2021) who performed a long-term statistical study and inferred that CME eruptions might be the source generating type IV radio emissions and found a low correlation with solar flares. On the other hand, type IV radio bursts may lack both association with flares and CME eruptions (Table 3). It is trustworthy that these kinds of type IV radio bursts coincide with the decaying phase of flares and/or triggered by post-eruption loops (Morosan et al., 2019; Kumari et al., 2021). Generally, solar radio bursts can be used as a potential precursor to track incoming space weather hazards such as geomagnetic storms and enhancement of solar radiation. There are more than 150 e-CALLISTO spectrograms installed around the world and operate simultaneously. The observation at a single station is limited by the sensitivity of the antenna. Despite technical issues, a burst can be viewed by more than one spectrogram and

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae
Discussions
Open Access
EGU

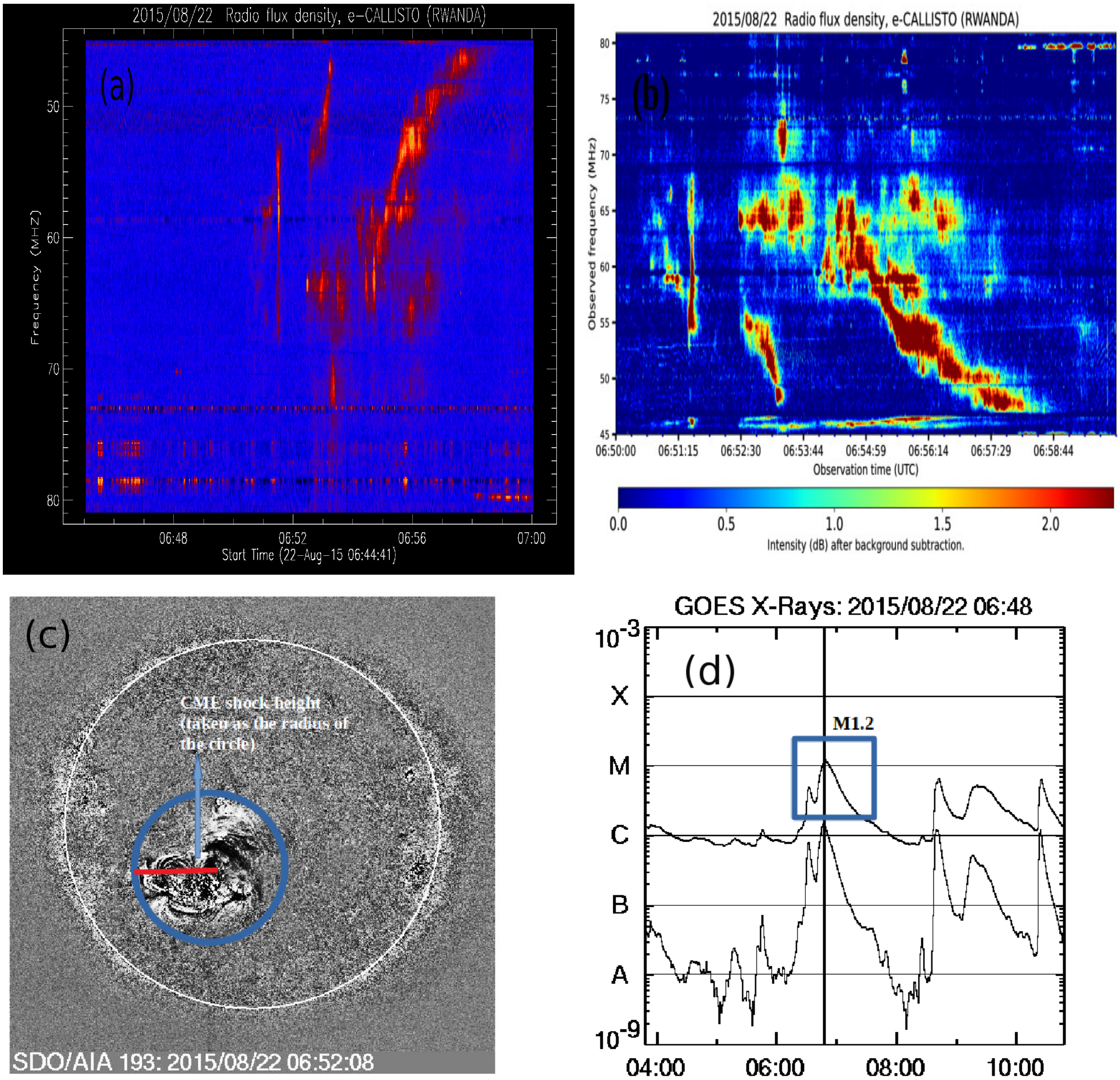

Figure 2. (a) The dynamic spectrum of the 2015 August 22 type II Burst detected by CALLISTO station in RWANDA part of the e-CALLISTO array. The burst shows a clear band splitting of the fundamental lane. (b) The dynamic spectrum of August 22, 2015, was processed to remove the radio frequency interferences (RFIs). (c) A CME image associated with the 2015 August 22 type II burst observed by the Solar Dynamic Observatory onboard the Atmospheric Imaging Assembly (SDO/AIA) closer to the time of type II burst onset time. A blue circle is fitted to the Extreme Ultraviolet Image (EUVI), its radius is taken as the CME shock height (red line). (d) An x-ray flare (M1.2) associated with the 2015 August 22 type II burst as observed by the Geostationary Operational Environmental Satellite (GOES).

this determines the uniqueness of the e-CALLISTO network. With the help of dynamic spectra provided by this network, it has been shown in the article by (Ndacyayisenga et al., 2021) that space weather can continuously be monitored at a large scale.

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae Discussions

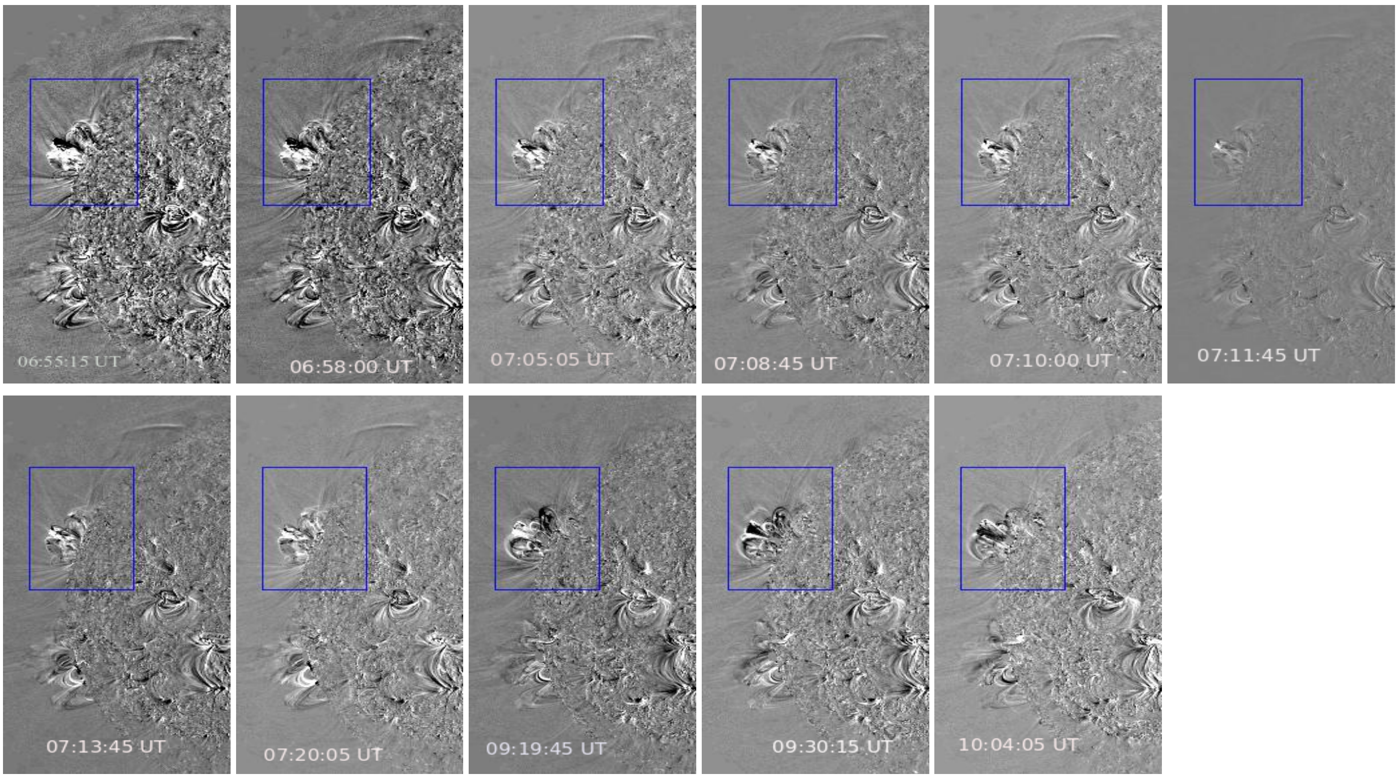

Figure 3. SDO/AIA portion images of the Sun using 171Å bandpass on November 3, 2014. These are running difference images corresponding to 11 type III radio bursts oberved on November 3, 2014 from 06:55 UT to 10:04 UT, respectively. AIA jets are bright knots of emission moving along the jets, herein at the peak of the brightening of 171 Å with a characteristic temperature of log T=6. The blue rectangle encloses the potential site of radio emission and/or the site where jets are originated. It is mentioned here that there is data gaps in EUVI data for these events.

Therefore a combination of information provided by each member of the e-CALLISTO network may reveal hidden features in space weather diagnostics.

4 Summary and conclusion

We have studied 202 solar radio bursts detected by CALLISTO spectrogram located at the University of Rwanda, College of Education. The obtained results show that during its first year of operation, 5 type II, 175 type III and 22 type IV radio bursts were detected in the frequency range 45–80.9 MHz. The current study shows that all type II radio bursts detected by this instrument are flare related and only $\sim$ 37% of type III bursts are triggered by impulsive flares while type IV radio bursts are poorly associated with flares. We found that the remaining non-flare related type III bursts might have been triggered by small-scale features or weak energy events present in the solar corona according to the literature and with the help of SDO/AIA

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

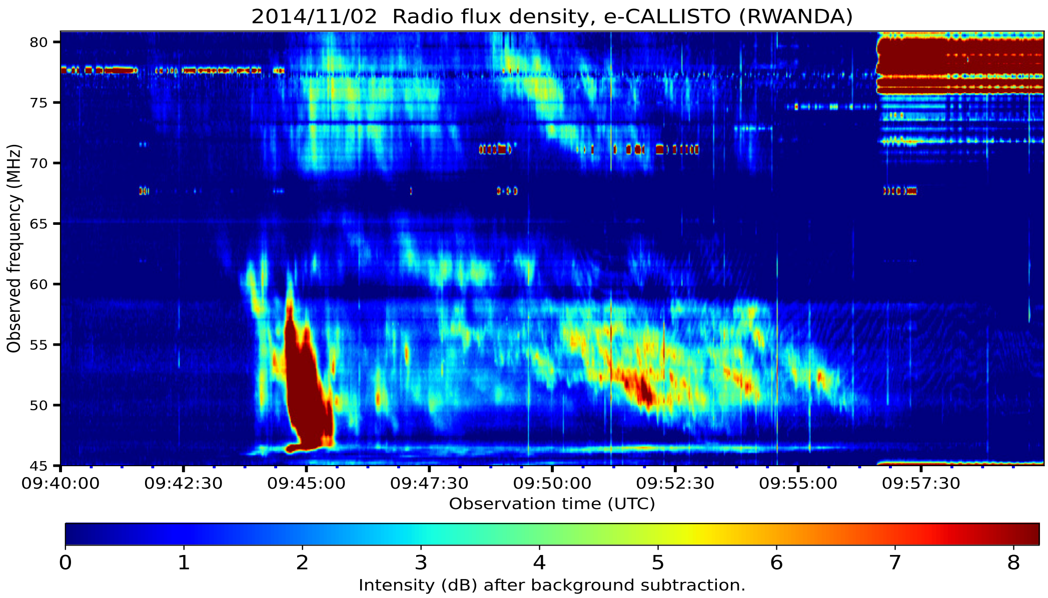

Figure 4. The dynamic spectrum of the November 2, 2014 type III burst followed by a type II burst detected by CALLISTO station in RWANDA part of the e-CALLISTO array.

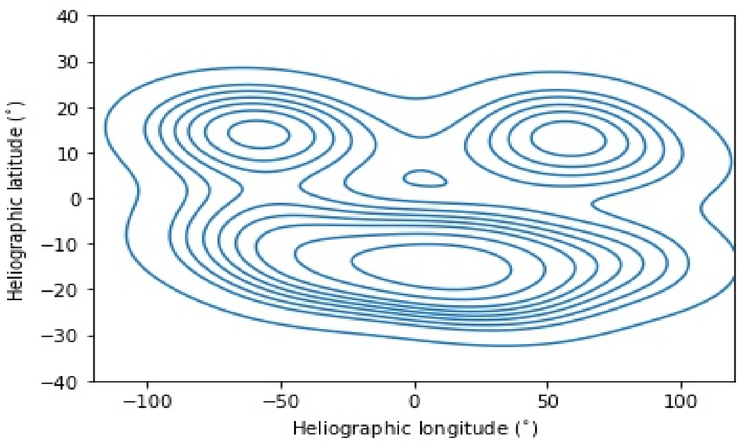

Figure 5. Heliographic longitude vs. heliographic latitude of flares that have triggered the type III radio bursts.

images in the 171 Å bandpass. On the other hand, all type II radio bursts are accompanied by CMEs and only ∼44% of type IIIs are accompanied by CMEs with 34 cases where CMEs precede type IIIs. The majority (∼ 82%) of the type IV radio bursts are accompanied by CMEs. Observed radio bursts may be used as a precursor for space weather diagnostics. The observation of SRBs from a single station such as the one in Kigali, Rwanda, is limited by the sensitivity of the antenna. More instruments for a wide coverage and regular maintenance of such instruments is recommended for a better monitoring and prediction of

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

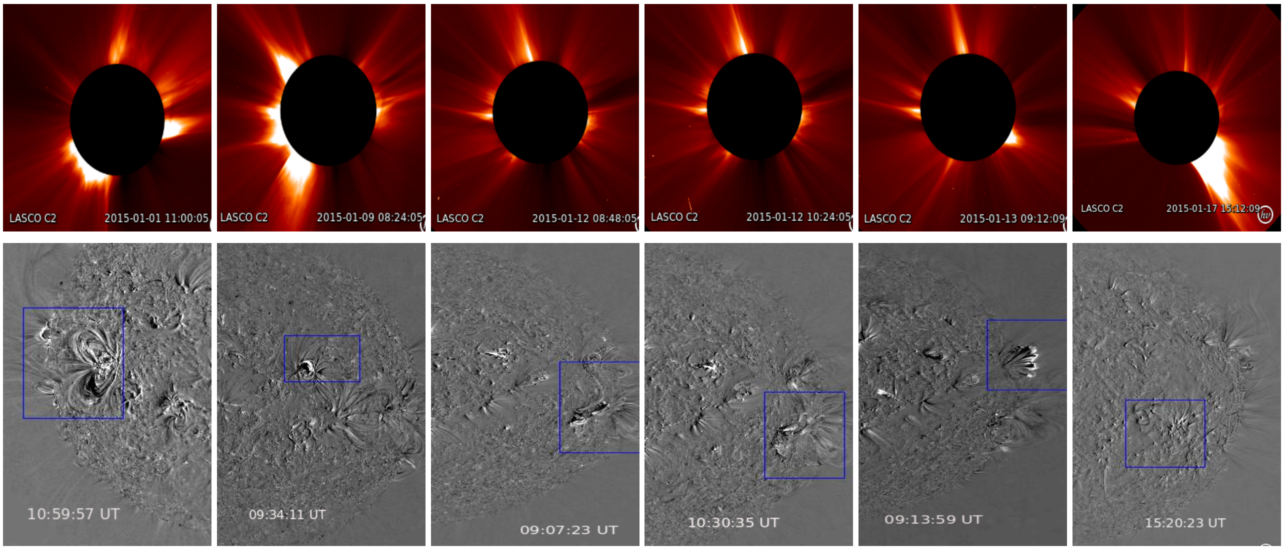

Figure 6. SOHO/LASCO images of the Sun using coronagraph C2 and their corresponding running difference images from SDO/AIA using 171 Å bandpass in January 2015. The two type IV bursts observed on January 12, 2015 (Middle part) are independent of CME-driven shocks while the first two and the last two are resulting from CME-driven shocks. The blue rectangle encloses the potential site of emission. Like fot type IIIs, there is EUVI data gaps following these dates.

space weather from the ground, in supplement to existing monitoring using space borne instruments. Conclusively, the regular maintenance of the CALLISTO spectrometer in Rwanda will contribute with integrity on the space weather monitoring by tracking the Sun in its time range throughout the year.

Author contributions. T. Ndacyayisenga, Jean Uwamahoro and A. C Umuhire conceived of the presented idea and the design of the study. T. Ndacyayisenga manually gathered the data used. C. Monstein helped in programming for data analysis. Analysis and intrepretation of the results are done by T Ndacyayisenga and A. C Umuhire who later drafted the manuscript. This manuscript is critically reviewed by Jean Uwamahoro and C. Monstein for intellectual content. Oversight, leadership responsibility for the research activities, mentorship are the inputs from Jean Uwamahoro.

Competing interests. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be created as a potential conflict of interest.

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae
Discussions

Acknowledgements. The authors are grateful to all who worked for the development and operatin of instrument to make the data available and have been made extensive used in this article, namely SDO/AIA, GOES, CALLISTO and the Helioviewer (http://helioviewer.org). This study also used version 2.1.5 of the SunPy open source software package (SunPy Community et al., 2020).

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae Discussions

References

Alissandrakis, C. E. and Patsourakos, S.: Hot coronal loops associated with umbral brightenings, A& A, 556, A79, https://doi.org/10.1051/0004-6361/201321787, 2013.

Alissandrakis, C. E., Nindos, A., Patsourakos, S., Kontogeorgos, A., and Tsitsipis, P.: A tiny event producing an interplanetary type III burst, A& A, 582, A52, https://doi.org/10.1051/0004-6361/201526265, 2015.

Bain, H. M. and Fletcher, L.: Hard X-ray emission from a flare-related jet, A&A., 508, 1443–1452, https://doi.org/10.1051/0004-6361/200911876, 2009.

Bastian, T. S.: Radio Emission from Flare Stars, Sol. Phys., 130, 265–294, https://doi.org/10.1007/BF00156794, 1990.

Benz, A. O., Monstein, C., and Meyer, H.: Callisto A New Concept for Solar Radio Spectrometers, Sol. Phys, 226, 143–151, https://doi.org/10.1007/s11207-005-5688-9, 2005.

Benz, A. O., Monstein, C., Meyer, H., Manoharan, P. K., Ramesh, R., Altyntsev, A., Lara, A., Paez, J., and Cho, K. S.: A World-Wide Net of Solar Radio Spectrometers: e-CALLISTO, Earth Moon and Planets, 104, 277–285, https://doi.org/10.1007/s11038-008-9267-6, 2009.

Bougeret, J. L., Kaiser, M. L., Kellogg, P. J., Manning, R., Goetz, K., Monson, S. J., Monge, N., Friel, L., Meetre, C. A., Perche, C., Sitruk, L., and Hoang, S.: Waves: The Radio and Plasma Wave Investigation on the Wind Spacecraft, Space Sci. Rev., 71, 231–263, https://doi.org/10.1007/BF00751331, 1995.

Cairns, I. H., Knock, S. A., Robinson, P. A., and Kuncic, Z.: Type II Solar Radio Bursts: Theory and Space Weather Implications, Space Sci. Rev., 107, 27–34, https://doi.org/10.1023/A:1025503201687, 2003.

Cane, H. V. and Reames, D. V.: Soft X-Ray Emissions, Meter-Wavelength Radio Bursts, and Particle Acceleration in Solar Flares, APJ, 325, 895, https://doi.org/10.1086/166060, 1988.

Caroubalos, C., Maroulis, D., Patavalis, N., Bougeret, J. L., Dumas, G., Perche, C., Alissand rakis, C., Hillaris, A., Moussas, X., Preka-Papadema, P., Kontogeorgos, A., Tsitsipis, P., and Kanelakis, G.: The New Multichannel Radiospectrograph ARTEMIS-IV/HECATE, of the University of Athens, Experimental Astronomy, 11, 23–32, 2001.

Cliver, E. W., Webb, D. F., and Howard, R. A.: On the origin of solar metric type II bursts, Sol. Phys, 187, 89–114, https://doi.org/10.1023/A:1005115119661, 1999.

Dewdney, P. E., Hall, P. J., Schilizzi, R. T., and Lazio, T. J. L. W.: The Square Kilometre Array, Proceedings of the IEEE, 97, 1482–1496, 2009.

Dididze, G., Shergelashvili, B. M., Melnik, V. N., Dorovskyy, V. V., Brazhenko, A. I., Poedts, S., Zaqarashvili, T. V., and Khodachenko, M.: Comparative analysis of solar radio bursts before and during CME propagation, A&A, 625, A63, https://doi.org/10.1051/0004-6361/201629489, 2019.

Dulk, G. A.: Radio Emission from the Sun and Stars, Annual Review of Astronomy and Astrophysics, 23, 169–224, https://doi.org/10.1146/annurev.aa.23.090185.001125, 1985.

Ganse, U., Kilian, P., Vainio, R., and Spanier, F.: Emission of Type II Radio Bursts - Single-Beam Versus Two-Beam Scenario, Sol. Phys, 280, 551–560, https://doi.org/10.1007/s11207-012-0077-7, 2012.

Gary, D. E., Bastian, T. S., Chen, B., Fleishman, G. D., and Glesener, L.: Radio Observations of Solar Flares, in: Science with a Next Generation Very Large Array, edited by Murphy, E., vol. 517 of *Astronomical Society of the Pacific Conference Series*, p. 99, 2018.

Ginzburg, V. L. and Zhelezniakov, V. V.: On the Possible Mechanisms of Sporadic Solar Radio Emission (Radiation in an Isotropic Plasma), Soviet Astronomy, 2, 653, 1958.

https://doi.org/10.5194/angeo-2021-26
Preprint. Discussion started: 7 May 2021

Annales Geophysicae
Discussions

Gorgutsa, R. V., Gnezdilov, A. A., Markeev, A. K., and Sobolev, D. E.: An upgrade of the izmiran's solar digital radio spectrograph: First results, Astronomical and Astrophysical Transactions, 20, 547–549, https://doi.org/10.1080/10556790108213597, 2001.

Guhathakurta, M., Davila, J. M., and Gopalswamy, N.: The International Space Weather Initiative (ISWI), Space Weather, 11, 327–329, https://doi.org/10.1002/swe.20048, 2013.

Guidice, D. A., Cliver, E. W., Barron, W. R., and Kahler, S.: The Air Force RSTN System, in: Bulletin of the American Astronomical Society, vol. 13, p. 553, 1981.

Haubold, H. J., Gadimova, S., and Balogh, W.: Contributions of the United Nations Office for Outer Space Affairs to the International Space Weather Initiative (ISWI), arXiv e-prints, arXiv:1011.5663, 2010.

Innes, D. E., Cameron, R. H., and Solanki, S. K.: EUV jets, type III radio bursts and sunspot waves investigated using SDO/AIA observations, A&A, 531, L13, https://doi.org/10.1051/0004-6361/201117255, 2011.

Kaiser, M. L.: The STEREO mission: an overview, Advances in Space Research, 36, 1483–1488, https://doi.org/10.1016/j.asr.2004.12.066, 2005.

Kishore, P., Kathiravan, C., Ramesh, R., Rajalingam, M., and Barve, I. V.: Gauribidanur Low-Frequency Solar Spectrograph, Sol. Phys, 289, 3995–4005, https://doi.org/10.1007/s11207-014-0539-1, 2014.

Klassen, A., Gómez-Herrero, R., and Heber, B.: Electron Spikes, Type III Radio Bursts and EUV Jets on 22 February 2010, Sol. Phys., 273, 413–419, https://doi.org/10.1007/s11207-011-9735-4, 2011.

Klassen, A., Gómez-Herrero, R., Heber, B., Kartavykh, Y., Dröge, W., and Klein, K. L.: Solar origin of in-situ near-relativistic electron spikes observed with SEPT/STEREO, A&A, 542, A28, https://doi.org/10.1051/0004-6361/201118626, 2012.

Kondo, T., Isobe, T., Igi, S., Watari, S.-i., and Tokumaru, M.: The New Solar Radio Observation System At Hiraiso, Communications Research Laboratory Review, 40, 85, 1994.

Krucker, S., Kontar, E. P., Christe, S., Glesener, L., and Lin, R. P.: ELECTRON ACCELERATION ASSOCIATED WITH SOLAR JETS, The Astrophysical Journal, 742, 82, https://doi.org/10.1088/0004-637x/742/2/82, 2011.

Kumari, A., Morosan, D. E., and Kilpua, E. K. J.: On the Occurrence of Type IV Solar Radio Bursts in Solar Cycle 24 and Their Association with Coronal Mass Ejections, APJ, 906, 79, https://doi.org/10.3847/1538-4357/abc878, 2021.

Lemen, J. R., Title, A. M., Akin, D. J., Boerner, P. F., Chou, C., Drake, J. F., Duncan, D. W., Edwards, C. G., Friedlaender, F. M., Heyman, G. F., Hurlburt, N. E., Katz, N. L., Kushner, G. D., Levay, M., Lindgren, R. W., Mathur, D. P., McFeaters, E. L., Mitchell, S., Rehse, R. A., Schrijver, C. J., Springer, L. A., Stern, R. A., Tarbell, T. D., Wuelser, J.-P., Wolfson, C. J., Yanari, C., Bookbinder, J. A., Cheimets, P. N., Caldwell, D., Deluca, E. E., Gates, R., Golub, L., Park, S., Podgorski, W. A., Bush, R. I., Scherrer, P. H., Gummin, M. A., Smith, P., Auker, G., Jerram, P., Pool, P., Soufli, R., Windt, D. L., Beardsley, S., Clapp, M., Lang, J., and Waltham, N.: The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO), Sol. Phys., 275, 17–40, https://doi.org/10.1007/s11207-011-9776-8, 2012.

Lin, R. P., Potter, D. W., Gurnett, D. A., and Scarf, F. L.: Energetic electrons and plasma waves associated with a solar type III radio burst, APJ, 251, 364–373, https://doi.org/10.1086/159471, 1981.

Lin, R. P., Levedahl, W. K., Lotko, W., Gurnett, D. A., and Scarf, F. L.: Evidence for Nonlinear Wave-Wave Interactions in Solar Type III Radio Bursts, APJ, 308, 954, https://doi.org/10.1086/164563, 1986.

Mahender, A., Sasikumar Raja, K., Ramesh, R., Panditi, V., Monstein, C., and Ganji, Y.: A Statistical Study of Low-Frequency Solar Radio Type III Bursts, Sol. Phys, 295, 153, https://doi.org/10.1007/s11207-020-01722-z, 2020.

McLean, D. J. and Labrum, N. R.: Solar radiophysics : studies of emission from the sun at metre wavelengths, 1985.

Morosan, D. E., Kilpua, E. K. J., Carley, E. P., and Monstein, C.: Variable emission mechanism of a Type IV radio burst, A&A, 623, A63, https://doi.org/10.1051/0004-6361/201834510, 2019.

Ndacyayisenga, T., Uwamahoro, J., Sasikumar Raja, K., and Monstein, C.: A statistical study of solar radio Type III bursts and space weather implication, Advances in Space Research, 67, 1425–1435, https://doi.org/10.1016/j.asr.2020.11.022, 2021.

Nelson, G. J. and Melrose, D. B.: Type II bursts., pp. 333–359, 1985.

Nindos, A., Aurass, H., Klein, K. L., and Trottet, G.: Radio Emission of Flares and Coronal Mass Ejections. Invited Review, Sol. Phys, 253, 3–41, https://doi.org/10.1007/s11207-008-9258-9, 2008.

Nindos, A., Alissandrakis, C. E., Hillaris, A., and Preka-Papadema, P.: On the relationship of shock waves to flares and coronal mass ejections, A&A, 531, A31, https://doi.org/10.1051/0004-6361/201116799, 2011.

Nindos, A., Kontar, E. P., and Oberoi, D.: Solar physics with the Square Kilometre Array, Advances in Space Research, 63, 1404–1424, https://doi.org/10.1016/j.asr.2018.10.023, 2019.

Pick, M. and Vilmer, N.: Sixty-five years of solar radioastronomy: flares, coronal mass ejections and Sun Earth connection, A& A Rev., 16, 1–153, https://doi.org/10.1007/s00159-008-0013-x, 2008.

Reid, H. A. S. and Ratcliffe, H.: A review of solar type III radio bursts, Research in Astronomy and Astrophysics, 14, 773–804, https://doi.org/10.1088/1674-4527/14/7/003, 2014.

Rucker, H. O., Macher, W., Fischer, G., Oswald, T., Bougeret, J. L., Kaiser, M. L., and Goetz, K.: Analysis of spacecraft antenna systems: Implications for STEREO/WAVES, Advances in Space Research, 36, 1530–1533, https://doi.org/10.1016/j.asr.2005.07.060, 2005.

Saint-Hilaire, P., Vilmer, N., and Kerdraon, A.: A Decade of Solar Type III Radio Bursts Observed by the Nançay Radioheliograph 1998-2008, APJ, 762, 60, https://doi.org/10.1088/0004-637X/762/1/60, 2013.

SunPy Community, Barnes, W. T., Bobra, M. G., Christe, S. D., Freij, N., Hayes, L. A., Ireland, J., Mumford, S., Perez-Suarez, D., Ryan, D. F., Shih, A. Y., Chanda, P., Glogowski, K., Hewett, R., Hughitt, V. K., Hill, A., Hiware, K., Inglis, A., Kirk, M. S. F., Konge, S., Mason, J. P., Maloney, S. A., Murray, S. A., Panda, A., Park, J., Pereira, T. M. D., Reardon, K., Savage, S., Sipőcz, B. M., Stansby, D., Jain, Y., Taylor, G., Yadav, T., Rajul, and Dang, T. K.: The SunPy Project: Open Source Development and Status of the Version 1.0 Core Package, APJ, 890, 68, https://doi.org/10.3847/1538-4357/ab4f7a, 2020.

Vršnak, B. and Cliver, E. W.: Origin of Coronal Shock Waves. Invited Review, Sol. Phys, 253, 215–235, https://doi.org/10.1007/s11207-008-9241-5, 2008.

Wild, J. P.: Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. III. Isolated Bursts, Australian Journal of Scientific Research A Physical Sciences, 3, 541, https://doi.org/10.1071/PH500541, 1950.

Zhang, J., Dere, K. P., Howard, R. A., Kundu, M. R., and White, S. M.: On the Temporal Relationship between Coronal Mass Ejections and Flares, The Astrophysical Journal, 559, 452–462, https://doi.org/10.1086/322405, 2001.