<u>Title:</u> **Space Weather Study through Analysis of Solar Radio Bursts detected by CALLISTO Spectrometer.**

<u>Answers to the referee #3 comments</u>

Firstly, we thank the referee for providing useful comments on our manuscript. Following the referee's comments, we have carefully gone through the manuscript and revised it. **For the sake of convenience, the newly added text in the manuscript is highlighted in boldface**. Herewith, we provide the answers and/or explanations to the referee's comments:

(a) <u>General view</u>

Comment #1

The manuscript presents the single station CALLISTO Spectrometer observations in Rwanda. The authors present different types of radio bursts but do not provide even convincing hypothesis on how the radio emission can be employed in the space weather diagnostics. Further, the study presented in this manuscript is very biased regarding the event selection. The sensitivity of CALLISTO instrument is quite low, which indicates that only strong and intense radio bursts will be observed while weak events will not be detected. This effect is enhanced with strong RFI disturbances in the considered observations. As a result, in particular all the type II bursts are very intense events and therefore associated with both flares and CMEs.

Response:
CALLISTO instrument was designed in the framework of IHY2007 and the idea of providing a cheap instrument to support developing countries through NASA- and UN-initiative in solar radio astronomy. Total cost for such a telescope was decided to be in the order of US2000$ which every interested institute can afford. This financial constraint was only possible by selecting a cheap antenna (LPDA) with a gain of ~6 dB, no tracking system and a low cost frequency agile spectrometer as a back-end.

Given these constraints only strong bursts with several dB above background radiation and rfi can be detected. Any high sensitive digital back-end with similar frequency range would cost in the order of 100 times more than a CALLISTO spectrometer. Nevertheless, such an instrument is very important and adds its contribution to space weather studies especially in developing countries. In fact, the instrument effectively detects strong SRBs and as we know, mostly those strong radio bursts are associated with solar events (CMEs, Solar flares) which are likely to be geoeffective.

Comment # 2

Unfortunately, it seems that the authors do not fully understand the subject they are addressing. They talk about geoeffectiveness and arrival of the disturbance to Earth, but they do not even mention in situ observations. In the manuscript the question on, how the CME arrival to Earth was estimated and how the associated radio emission helps in that was not addressed. Further, the identification of jets in the presented figure in not correct. Even associations of different types of the radio bursts with eruptive events, such as CMEs and flares is not clear and is some cases incorrect. Figures are also not good, sometimes distorted, but also misinterpreted. Additionally, English language of the manuscript is also quite bad. Due to all mentioned issues, and also the point that the manuscript does not bring any new results, I cannot recommend publication of this manuscript. My suggestion is rejection.

Response:

The main objective of the study is to show the capability of CALLISTO spectrometers to inform in advance incoming solar phenomena (i.e CME) likely to impact Earth, by for example driving a Geomagnetic storm). This study was limited to indicating correlations between early detected SRBs and subsequent earth impact. The reviewer is correct as authors did not consider using Interplanetary data / measurements for the study. The manuscript has been reviewed to improve to be understood in terms of english.

Comment #3

Unfortunately, I cannot induce the authors to work on the manuscript improvements. I support the idea of the authors to promote their observations, however then the scope of the manuscript needs to be very different. I have provided numerous detailed comments of the manuscript, hoping that will help to the authors to understand what is the problem in the manuscript and how to address it next time.

Response:

The authors thank you for these useful comments and declare that they like challenging work. Understanding the real problem is a key to the improvement of the current paper. However, we now provide sufficient discussion on the space weather part which was initially not done.

(b) General comments

Comment #1

Employed data set suffers from the preselection effects. The sensitivity of CALLISTO instrument is low, which indicates that only strong and intense radio bursts will be observed while weak events will be not detected. This effect is enhanced with strong RFI disturbances in the considered observations. As a result, all studied radio bursts, all the type II bursts are very intense events. In a case of type II bursts this will result in the 100 % association with both flares and CMEs. The problem of the instrument sensitivity needs to be discussed and data should be compared with observations of some other instrument (other than CALLISTO).

Response:

We agree with the referee that CALLISTO only observes strong radio bursts. CALLISTO is a frequency-agile spectrometer that is easily transportable and can be used in many observatories. Such a spectrometer is needed to complement interferometers. Its main goal is solar radio observation.

The aim of the current paper is not to compare the efficiency of the CALLISTO spectrometer but to demonstrate the capability of such an instrument which is part of the global network to contribute to the space weather study through observation of solar radio bursts. It is good that the instrument can detect strong radio bursts which in most cases are associated with solar storms that are likely to impact earth's magnetosphere and ionosphere. We appreciate the referee for the suggestion to make a comparison of CALLISTO with any other spectrometer. The instrument used is part of a global network of CALLISTO spectrometers to provide a global coverage. In the current version of the paper, we tried to provide sufficient discussions on the space weather part which was initially not done. We shall also provide a general comparison of the instrument with others.

Comment # 2

The explanation on how the association of studied radio events and CMEs/flares is not present at all. When the authors consider radio emission is associated with eruptive event? What is the time window they use?

Response:

The current study aims in demonstrating the capability of such an instrument which is part of the global network to contribute to the space weather study through observation of solar radio bursts. The data used are provided by CALLISTO station in Rwanda during its first year of operation from October 2014 to September 2015 during the SC 24. As an advantage, the considered period overlapped the availability of multiple spacecraft orbiting the Sun to make an accurate association of the moving radio bursts identified with the occurrence of CMEs.

To confirm the CME -SRBs association, we checked their time coincidence (for this study, CMEs that occurred within one hour of the onset of the radio bursts were considered). we used white–light coronagraph data from the Large Angle and Spectrometric Coronagraph (LASCO C2) onboard the Solar and Heliospheric Observatory (SOHO) and the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) onboard the Solar Terrestrial Relationship Observatory (STEREO) Ahead (A) and Behind (B) spacecrafts. For some cases where the identification was not clear, the CMEs were checked manually around the time of the moving burst events. The CME source regions were checked for events where multiple CMEs occurred at the same time to correlate them with associated bursts using CALLISTO images.

Regarding flare association, the onset, peak and end time of the flare were checked from the x-ray flare plot from the Geostationary Operational Environmental Satellite (GOES). We confirmed the association by checking their time coincidance, most likely when the radio burst is present between the onset and end times of the associated flare, we treat it as flare associated .

Comment # 3

Further, I do not really see how presented study is related to Space Weather.
There is no explanation in the manuscript which criterial are used to associate radio bursts and the possible geomagnetic impact.

Response:

Observed solar Radio bursts (SRBs) do not directly drive geomagnetic storms and other space weather adverses. However solar radio bursts are observed often associated with flares and/or CMEs which are precursors and major drivers of space weather manifestations including geomagnetic storms. As such, SRBs are used as a proxy and part of good data for model prediction of space weather. In the new version of the paper sufficient discussions with linkage to space weather are provided which was initially not done.

Comments # 4

Number of definitions is incorrect, e.g. association of the type IV burst and the sock wave... Some figures are not well done and some are incorrectly Interpreted.

Response:

We thank the referee for pointing out this issue. The part of type IV bursts and their association with eruptive events is revised and corrected for the mistakes. The figures are now well interpreted.

(c) **Detailed comments**

Comment # 1

Page 1, line 20: Abbreviation ”CMEs” needs to be introduced.

Response:

The line is modified as : …… often associated with coronal mass ejections (CMEs) and ……...

Comment # 2

Page 2, line 25: The authors write: “they are generated when solar flares send electron beams streaming into the heliosphere via plasma mechanism”.
This statement is not completely correct, the electron beams generated during the flaring process propagate along open or quasi-open magnetic field lines and they can induce Langmuir waves which will the cause the radio emission at plasma frequency and/or its harmonic.

Response:

We thank the referee. The paragraph is modified. …. they are generated by electrons propagating along open magnetic field lines and trigger the plasma oscillations (also known as Languir waves) during their travel in the solar corona and interplanetary medium (IPM) (Ginzburg and Zhelezniakov, 1958; Zheleznyakov, 1970, etc).

Comment # 3

Page 2, line 26: The authors write that type III bursts duration is 1-3 s. However, as duration of the type IIIs depends on the observing frequency it is necessary to specify the frequency range together with the durations.

Response:
The statement is formulated as follows: Type III radio bursts drift from ~ 200 MHz to 30 MHz in less than 10 s and reach 30 kHz in about 1 h.

Comment # 4

Page 2, line 27: The authors say: "The impulsive flares in X-ray and/or H α frequencies..." It should be x-ray and $H\alpha$ wavelengths.

Response:

We thank the referee. The error is corrected.

Comment # 5

Page 2, line 31: The authors already used the abbreviation "CME" so no need to use the full name.

Response:

The abbreviation is maintained.

Comment # 6

Page 2, line 36: The authors should also mention very important and recently refurbished Nançay observations.

Response:

We have added the recommended observatory.

Comment # 7

Page 2 footnoote 3. The link for the "callistoQuicklooks" does not work.

Response:
We have provided a correct link. http://soleil.i4ds.ch/solarradio/callistoQuicklooks/

Comment # 8

Page 3, line 58: What does mean ‘through a channel of 80.9 MHz to 45 MHz?
Response:
The statement is rephrased as follows: All bursts were observed in the frequency range of 45 MHz to 80.9 MHz.

Comment # 9

Table 1: The authors do not define when they consider the radio burst to be "associated with flares and/or CMEs". What is the time window in which two phenomena are considered to be related?

Response:

To confirm the CME -SRBs association, we checked their time coincidence (for this study, CMEs that occurred within one hour of the onset of the radio bursts were considered). we used white–light coronagraph data from the Large Angle and Spectrometric Coronagraph (LASCO C2) onboard the Solar and Heliospheric Observatory (SOHO) and the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) onboard the Solar Terrestrial Relationship Observatory (STEREO) Ahead (A) and Behind (B) spacecrafts. For some cases where the identification was not clear, the CMEs were checked manually around the time of the moving burst events. For the events where multiple CMEs occurred at the same times, we checked the source region of the moving bursts from CALLISTO images to associate them with the correct CME.

Regarding flare association, the onset, peak and end time of the flare were checked from the x-ray flare plot from the Geostationary Operational Environmental Satellite (GOES). We confirmed the association by checking their time coincidance, most likely when the radio burst is present between the onset and end times of the associated flare, we treat it as flare associated .

Refer to comment # 2

Comment # 10
Page 4, line 75: The authors state wrongly: "type IV bursts may be due to small-scale feature events present in the solar corona. First, the type IV bursts are generally associated with CMEs, so they cannot be put in the same category as type III bursts that are not flare associated. Second, what are ‘small-scale feature events’ ? Do the authors refer to nanoflares, small scale reconnection events or something else?

Response:

We thank the referee for this comment. Type III radio bursts and type IVs are separate, no way to put them in the same category. The two lines are modified as follows: The remaining non-flare associated type III radio bursts may be due to small-scale feature events present in the solar corona.

Comment # 11

Page 4, line 78: The authors write incorrect, type II bursts and not type IV radio bursts are triggered by CME-driven shocks. The type IV emission is considered to be associated with CMEs, but not CME-driven shocks.

Response:

The statement is rephrased as follows: In similar way, it is believed that the majority (~82%) of type IV radio bursts are associated with CMEs.

Comment # 12

Page 4, line 79: On figure 2 there is absolutely no information that would indicate that studied event was geoeffective. So, the following statement has no ground: "the one of August 22, 2015 is chosen based on its geoeffectiveness as displayed in Figure 2."

Response:

The statement is rephrased as follows: Among type II bursts detected by the instrument, the one of August 22, 2015 is chosen as due to its visible dynamic spectrum, hence flexible for spectral data analysis.

Comment # 13

Figure 2 (Page 7): Panel c) does not show the CME itself but it shows the associated EUV wave, one of the on disc signatures of CME. Considering blue circle as a CME-driven shock is very provisional consideration, and needs to be better justified and with some references.

Response:

In Figure 2 c, a LASCO C2 CME image will be used to clear the signature of the CME appearance.

The CME shock height was taken as the radius of the circle fitted to the outermost part of the disturbance; the assumption is that the disturbance expands spherically above the solar surface. Hence the CME shock height is shown by the red line. More details on the method used can be found in Gopalswamy et al., 2013.

Comments # 14

Page 4, line 81: What means "The event has a band split fundamental structure with the corresponding frequencies ranging between 46-56 MHz and 46-75 MHz,"? I believe it should be written something like: the fundamental band of the type II burst shows the band split. It should be also explained what is band split, and what are the listed frequencies? References need to be added describing the band split, eg. Vrsnak et al., 2001 and some recent work like Mahrous et al., 2018.

Response:

We thank the referee for the useful comment and suggestion. The detailed discussions are provided in the new version of the manuscript.

Comment # 15

Page 4, line 84: The authors state that the CME occurred at 07:12 UT. Where did he occurred, in the EUV images or in coronagraph images, and which one SOHO/LASCO C2? All this needs to be specified.

Response:
The sentence is revised and rephrased. The August 22, 2015 CME shock was only detected in SDO/AIA as a EUV wave as shown in Figure 2(c). However, the CME evolution could be observed and measured within LASCO C2 from 07:12 UT after the shock.

Comment # 16

Page 4, line 85-86: I am wondering how the CME with the speed of about 640 km/s arrived from the Sun to Earth in less than 24 hours?! This is surely not possible. The authors should check the association of the solar event and the one observed in situ. The disturbance propagating with the speed of about 700 km/s will need about 2.5 days to come to Earth. Further, the way shock height is estimated is not scientifically justified.

Response:
We thank the referee for this comment.
Depending on the speed, a typical CME reaches the Earth between 1- 5 days.

We report that a CME of 2015/08/22 at 07:12 UT with a speed of 643 Km/s reached Earth on 2015/08/24 causing a minor storm (~ -30 nT).
The CME shock height was taken as the radius of the circle fitted to the outermost part of the disturbance; the assumption is that the disturbance expands spherically above the solar surface. Hence the CME shock height is shown by the red line. More details on the method used can be found in Gopalswamy et al., 2013.

Comment # 17
Page 5, line 88: What does mean that flare occurred at 06:49 UT? Was that the flare start of the maximum? All this needs to be specified.

Response:

The statement is modified as follows: ….., that started at 06:49 UT and …….

Comment # 18

Page 5, line 89-90: The simultaneous occurrence of the flare and CME is not the point which makes difficult understanding which one of them is generating coronal shock. It is the simultaneous flare impulsive phase and the CME acceleration phase that does not allow us to clearly understand if the shock is flare-generated or CME-driven.

Response:

We thank the referee for this important comment. The sentence is revised .
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Comment # 19

Figure 3 (page 8): In the presented images no clear jets are observed. What the authors call bright 'nods' are the brightenings observed when the closed loop system moves. Usually, jets are observed propagating along the open filed lines, and I see nothing like this in the presented figure. And in particular, that should be the case when jets are associated with type III radio bursts – signatures of fast electron beam propagating along open field lines. We can observe open field lines in the figure but none of them shows brightening indicating jet propagation.

Response:

The aim of Figure 3 is to show the potential site where non-flare type III radio bursts are believed to originate. We have looked at the Sun and taken portions of the Sun containing the region of interest. We will increase the size of the images but we expected that the expanded edge corresponds to a jet. Hence if it shows the region of open magnetic field lines, that is the path of electron beams emitting type III radio bursts.

Comment # 20

Page 5, line 102-103: This sentence has no sense. Where the authors see propagating waves?

Response:
We thank the referee. we have removed the sentence.

Comment # 21

Page 5, line 104-105: This sentence is not justified. In order to associate type III bursts with CME at least the source positions of type III bursts need to be checked and compared with the source region of CMEs. The authors should study literature a bit better. Namely, numerous type III bursts can appear during the so called type III storms that can last for days. And, it is generally considered that they are associated with the complex active regions observed on the visible side of the solar disc.

Response:

We thank the referee. We used the CME catalog and images at https://helioviewer.org to confirm the association between type III bursts and CMEs. Since we did not check their source position, we have dropped the statement.

Comment # 22

Page 5, line 113: What does this sentence mean?

Response: We thank the referee. The sentence was removed as it has no meaning.

Comment # 23

Page 5, line 114: What is 'backbone of the CME-driven shocks' ? Why the authors think type IV bursts are 'poorly associated with flares? This statement needs to be justified and references provided.

Response:

It is well established that type IV bursts are generated by energetic electrons trapped in a magnetic structure, e.g. an erupting flux rope in the framework of a CME.
Type IV radio bursts are classified into two categories: Stationary type IV bursts and moving type IV bursts. Stationary type IVs prevail over the presence of non-thermal electrons in the solar corona for several hours in relationship with flare and the liftoff of a CME. Moving type IV radio bursts are believed to originate due to synchrotron or gyro-synchrotron emitting electrons, gyrating inside helical magnetic fields within the CME flux rope.
Thus, it is erroneous to conclude that type IV bursts originate from the backbone of the CME-driven shocks and that they are poorly associated with solar flares.
Therefore, the statement is rephrased and modified as: ***Table 3 lists all type IV radio bursts observed by the network and their association with the solar phenomena. From this table, it can be seen that type IV bursts are highly associated with CMEs which indicates that their presence can be used to map the location of trapped electrons and studying the CME kinematics during the phases of eruption processes (Kumari et al., 2021).***

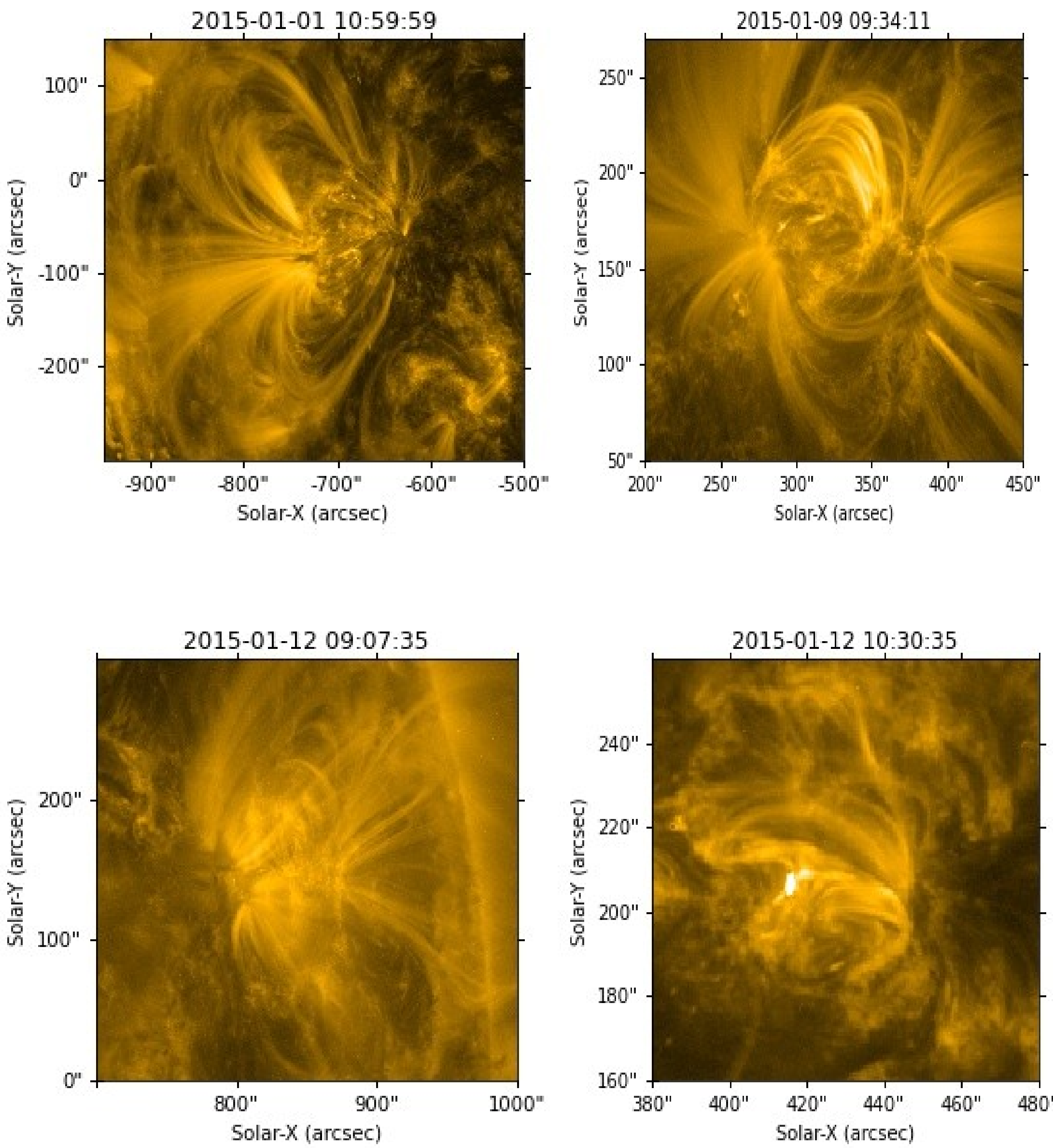
N.B: Table 2 will be removed (Referee # 1)

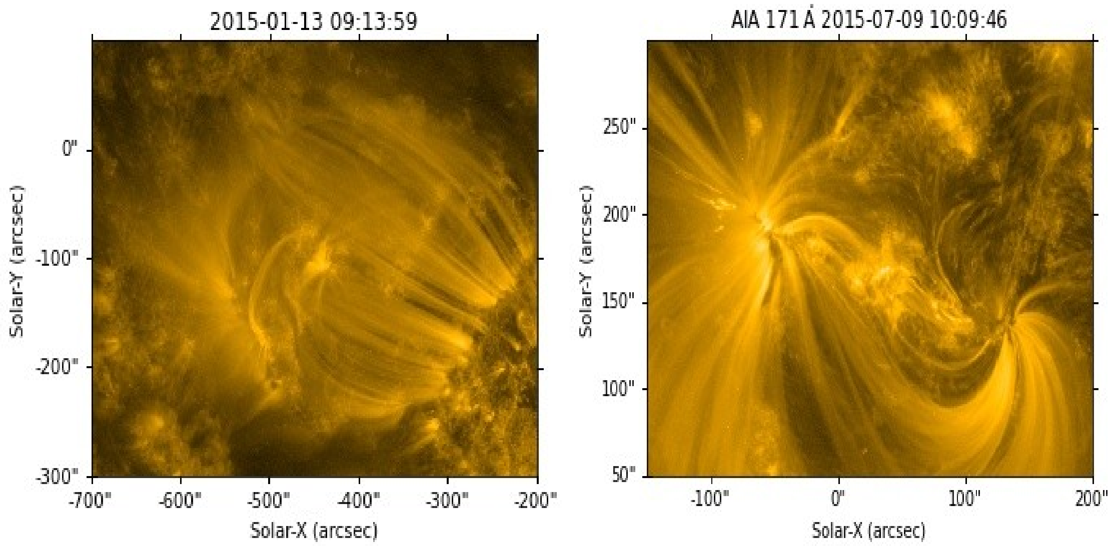
Comment # 24

Page 6, line 117 – 118: Figure 6 does not show any type IV radio bursts, but it shows somehow distorted images of CMEs in the SOHO/LASCO C2 filed of view. The running difference images of SDO, 171 A are also very bad. It is not completely clear where is the solar limb and the Sun seems distorted.

Response:
Like for other radio bursts, the association of type IV bursts with CMEs were carried out using the catalog from http://hec.helio-vo.eu/hec/hec_gui.php
From this source, the catalog comprised SOHO/LASCO and STEREO A/B. But for some cases we used https://helioviewer.org (currently not opening) to see whether there was a CME.
Figure 6 aims to show the images of CMEs and their corresponding potential site on the solar surface for the dates where non-flare associated type IV radio bursts were detected. The figure does not indicate any type IV radio burst at all.

We now modify the figure as per attached below with the aim of showing the magnetic loops embedded in the solar corona where we expect to be the site of trapped electrons responsible for Type IV emissions. The figure will display a sample of six AIA/SDO images in 171 Å band filter corresponding to the dates of type IV radio bursts in the January 2015.





Comment # 25

Page 6, line 118-119: How is this visible?

Response:
The initial statement is: ***The first two type IV bursts are accompanied by CMEs followed by another two without CMEs and then two type IV with CMEs.***
We have dropped the statement as an effect of Figure 6 reformulation.

Comment # 26
Page 6, line 122-124: The authors first state the some type IV radio burst may be not associated with flares and CMEs. And in the following sentence they state that this kind of type IV bursts coincide with the decaying phase of flares or post eruption loops. These two sentences are in contradiction.

Response:
Page 6, lines 122 - 124 are modified as follows:

It is trustworthy that 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) but they may lack both association with flares and CME eruptions (Table 3).

Comment # 27

Page 6, line 124: This is very general sentence, not related at all to presented study. It cannot be considered as conclusion.

Response:

We thank the referee for this comment. The statement is dropped.

Comment #28

Page 7, line: By e-CALLISTO we can be continuously monitor radio emission and not Space Weather.

Response:

We thank the referee. The statement is corrected.

Comment # 29

Page 9, line 141: Which radio bursts may be used as a precursor for space weather diagnostics? And how? The authors did not really provide convincing evidence, actually any evidence how we can use radio observations for space weather diagnostics.

Response:

The line and the paragraph is modified as follows:

Observed radio bursts (type II, III and type IV) may be used as a precursor for space weather diagnostics since they are often associated with space weather drivers such as CMEs and SFs. Solar radio bursts can be detected at the ground level, hence serving as the advance warning of incoming associated solar transient events. Therefore, they provide insights to predict/forecast the incoming space weather hazards. HF communications and the ionosphere are disturbed by the X-ray and EUV wavelengths along with the solar energetic particles that reach Earth whinin few hours and they are signatures of solar flares and CMEs.