nature portfolio

Peer Review File

Imaging spectroscopy reveals spike-like repeating radio burst pairs in the solar corona

Corresponding Author: Dr Suli Ma

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The study presented in this manuscript is of interest with the authors reporting a new type of short radio burst observed at 30-50 MHz. Below I present some comments regarding the manuscript.

1. Panels (g-h) Figure 4, show a different behavior compared to the rest of the panels in the same figure. The peak flux distribution of the earlier and delay components tends to decrease when the bursts are of greater intensity. It would be interesting to know if there is a relation between the peak flux and the frequency.

2. Most of the drift rate (df/dt) of the primary and secondary components tend to have negative values. Nevertheless, the positive drift rate suggests that part of an electron beam distribution responsible of the early burst chain generates turbulent medium which propagates inwards to the low corona where a reflection of the burst occur. The lower value of the positive drift rates in comparison with the negative ones, could explain the reason why the peak flux of the delayed component is weaker, since the time for the energy release would be greater.

3. In this work simulations of fundamental and harmonic point sources injected with different anisotropy factor between 0.1-0.3 are presented. If the simulation takes into account coulomb effects it would be worthwhile to provide information about the ambient density values handled in the simulations. If an electron beam interacts with nonhomogeneous structures, the weaker intensity of the delayed component might also be related to a low interaction of accelerated electrons within a region with a lower density.

4. The idea of the sentence between lines 687-688 is incomplete: "The peak time and the FWHM for each burst, as exemplified in Figure 2c."

Reviewer #2

(Remarks to the Author)
Note: Please see attached PDF for better formatted report.

Review for "First Observation and Interpretation of Spike-like Repeating Burst Pairs" – Suli Ma et al. - NCOMMS-25-20309

The authors present novel observations of a new type of solar radio burst associated with a flaring active region observed by the Low Frequency Array (LOFAR) which they term "Spike-like repeating burst pairs". The authors present in detail a single event and statistics of hundreds of events observed across a 1h40 observation period during which GOES X-ray levels indicate a C-class flare occurs. Lastly, they perform turbulent radio scattering simulations and provide a convincing explanation and model that explains these repeating pairs are short lived coronal emission at the 2nd harmonic of the local plasma frequency where the burst pair is understood as the outwards directed emission measured first, with a reflection/echo of the burst arriving second.

The work is very well presented, the radio observations are clear and clearly presented and the simulation to explain them is

plausible, appropriate and convincing. I do not have concerns about the methodology, data analysis or statistics which all appear sound to me. Given the LOFAR observations, I believe their event and statistical results could be reproduced. Reproduction of their turbulence simulation results would require some more detail on the specific simulation set-up – but I think there is sufficiently cited prior literature on these simulations that this only requires minor changes.

However, in evaluating the works significance to the field and related fields, I feel there is an element missing that places it in a wider context: Specifically, the introduction does not convincingly motivate why it is of note or importance to have discovered these bursts besides being of taxonomic interest in the zoo of coronal radio emissions, and no clear conclusions of new insight or future lines of inquiry are drawn. The paper ends with a very brief discussion section which mostly just restates the results

As far as I am aware, the basic physics of direct harmonic emission and delayed emission via reflection at a lower height is already well understood in other radio burst contexts, and the turbulence parameters/model to explain the bursts here appear to use established parameters rather than being used to learn about the physics of the corona.

Additionally, given these bursts are from one 1h40 interval of time and clearly associated with an AR, and in particular a C-class flare, it is unclear if they occur in other circumstances – are they always associated with ARs or e.g. jets from coronal holes or other sources.

I would therefore ask the co-authors to consider this. Please:
- In the introduction present some motivation as to why a general Nature communications reader would be interested in coronal radio emission in general, and these repeating bursts in particular.
- Relate their inferred physical parameters and the success of their model to a conclusion – what solar and/or plasma physics has been learned or what lines of investigation would be possible next? Reflecting this takeaway(s) would also be appropriate to add as a last sentence in the abstract.

In both cases, this amounts to a request to expand and contextualize based on the abstract statement “Solar radio bursts … provide unique insights into the physical processes in the solar corona”.
If compelling context and takeaways can be provided I would be happy to review a revision and assess if these conclusions are supported by the discovery and characterization of these bursts.
As well as this top level concern, I have a number of minor comments aimed at improving the clarity and interpretation of the work. Where these relate to or provide suggestions for the physical contextualization requested above, I have *** wrapped the comments in asterisks ***

Title
The title should specify the solar corona / plasma radio emission context of the bursts. The term “burst” could relate to a very wide range of physical contexts. Is “Solar-flare associated” appropriate?
Abstract
***As mentioned above, a wrap up sentence of what the detection and interpretation of these bursts amounts to physically would be welcome. ***

Intro
061 – A reference for plasma emission process would be useful.
065 – Please define type iii for general reader – the result of electron beams injected on open field lines, and provide references
067 – Please define drift rates – I’d suggest stepping back and explaining that most radio bursts move outwards from the Sun from high to low density, and therefore from high to low plasma frequency, and that therefore their emission frequency tends to change or drift with time. This would also be helpful to explain the type III nomenclature (that it implies a certain range of drift rates different to other types of radio burst).
070 – Please define spike – a sharp, short-lived increase in flux perhaps? What does short-lived mean?
086 – it’s a little confusing to have lower case n represent both refractive index and plasma density, perhaps you could use capital N_e for plasma density?
086 – f (frequency of emission I assume?) needs to be defined.
106 – Please specify that “individual” vs “chains” refers to similarly timed events at different frequencies

Observations and Results
115- Were the observations taken specifically to target this AR? Were they part of a routine survey? Are they selected from a broader range of time just to focus on one C-class flare? (and if so, ***do the repeating burst pairs only occur during the flare time?***)
116 – For a general reader – what physical regime/location does fpe 30 -70 correspond to? (Low-mid corona right?)
123 – Please provide the latitude of the AR and explain how you determine association? Imaging results, that the AR is the only major active source, something else?
123 - What is “the event”? A single flare? All the radio activity of the sun observed by LOFAR from 10:10-11:50? (in which case, maybe “the observations are associated with”)?

Suggested edit : “The repeating bursts are observed during a C-class flare associated with active region AR…”

127 – Recommend also citing Altschuler & Newkirk (https://ui.adsabs.harvard.edu/abs/1969SoPh....9..131A/abstract)

Fig 1
– The brown lines and bounding boxes in all panels are too thin and faint, please make them stand out more. Also red and brown are indistinguishable (at least speaking as a colorblind person).
- Suggest including an SFU colorbar
*** GOES curve – see suggestion for line 570 – you could get a very high time resolution EUV flux above the AR which you could also overlay here to strengthen the connection between the bursts and jetting.***

Repeating burst pairs and the active region
132 – Specify radio flux observed by LOFAR
132 – I recommend noting here that the y-axis on all dynamic spectra here are presented with frequency from high to low, and that correspondingly a higher y value implies higher altitude. I know this is normal for the coronal radio community, but it is the opposite for space-based/solar wind radio folks and its worth calling it out for shared intuition.
134 – "T" missing in Type
136 – Again, please explain that chains means simultaneous bursts at different frequencies. Please comment of whether these frequencies are typically harmonically related.
139 – The statement that a separation of a few seconds implies they are closely related is not obvious to general reader, is it small compared to typical waiting times between unrelated radio bursts? Is it consistent between spike pairs? Does it compare to some expected echo timescale on coronal length scales? (I think the stronger evidence that they are closely related is that they reoccur at the same frequency).

Detection and Measurement of Repeating Burst Pairs

Fig 2
(Panel A)
Suggest including an SFU colorbar.
(Panel C)
- As a colorblind person, brown and red curves are indistinguishable, please choose alternate colors (recommend brown → black), and make lines thicker (would also be useful to make lines in panels b and d thicker.
- The zoom-in panel is confusing as it appears contiguous with the zoomed out data, I'd recommend making it a little smaller, and shifted up from the zoomed out data, and put a box around the zoomed out portion the zoomed in box corresponds to and link the corners.
- The dashed magenta and turquoise lines are also too faint to distinguish the colors of.
(Caption)
- Panels c-h of which figure?
- HWHM and FWHM are acronyms used for the first time in the paper in this caption so should be spelled out.
- Which burst in the chain in panel (a) is shown in panels (c) and (d)? Recommend labeling the three bursts I,II, III in panel (a) and use this to refer to them (also line 229)
- What range of time are the curves in panel (b) integrated over? Recommend annotating this in panel (a)

185 – Is the example shown what you call a chain?
189 – How is burst central frequency defined? The peak frequency after integrating the burst in time or the peak frequency extracted as a certain single time?
253 – Please compare/contrast these drift rates to other typical radio burst drift rates
253 – Remind the reader this likely indicates the source of the bursts are moving away from the Sun, but slowly compared to other types of radio bursts

Fig 3a,b – Recommend column normalizing the dynamic spectra by the Gaussian fit to each column to pull out the trend in peak flux that is being fit to.

275 – "farthest"

Statistics of Time, Frequency and Peak Flux Measurements

Fig 3D – The red and green contours are too faint in print to make out, please make the lines thicker

317 – Please clarify that all 1000 bursts are identified from the single observation shown in figure 1.

Fig 4b – The yellow text is hard to read in print, perhaps place in dark text-box
Fig 4c – since all instances where tD is shorter than tE would be crammed below 1 on this plot, it would be useful to plot this on a logarithmic x-axis to emphasize that the ratio is really mostly >= 1
Fig4 d/e – it would be useful to make the x-axis have the same range for both these panels

381 – You say <12kHz would not be discernible, but report a difference in peak frequency of 10 kHz which seems to be a contradiction. Perhaps it would be better to say, "however this 10kHz difference is comparable to the LOFAR spectral resolution and therefore these values could be consistent".
392 – What is the standard error on the drift rate fits? How does it compare to this range of variation?
398/fig4 l – For the drift rates, a scatter plot of df/dt_delayed vs df/dt_early would be more informative than the ratio (and better support the authors assertion that they share a sign).

404 – For reproducibility, please provide a reference and/or link for the software used to generate the PFSS model, and specify the magnetogram and source surface height used for boundary conditions.

Fig 5
– *** It would be interesting to highlight a few bursts from the same chain – do you see these align along the radial direction? ***
– *** Have you tried to colorize according to drift rate? It'd be interesting to know if the ones with drift rate closest to zero are aligned with where you might expect the apex of the closed loops to be. (If promising, this could be a novel takeaway for the paper too). ***
- Some quantitative tick marks attached to at least one of the color bars would be helpful
Panel (C) – the yellow joining lines are very hard to see in print, please experiment with making them clearer
(Panels C/D) – I recommend using the standard AIA 171 color table for the background image, on the greyscale in print it is hard to discern coronal features.

459 – "depart" → "displacement"
484 – It would make sense to start a new section to discuss the simulations
484 – Anisotropy in what physical quantity?
484-488 – A reference to figure 6 seems appropriate somewhere here
487 – Is this a spherically symmetric simulation? How does the mean density behave with height? Is alpha constant with height? ***How sensitive are the results and consistency with observations to these parameters? Can you learn anything about the turbulent corona from evaluating this? ***

*** 570 – I find this connection about observed EUV/jetting activity being tied to these events plausible and it appears to me very straightforward to test and support this statement. I strongly recommend the authors produce a supplemental movie of a cutout of the AIA data from e.g. http://jsoc.stanford.edu/ajax/lookdata.html or https://www.lmsal.com/get_aia_data/ at the max cadence (I think 10s – the second link actually permits the cutout to be set to move with the image), and also to plot a timeseries of the sum of pixel intensities from the cutout and mark a vertical bar every time one of their burst events occurs. I think tying the authors observations to another physical observable would make the connection to other studies much stronger. ***

The distribution of centroid frequencies would be useful to report, and for the authors to comment on what range of apparent heliocentric distances/alittude above the AR this corresponds to

Discussion

*** 577 – Please specify the solar active region and C-class flare context of these results – observed above a solar active region at coronal radio frequencies, 1000s are seen in a 1h50 period ***
582 – it makes intuitive sense to me that the source being spread over a large area corresponds to a dilution of the frequency drift rate
587 – "Reminiscent" is a little vague, can you quantify? Are all the relevant quantities the same order of magnitude? Within a factor of 2? within 10%? Do they occur at the same frequency range?
638 – "The radio emission initially directed downwards reflects..."
*** 641 – can you make some inference about the scale height of the density fall off form this information? ***
*** 634 – Why does all the emission appear to occur a signficant height above the AR? Is there some timescale needed for the langmuir waves to form and/or couple to EM emission? Can you gain some physical insight from this? ***

*** As mentioned at the top-level of this review The manuscript ends quite abruptly in the discussion – a wrap up/summary with important takeaways for the reader Is needed – what have we gained by identifying these bursts associated with flaring solar Active regions and identifying a plausible mechanism that explains them? Why should a general nature comms reader care about the discovery? (A similar motivation statement is needed in the introduction in my opinion.) ***

End material – Please add links to the data sources used in this work (LOFAR, AIA, HMI,, PFSS software, PFSS magnetogram)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
After conducting a second review of the manuscript entitled "First Observation and Interpretation of Solar Radio Spike Repeating Burst Pairs" and verifying that my previous concerns have been adequately addressed in the revised version, I confirm the relevance of the work and its contribution to the study of short solar radio bursts. In this revision, the authors clarify the physical implications of their findings and provide additional details on the methodology used for data analysis. The methodology is robust and appropriate for the type of research conducted in this study.

The study provides insight into how coronal turbulence may affect the observed radio signals in the solar corona. In particular, anisotropic scattering may cause radio waves to propagate preferentially along the magnetic field, leading to the

generation of spike repeating burst pairs with delayed faint components that typically exhibit reduced drift rates.

As a minor suggestion, the authors may consider briefly describing the possible types of turbulence that could lead to the anisotropic scattering involved in the proposed physical scenario.

There appears to be a typographical error in the caption of Figure 4: an exponent “9” appears after “(g–h)”.

A comma appears to be missing after the phrase “…the mean of the Gaussian sector of the function” in line 932.

In the caption of Figure 2 (line 264), the word “dotted” in the phrase “The magenta and turquoise dotted horizontal lines denote …” appears to be incorrect, since the magenta and turquoise horizontal lines are not dotted.

Reviewer #2

(Remarks to the Author)
Review for "First Observation and Interpretation of Solar Radio Spike Repeating Burst Pairs” – Suli Ma et al. - NCOMMS-25-20309A

Thank you to the authors for their careful attention to my prior comments and the significant changes to their manuscript.

I consider my major comment (the wider context and meaning of the authors results) to be greatly strengthened and better discussed throughout the manuscript, and the edits stemming from my minor comments are all satisfactory. I attach a last few minor comments that are mostly minor presentation suggestions and a couple of discussion points based on the new content the authors added. I’d in particular draw attention to my last comment which encourages the authors to emphasize the physical insight their model and observations together provide.

Minor Comments

084 – “of the first burst formed by…”
088 – I think I understand the authors intention but I don’t think its phrased quite right. I think they mean the refractive index “can be <<1 in the vicinity of the emission site.”
103-106 – The point about radar reflection is a valuable point of context, I would suggest specifying that you are discussing radar signals launched from Earth, and mention the frequency range.
127 – the observing program/project names could probably be a footnote (if Ncomms formatting allows that).
134 – suggest specifying the new radio bursts are observed to be co-spatial, or above” the AR discussed here (otherwise the sentence could be describing two unrelated things).
145 – “along with the GOES soft X-ray flux and AIA 171 flux.” (“overlaid” implies in the same panel, and should mention the aia flux. Please also explain if the AIA flux is summed over full AIA images, or from a sub-region/cutout of the AR.
151 – “An intriguing feature…: sounds like the feature could be incidental to the work, I suggest being clear that they are the central phenomenon that will be studied.
162/163 – since subscripts “E” and “D” are used a lot later on, it would be useful to place these in parentheses following the introduction of the terms “earlier” and “delayed”.

Fig 1 – The future in (b) labeled as III and in (c) labeled as spike are very hard to see (especially in print). I suggest the authors try to saturate the darker end of their color-map a little more.
Fig 1 caption – same comment on the AIA flux as line 145, please specify “AIA 171A” and whether it is a full disk summed flux or a sub-region/cutout
Fig 1 ordering of panels – very, very minor but I would swap the (j,k,l) and (m,n) rows so that they are presented in the order in which they are discussed in the text.

331 – since quantitative drift rates are given for drift pairs and type IIIs in this sentence, it would be nice to quote a typical reported drift rate for spikes from [18]/

464 – given this 1 sfu error, does it make sense have histogram bin widths < 1sfu in fig 4h?

471-472 – to my eyes, the delayed component also shows a weak (weaker than the earlier component for sure) increasing trend also. It at least appears clearly that the lower bound of the peak delayed fluxes is increasing with frequency. Perhaps the authors can do a quick linear regression to both these plots and determine if the slope is consistent or inconsistent with zero in both cases.

491 = Perhaps “apparent spatial distribution” to convey that the actual original photons were likely produced co-spatially but just took different paths to the observer.

Fig 4f – if the AIA flux shown in fig 1 is from a cutout of the AR, it would be useful to include a box showing that cutout here.

681 – cite [18] again for “solar radio spike”

781 – the “cospatial” statement should point the reader to fig 9 (it hasn’t been introduced before then).

867 – “...spectral bandwidths and central frequencies...”

884 – I think the conclusions of the simulation could be emphasized even more – highlighting that it is often ambiguous about whether plasma emission is at the fundamental or harmonic and in this case they have strong evidence it is harmonic, they provide strong support to previous work suggesting a density fluctuation anisotropy factor of 0.1-0.2, and their reflection time delay gives a measurement of density scale height. I would encourage the authors to emphasize all these point which are all very useful physical insights into the plasma emission and environment where these bursts occur.

Response to Referees:

First Observation and Interpretation of Spike-like Repeating Burst Pairs

Ma,S., Kontar E., Clarkson, D., Chen, H. and Yan, Y.

March 2, 2026

Manuscript ID: NCOMMS-25-20309
Title: First Observation and Interpretation of Spike-like Repeating Burst Pairs
Authors: Ma,S., Kontar E., Clarkson, D., Chen, H. and Yan, Y.

Response to Reviewer 1

We thank Reviewer 1 for their positive assessment and valuable suggestions. Below we address each comment.

The study presented in this manuscript is of interest with the authors reporting a new type of short radio burst observed at 30-50 MHz. Below I present some comments regarding the manuscript.

1. Panels (g-h) Figure 4, show a different behavior compared to the rest of the panels in the same figure. The peak flux distribution of the earlier and delay components tends to decrease when the bursts are of greater intensity. It would be interesting to know if there is a relation between the peak flux and the frequency.

   Re: As suggested, we have added Figure 4m,n to show the peak flux vs peak frequency of the earlier and delayed components, along with a corresponding description in the text.

2. Most of the drift rate (df/dt) of the primary and secondary components tend to have negative values. Nevertheless, the positive drift rate suggests that part of an electron beam distribution responsible of the early burst chain generates turbulent medium which propagates inwards to the low corona where a reflection of the burst occur. The lower value of the positive drift rates in comparison with the negative ones, could explain the reason why the peak flux of the delayed component is weaker, since the time for the energy release would be greater.

   Re: We thank the referee for the valuable comments. Relevant discussion has now been incorporated into the revised manuscript.

3. In this work simulations of fundamental and harmonic point sources injected with different anisotropy factor between 0.1-0.3 are presented. If the simulation takes into account coulomb effects it would

be worthwhile to provide information about the ambient density values handled in the simulations. If an electron beam interacts with nonhomogeneous structures, the weaker intensity of the delayed component might also be related to a low interaction of accelerated electrons within a region with a lower density.

Re: Yes, the simulations do take into account free-free absorption consistently; we added some details and reference to the code by Kontar et al for further details.

4. The idea of the sentence between lines 687-688 is incomplete: "The peak time and the FWHM for each burst, as exemplified in Figure 2c."

   Re: Correction has been made to make it complete.

Response to Reviewer 2

We appreciate Reviewer 2's thorough review and constructive criticism. We have addressed all concerns as detailed below.

"The authors present novel observations of a new type of solar radio burst associated with a flaring active region observed by the Low Frequency Array (LOFAR) which they term "Spike-like repeating burst pairs". The authors present in detail a single event and statistics of hundreds of events observed across a 1h40 observation period during which GOES X-ray levels indicate a C-class flare occurs. Lastly, they perform turbulent radio scattering simulations and provide a convincing explanation and model that explains these repeating pairs are short lived coronal emission at the 2nd harmonic of the local plasma frequency where the burst pair is understood as the outwards directed emission measured first, with a reflection/echo of the burst arriving second."

"The work is very well presented, the radio observations are clear and clearly presented and the simulation to explain them is plausible, appropriate and convincing. I do not have concerns about the methodology, data analysis or statistics which all appear sound to me. Given the LOFAR observations, I believe their event and statistical results could be reproduced. Reproduction of their turbulence simulation results would require some more detail on the specific simulation set-up – but I think there is sufficiently cited prior literature on these simulations that this only requires minor changes."

Re: We have added the additional details on the simulation set-up, so our results are reproducable.

"However, in evaluating the works significance to the field and related fields, I feel there is an element missing that places it in a wider context: Specifically, the introduction does not convincingly motivate why it is of note or importance to have discovered these bursts besides being of taxonomic interest in the zoo of coronal radio emissions, and no clear conclusions of new insight or future lines of inquiry are drawn. The paper ends with a very brief discussion section which mostly just restates the results"

"As far as I am aware, the basic physics of direct harmonic emission and delayed emission via reflection at a lower height is already well understood in other radio burst contexts, and the turbulence parameters/model to explain the bursts here appear to use established parameters rather than being used to learn about the physics of the corona."

Re: The reflection of radio signal by the Sun is an unsolved puzzle after over 50 years of active research, The paper [**?**] summarises numerous unsuccessful attempts. Unlike planetary reflections, the Sun proved to be a challenge for the radar experiments; the echo is much weaker than expected. The ob-

servation of the natural echo (scattered harmonic emission) provides insights as how and where the radio signal is reflected, suggesting anisotropic scattering weakening the radar signal; potentially opening a new avenue for new radio wave scattering experiments.

"Additionally, given these bursts are from one 1h40 interval of time and clearly associated with an AR, and in particular a C-class flare, it is unclear if they occur in other circumstances – are they always associated with ARs or e.g. jets from coronal holes or other sources."

Re: An animation has been added assoicated with Figure 6 in the latest revision. It depicts the evolution of the active region observed by AIA and the centroids of the repeating pairs at times when imaging is possible. Further evidence supports that these bursts are predominantly associated with the left part of AR12665.

I would therefore ask the co-authors to consider this. Please:

- — In the introduction present some motivation as to why a general Nature communications reader would be interested in coronal radio emission in general, and these repeating bursts in particular.

  Re: We have presented some motivation in the revision.

- — Relate their inferred physical parameters and the success of their model to a conclusion — what solar and/or plasma physics has been learned or what lines of investigation would be possible next? Reflecting this takeaway(s) would also be appropriate to add as a last sentence in the abstract.

  Re: We have added a last sentence in the abstract according to the referee's suggestion.

In both cases, this amounts to a request to expand and contextualize based on the abstract statement **"Solar radio bursts . . . provide unique insights into the physical processes in the solar corona".**

"If compelling context and takeaways can be provided I would be happy to review a revision and assess if these conclusions are supported by the discovery and characterization of these bursts."

"As well as this top level concern, I have a number of minor comments aimed at improving the clarity and interpretation of the work. Where these relate to or provide suggestions for the physical contextualization requested above, I have *** wrapped the comments in asterisks ***"

- **Title**

- ***The title should specify the solar corona/plasma radio emission context of the bursts. The term "burst" could relate to a very wide range of physical contexts. Is "Solar-flare associated" appropriate?***

  Re: We have updated to "First Observation and Interpretation of Solar Radio Spike Repeating Burst Pairs"

- **Abstract**

  ***As mentioned above, a wrap up sentence of what the detection and interpretation of these bursts amounts to physically would be welcome. ***

  Re: A wrap up sentence has been added.

- **Intro**

1. **061** "A reference for plasma emission process would be useful."

   Re: A reference has been added.

2. **065** – Please define type iii for general reader – the result of electron beams injected on open field lines, and provide references

   Re: Corresponding contents have been added in the revision.

3. **067** – Please define drift rates – I'd suggest stepping back and explaining that most radio bursts move outwards from the Sun from high to low density, and therefore from high to low plasma frequency, and that therefore their emission frequency tends to change or drift with time. This would also be helpful to explain the type III nomenclature (that it implies a certain range of drift rates different to other types of radio burst).

   Re: Corresponding contents have been added in the revision.

4. **070** – Please define spike – a sharp, short-lived increase in flux perhaps? What does short-lived mean?

   Re: Definition of spike have been added in revision.

5. **086** – it's a little confusing to have lower case n represent both refractive index and plasma density, perhaps you could use capital N_e for plasma density?

   Re: We accepted the referee's suggestion and use N_e for plasma density in revision.

6. **086** – f (frequency of emission I assume?) needs to be defined.

   Re: f is defined.

7. **106** – Please specify that "individual" vs "chains" refers to similarly timed events at different frequencies

   Re: We have changed "individual" into "isolated", and we also added the description that the chains are along frequency at the similarly timed spikes.

- **Observations and Results**

1. **115** - Were the observations taken specifically to target this AR? Were they part of a routine survey? Are they selected from a broader range of time just to focus on one C-class flare?

   Re: Context of the LOFAR observing project is included (approx. 2hr periods near noon over several days). The bursts were identified in the data, but not targeted for specific observation.

   (and if so, ***do the repeating burst pairs only occur during the flare time?***)

   Re: We only have the two hour window of LOFAR data, so we can not say if they occur outside this particular flare.

2. **116** – For a general reader – what physical regime/location does fpe 30 -70 correspond to? (Low-mid corona right?)

   Re: Included the context of the mid-corona.

3. **123** – Please provide the latitude of the AR and explain how you determine association? Imaging results, that the AR is the only majoractive source, something else?

   Re: It is imaging result and the AR is the only major active source.

4. **123** - What is "the event"? A single flare? All the radio activity of the sun observed by LOFAR from 10:10-11:50? (in which case, maybe "the observations are associated with")? Suggested edit : "The repeating bursts are observed during a C-class flare associated with active region AR..."

   Re: This part is rewrite according the referee's suggestion.

5. **127** – Recommend also citing Altschuler & Newkirk (https://ui.adsabs.harvard.edu/abs/1969SoPh....9..131A/a

   Re: The paper has been cited.

6. **Fig 1** – The brown lines and bounding boxes in all panels are too thin and faint, please make them stand out more. Also red and brown are indistinguishable (at least speaking as a color-blind person). - Suggest including an SFU colorbar

   Re: The color table has been changed and the SFU colorbar is included in revision.

   GOES curve – see suggestion for line 570 – you could get a very high time resolution EUV flux above the AR which you could also overlay here to strengthen the connection between the bursts and jetting.

   Re: The EUV flux above the AR has been overlaid on Figure 1.

- **Repeating burst pairs and the active region**

1. **132** – Specify radio flux observed by LOFAR

   Re: It has been corrected.

2. **132** – I recommend noting here that the y-axis on all dynamic spectra here are presented with frequency from high to low, and that correspondingly a higher y value implies higher altitude. I know this is normal for the coronal radio community, but it is the opposite for space-based/solar wind radio folks and its worth calling it out for shared intuition.

   Re: We added an explanation in the revision.

3. **134** – "T" missing in Type

   Re: This has been corrected.

4. **136** – Again, please explain that chains means simultaneous bursts at different frequencies. Please comment of whether these frequencies are typically harmonically related.

   Re: Relevant information has been added in revision.

5. **139** – The statement that a separation of a few seconds implies they are closely related is not obvious to general reader, is it small compared to typical waiting times between unrelated radio bursts? Is it consistent between spike pairs? Does it compare to some expected echo timescale on coronal length scales? (I think the stronger evidence that they are closely related is that they reoccur at the same frequency).

   Re: This part has been modified by considering the question and suggestion by the referee.

- **Detection and Measurement of Repeating Burst Pairs**

1. **Fig 2** (Panel A) Suggest including an SFU colorbar. (Panel C) - As a colorblind person, brown and red curves are indistinguishable, please choose alternate colors (recommend

brown → black), and make lines thicker (would also be useful to make lines in panels b and d thicker. - The zoom-in panel is confusing as it appears contiguous with the zoomed out data, I'd recommend making it a little smaller, and shifted up from the zoomed out data, and put a box around the zoomed out portion the zoomed in box corresponds to and link the corners. - The dashed magenta and turquoise lines are also too faint to distinguish the colors of. (Caption) - Panels c-h of which figure? - Panels c-h of which figure?- HWHM and FWHM are acronyms used for the first time in the paper in this caption so should be spelled out. - Which burst in the chain in panel (a) is shown in panels (c) and (d)? Recommend labeling the three bursts I,II, III in panel (a) and use this to refer to them (also line 229) - What range of time are the curves in panel (b) integrated over? Recommend annotating this in panel (a)

Re: All relevant contents have been revised.

2. **185** – Is the example shown what you call a chain?

   Re: Yes, but it is only part of it, we have added explain in the revision.

3. **189** – How is burst central frequency defined? The peak frequency after integrating the burst in time or the peak frequency extracted as a certain single time?

   Re: Here the central frequency should be integrating central frequency. We clarify this in revision.

4. **253** – Please compare/contrast these drift rates to other typical radio burst drift rates

   Re: Relevant contents have been added.

5. **253** – Remind the reader this likely indicates the source of the bursts are moving away from the Sun, but slowly compared to other types of radio bursts

   Re: Have been added.

6. **Fig 3a,b** – Recommend column normalizing the dynamic spectra by the Gaussian fit to each column to pull out the trend in peak flux that is being fit to.

   Re: Have been done.

7. **275** – "farthest"

   Re: Have been corrected.

- **Statistics of Time, Frequency and Peak Flux Measurements**

1. **Fig 3D** – The red and green contours are too faint in print to make out, please make the lines thicker

   Re: The lines have become thicker now.

2. **317** – Please clarify that all 1000 bursts are identified from the single observation shown in figure 1.

   Re: The relevant content has been added.

3. **Fig 4b** – The yellow text is hard to read in print, perhaps place in dark text-box

   Re: The yellow has been changed into black in revision.

4. **Fig 4c** – since all instances where t_D is shorter than t_E would be crammed below 1 on this plot, it would be useful to plot this on a logarithmic x-axis to emphasize that the ratio is really mostly $>= 1$

   Re: We have tried a logarithmic x-axis, but the display shows extreme spread in low values near zero. Instead, we inverted the ratio from t_D/t_E to t_E/t_D. This also confines all sample values to a range below 1.

5. **Fig4 d/e** – it would be useful to make the x-axis have the same range for both these panels.

   Re: Now they have the same range.

6. **381** – You say $< 12kHz$ would not be discernible, but report a difference in peak frequency of 10 kHz which seems to be a contradiction. Perhaps it would be better to say, "however this 10kHz difference is comparable to the LOFAR spectral resolution and therefore these values could be consistent".

   Re: The relevant content has been corrected.

7. **392** – What is the standard error on the drift rate fits? How does it compare to this range of variation?

   Re: Relevant contents have been added in revision.

8. **398/fig4 l** – For the drift rates, a scatter plot of $df/dt_{delayed}$ vs df/dt_{early} would be more informative than the ratio (and better support the authors assertion that they share a sign).

   Re: The ratio panel has been replaced by a scatter plot.

9. **404** – For reproducibility, please provide a reference and/or link for the software used to generate the PFSS model, and specify the magnetogram and source surface height used for boundary conditions.

   Re: The relevant content has been added.

10. **Fig 5**

    – *** It would be interesting to highlight a few bursts from the same chain – do you see these align along the radial direction? ***

    Re: A few bursts from the same chain are placed in Figure 5d. The earlier bursts are closely spaced and likely aligned along a trajectory, in contrast to the subsequent bursts, which are merely closely spaced.

    – *** Have you tried to colorize according to drift rate? It'd be interesting to know if the ones with drift rates closest to zero are aligned with where you might expect the apex of the closed loops to be. (If promising, this could be a novel takeaway for the paper too). ***

    Re: Following the referee's suggestion, we have included the drift rate of the earlier burst centroids in Figure 5e.

11. - Some quantitative tick marks attached to at least one of the color bars would be helpful

    Re: Minor ticks have been added as suggested.

12. Panel (C) – the yellow joining lines are very hard to see in print, please experiment with making them clearer

    Re: We have updated the yellow joining lines to a sky-blue color.

13. (Panels C/D) – I recommend using the standard AIA 171 color table for the background image, on the greyscale in print it is hard to discern coronal features.

    Re: In response to the referee's comment, we tested the standard 171 color table. However, the structure was still obscured by the overlying field lines. We have therefore opted to show the 171 image alone, without any overlay, which has greatly enhanced its clarity.

14. **459** – "depart" → "displacement"

    Re: This has been corrected.

15. **484** – It would make sense to start a new section to discuss the simulations

    Re: In the revised manuscript, the simulations have been moved to a new section titled"Mechanism of Repeating Pairs" Additionally, a new "Summary" section has been added, and the "Discussion" has been removed.

16. **484** – Anisotropy in what physical quantity?

    Re: Included the definition of anisotropy under the Radio-wave Propagation Simulations section.

17. **484-488** – A reference to figure 6 seems appropriate somewhere here

    Re: As suggested, we have now added a reference to Figure 6 at the appropriate location.

18. **487** – Is this a spherically symmetric simulation? How does the mean density behave with height? Is alpha constant with height?

    Re: Additional details have been included in the simulation section. We provided the details and the reference to Kontar et al 2023 paper.

    ***How sensitive are the results and consistency with observations to these parameters? Can you learn anything about the turbulent corona from evaluating this? ***

    Re: The simulations are sensitive to anisotropy parameters and the anisotropy alpha 0.1 gives the best agreement with the observations. The level of turbulence is affecting the amount of scattering. We stress that we took the level of turbulence which was used before, i.e. we did not change it from the standard level used Kontar et al 2023 paper.

19. *** 570 – I find this connection about observed EUV/jetting activity being tied to these events plausible and it appears to me very straightforward to test and support this statement. I strongly recommend the authors produce a supplemental movie of a cutout of the AIA data from e.g. http://jsoc.stanford.edu/ajax/lookdata.html or https://www.lmsal.com/get_aia_data/ at the max cadence (I think 10s – the second link actually permits the cutout to be set to move with the image), and also to plot a timeseries of the sum of pixel intensities from the cutout and mark a vertical bar every time one of their burst events occurs. I think tying the authors' observations to another physical observable would make the connection to other studies much stronger. ***

    Re: Based on these suggestions, we have produced an accompanying animation (available with Figure 6 in the latest revision).

20. The distribution of centroid frequencies would be useful to report, and for the authors to comment on what range of apparent heliocentric distances/altitude above the AR this corresponds to.

    Re: Relevant contents have been included in the revision.

- **Discussion** (This section has been replaced by "**Mechanism of Repeating Pairs**" and "**Summary**" in revision.)

    1. *** 577 – Please specify the solar active region and C-class flare context of these results – observed above a solar active region at coronal radio frequencies, 1000s are seen in a 1h50 period ***
       Re: The relevant content has been added.
    2. **582** – it makes intuitive sense to me that the source being spread over a large area corresponds to a dilution of the frequency drift rate
       Re: "reduced" updated to "diluted", and an additional reference is included in the context of scattering-induced drift rate dilution of fine structures.
    3. **587** – "Reminiscent" is a little vague, can you quantify? Are all the relevant quantities the same order of magnitude? Within a factor of 2? within 10%? Do they occur at the same frequency range?
       Re: All relevant quantities are of the same order of magnitude within the given frequency range. We have revised the sentence accordingly for clarity.
    4. **638** – "The radio emission initially directed downwards reflects..."
    5. **Re:** The relevant content has been added.
    6. *** 641 – can you make some inference about the scale height of the density fall off form this information? ***
       Re: The density scale-height determines the delay. The 4 second delay requires the density scale height of $R_\odot/4$ - $R_\odot/3$, with larger scale-heights producing shorter delays.
    7. *** 634 – Why does all the emission appear to occur a significant height above the AR? Is there some timescale needed for the Langmuir waves to form and/or couple to EM emission? Can you gain some physical insight from this? ***
       Re: The observed frequency and temporal characteristics of the bursts imply that the electron beam must be spatially small and similar to that for spikes. Such compact beams become unstable over short distances, so they generate Langmuir waves and the resulting plasma emission after propagation of only a few beam lengths. Therefore, the observations indicate that the electrons responsible for the bursts are accelerated relatively close to the radio source at 30 MHz and are unlikely to originate very low in the corona.
    8. *** As mentioned at the top-level of this review The manuscript ends quite abruptly in the discussion – a wrap up/summary with important takeaways for the reader Is needed – what have we gained by identifying these bursts associated with flaring solar Active regions and identifying a plausible mechanism that explains them? Why should a general nature comms reader care about the discovery? (A similar motivation statement is needed in the introduction in my opinion.) ***
       Re: Relevant contents have been added in revision.

- **End material** – Please add links to the data sources used in this work (LOFAR, AIA, HMI, PFSS

software, PFSS magnetogram)

Re: This have been added in revision.

Additional Revisions

In addition to the specific points raised by the reviewers, we have:

- In response to the editor's suggestion, box-and-whisker plots have been added to Figure 4, and the extracted values are now presented in a new Table 1.
- In the revision, we restructured the manuscript by moving the original simulation and discussion content into two new sections, which we have named "Mechanism of Repeating Pairs" and "Summary".
- We have rephrased the Methods section for clarity.

We believe that our detailed responses and the corresponding revisions have adequately addressed all concerns raised by the reviewers. We are grateful for the opportunity to improve our manuscript and hope it now meets the high standards of *Nature Communications*.

References

[1] Coles, W. A.,Harmon, J. K., Sulzer, M. P., Chau, J. L. and Woodman, R. F., An upper bound on the solar radar cross section at 50 MHz, *Journal of Geophysical Research (Space Physics)* **A04102**, 111 (2006)

Response to Referees:

Imaging spectroscopy reveals spike-like repeating radio burst pairs in the solar corona

Ma,S., Kontar E., Clarkson, D., Chen, H. and Yan, Y.

April 23, 2026

Manuscript ID: NCOMMS-25-20309
Title: Imaging spectroscopy reveals spike-like repeating radio burst pairs in the solar corona
Authors: Ma,S., Kontar E., Clarkson, D., Chen, H. and Yan, Y.

Response to Reviewer 1

We thank Reviewer 1 again for their positive assessment and valuable suggestions. Below we address the remaining questions.

After conducting a second review of the manuscript entitled "First Observation and Interpretation of Solar Radio Spike Repeating Burst Pairs" and verifying that my previous concerns have been adequately addressed in the revised version, I confirm the relevance of the work and its contribution to the study of short solar radio bursts. In this revision, the authors clarify the physical implications of their findings and provide additional details on the methodology used for data analysis. The methodology is robust and appropriate for the type of research conducted in this study.

The study provides insight into how coronal turbulence may affect the observed radio signals in the solar corona. In particular, anisotropic scattering may cause radio waves to propagate preferentially along the magnetic field, leading to the generation of spike repeating burst pairs with delayed faint components that typically exhibit reduced drift rates.

1. As a minor suggestion, the authors may consider briefly describing the possible types of turbulence that could lead to the anisotropic scattering involved in the proposed physical scenario.

   Re: The possible nature of turbulence at ion-scales (kinetic Alfven waves) leading to anisotropic scattering was added.

2. There appears to be a typographical error in the caption of Figure 4: an exponent "9" appears after "(g–h)".

   Re: Thank the referee for mentioning this. We have checked and found the "9" is the page number, which might be considered by the graph editor later.

3. A comma appears to be missing after the phrase "...the mean of the Gaussian sector of the function" in line 932.

   Re: A comma has been added in revision.

4. In the caption of Figure 2 (line 264), the word "dotted" in the phrase "The magenta and turquoise dotted horizontal lines denote ..." appears to be incorrect, since the magenta and turquoise horizontal lines are not dotted.

   Re: The word "dotted" has been removed in revision.

Response to Reviewer 2

We appreciate Reviewer 2's thorough review again. We have addressed the remaining questions, as detailed below.

Thank you to the authors for their careful attention to my prior comments and the significant changes to their manuscript.

I consider my major comment (the wider context and meaning of the authors results) to be greatly strengthened and better discussed throughout the manuscript, and the edits stemming from my minor comments are all satisfactory. I attach a last few minor comments that are mostly minor presentation suggestions and a couple of discussion points based on the new content the authors added. I'd in particular draw attention to my last comment which encourages the authors to emphasize the physical insight their model and observations together provide.

Minor Comments

1. 084 – "of the first burst formed by..."

   Re: This has been corrected in revision.

2. 088 – I think I understand the authors intention but I don't think its phrased quite right. I think they mean the refractive index"can be $\ll 1$ in the vicinity of the emission site."

   Re: This has been corrected in revision.

3. 103-106 – The point about radar reflection is a valuable point of context, I would suggest specifying that you are discussing radar signals launched from Earth, and mention the frequency.

   Re: Yes, Earth mentioned and specified frequency now in the manuscript.

4. 127 – the observing program/project names could probably be a footnote (if Ncomms formatting allows that).

   Re: The relevant portion has been relocated to a footnote.

5. 134 – suggest specifying the new radio bursts are observed to be co-spatial, or above" the AR discussed here (otherwise the sentence could be describing two unrelated things).

   Re: A word of "co-spatially" has been added to specificity.

6. 145 – “along with the GOES soft X-ray flux and AIA 171 flux.” (“overlaid” implies in the same panel, and should mention the aia flux. Please also explain if the AIA flux is summed over full AIA images, or from a sub-region/cutout of the AR.

   Re: The sentence has been rewritten in the revision as suggested.

7. 151 – “An intriguing feature. . . : sounds like the feature could be incidental to the work, I suggest being clear that they are the central phenomenon that will be studied.

   Re: This word has been changed as suggested.

8. 162/163 – since subscripts “E” and “D” are used a lot later on, it would be useful to place these in parentheses following the introduction of the terms “earlier” and “delayed”.

   Re: This has been revised as suggested.

9. Fig 1 – The future in (b) labeled as III and in (c) labeled as spike are very hard to see (especially in print). I suggest the authors try to saturate the darker end of their color-map a little more.

   Re: Figure 1 has been modified as suggested.

10. Fig 1 caption – same comment on the AIA flux as line 145, please specify “AIA 171A” and whether it is a full disk summed flux or a sub-region/cutout

    Re: This has been revised as suggested.

11. Fig 1 ordering of panels – very, very minor but I would swap the (j,k,l) and (m,n) rows so that they are presented in the order in which they are discussed in the text.

    Re: We assume the referee is referring to Figure 4, because only that figure contains panels (j,k,l) and (m,n). The relevant part has been revised in light of this suggestion and the art editor’s suggestions.

12. 331 – since quantitative drift rates are given for drift pairs and type IIIs in this sentence, it would be nice to quote a typical reported drift rate for spikes from [18]/

    Re: The text has been updated to include the typical spike drift rates as noted in [18].

13. 464 – given this 1 sfu error, does it make sense have histogram bin widths ¡ 1sfu in fig 4h?

    Re: The bin widths have been changed to 1 sfu in revision.

14. 471-472 – to my eyes, the delayed component also shows a weak (weaker than the earlier component for sure) increasing trend also. It at least appears clearly that the lower bound of the peak delayed fluxes is increasing with frequency. Perhaps the authors can do a quick linear regression to both these plots and determine if the slope is consistent or inconsistent with zero in both cases.

    Re: We performed linear regression on both plots and included the results in the revised manuscript.

15. 491 = Perhaps “apparent spatial distribution” to convey that the actual original photons were likely produced co-spatially but just took different paths to the observer.

    Re: The ‘apparent’ has been added in the revision.

16. Fig 4f – if the AIA flux shown in fig 1 is from a cutout of the AR, it would be useful to include a box showing that cutout here.

    Re: The region has been marked as suggested.

17. 681 – cite [18] again for "solar radio spike"

    Re: The paper has been cited in revision.

18. 781 – the "cospatial" statement should point the reader to fig 9 (it hasn't been introduced before then).

    Re: This has been modified according to the referee's suggestion.

19. 867 – "...spectral bandwidths and central frequencies..."

    Re: This has been modified in revision.

20. 884 – I think the conclusions of the simulation could be emphasized even more – highlighting that it is often ambiguous about whether plasma emission is at the fundamental or harmonic and in this case they have strong evidence it is harmonic, they provide strong support to previous work suggesting a density fluctuation anisotropy factor of 0.1-0.2, and their reflection time delay gives a measurement of density scale height. I would encourage the authors to emphasize all these point which are all very useful physical insights into the plasma emission and environment where these bursts occur.

    Re: Yes, we added this to the conclusions.