nature portfolio

Peer Review File

An open-source tool for mapping war destruction at scale in Ukraine using Sentinel-1 time series

Corresponding Author: Mr Olivier Dietrich

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Dietrich,

Please allow us to sincerely apologise for the long delay in sending a decision on your manuscript titled "An Open-Source Tool for Mapping War Destruction at Scale in Ukraine using Sentinel-1 Time Series". It has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

* Please justify your methodological choices and discuss the usage of other information from SAR imagery, such as interferometric coherence and polarization.

* Please place your work firmly in the context of existing approaches and discuss potential reasons for differences in your results compared to others.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Teng Wang, PhD
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Joe Aslin
Deputy Editor
Communications Earth & Environment

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(https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

TL;DR: Reject.

The authors present an automated damage assessment mechanism for battle damage in Ukraine using publicly-available data from Sentinel-1 C-band SAR and modeling capabilities on Google Earth Engine. Additionally, the authors make available a dashboard where users can view assessed damage for any location in Ukraine as well as re-run assessment for areas that are not previously assessed.

Strengths:
* The paper is well-written and flows well. The inspiration, methodology, and results make sense. The figure are compelling and easy to understand.
* The users provide a simple and intuitive mechanism to make use of often-complicated SAR imagery to perform a meaningful task in the real world.
* Using SAR for battle damage assessment is still an unmet need. This methodology and write-up could help others build on top of this work to fill this growing need amongst the disaster responses community.

Weaknesses:
* Why was random forest selected as the model of choice? Did other models have inherent weaknesses or flaws? How does random forest compare to other baselines?
* Similarly, how does this SAR-based assessment method compare to other SAR-based damage assessment methods? Or even, EO-based damage assessment methods? The evaluations in the paper are lacking.
* The actual assessments output from this method drastically differ from those produced by the World Bank while they agree

reasonably with those produced by UNOSAT. Why? This is not discussed in detail. It would be really important to highlight the assessment choices made by both agencies and how they agree/differ with the assessment choices done by this method.
* The unseen results compared with UNOSAT are not good -- is this a limitation of the specific model chosen by the authors and could it be made better by other models, or is this limitation a function of assessment choices, available footprints, or something else? Overall, I would want this paper to dig a bit deeper into *why* the results are the way they are. As a result, this statement "we expect our method to transfer well to other geographical contexts" seems unfounded.
* Why F-0.2 as opposed to F-0.1 or F-0.15 or anything else? The authors use few words to describe this decision. Perhaps showing a sweep of results over this low-F threshold setting would be more useful.
* Since the venue is Nature Comms, do the authors have any feedback from real users? Some discussion about how users have worked with this method in the real world would be useful.

Reviewer #2 (Remarks to the Author):

This manuscript presents an interesting and innovative analysis of Copernicus Sentinel-1 synthetic aperture radar (SAR) imagery to map damage to buildings in Ukraine using a machine learning method inside Google Earth Engine (GEE). The main claim of the manuscript is that applying the Random Forest machine learning algorithm to the time series of SAR amplitudes, with training data provided by the UNOSAT mapping of damage and with a database of building footprints, can accurately and efficiently detect major damage to buildings. This claim seems well demonstrated for the application to Ukraine war damage and it should be of interest to a wide variety of scientists and other geographic data users. The use of a whole year of reference SAR imagery is likely a key part of their successful calculations because some areas will have strong seasonal effects on the SAR amplitude, especially in croplands that dominate most of the land area of Ukraine.

The authors use the Sentinel-1 ground-range detected (GRD) products from Copernicus that have been further post-processed by Google before loading into the Google Earth Engine. The GEE Sentinel-1 GRD products have a 10 by 10-meter pixel spacing, but the authors do an additional averaging of 3 by 3 pixels to do their calculations with a roughly 30-meter resolution. The authors mention the 3x3 pixel averaging in the context of comparing to the building damage mapped by UNOSAT, but do not mention that the final map is similarly smoothed to approximately 30-meter resolution. This spatial smoothing is likely an important step for reducing the noise in the SAR backscatter amplitude images, but it is important to state clearly in the text. The authors compare their SAR amplitude-based method to the SAR interferometric phase-based coherence method and note that the phase-based coherence requires a calculation over a number of pixels (typically 60 by 60 meters for Sentinel-1), but it seems that this method also requires averaging to 30 by 30-meter resolution to be accurate so the resolution advantage is not so great.

The authors build upon the efficient computation and visualization system of Google Earth Engine, which is a big advantage of their implementation. The GEE system does not yet support the complex SAR pixel values necessary for phase-based computations, so interferometric coherence cannot be calculated in GEE. The Google Earth Engine Sentinel-1 SAR amplitude products include orthorectification but not the radiometric terrain-correction that is important for areas with significant slopes. The cities in Ukraine are all on flat or slightly sloping land, so the use of the GEE Sentinel-1 SAR products works well there. It may not work as well for towns and cities in more hilly or mountainous areas, so the authors should add this to their list of limitations. The NASA OPERA project is now providing radiometrically terrain-corrected (RTC) Sentinel-1 SAR amplitude images globally since March 2024, so there is a new source of RTC products that could improve the accuracy of the SAR amplitude time-series analysis proposed here. The upcoming NASA-ISRO SAR (NISAR) mission will also routinely provide RTC products globally

It is very helpful that the authors provide dashboard applications in GEE to view their mapping results and to run their classification code, so readers can run the classifications at the full resolution available for any location in Ukraine. This allowed me to view the effective resolution of the damage probability estimate map. I would recommend that the authors store copies of their final results map and the classification code in a permanent repository, such as Zenodo, in addition to providing the GEE system links that could be removed at any time.

The authors do not mention the long history of using SAR amplitude images to map damage from natural disasters or human-induced effects. For example, Gamba et al. (2007) used multi-temporal SAR images to map damaged buildings after the 2003 Bam earthquake in Iran. The use of SAR interferometric coherence changes or coherent change detection also has a long history, including the Fielding et al. (2005) paper on mapping damage to buildings in the same Bam earthquake. The authors also don’t mention the collapse of the Kakhovka dam in Ukraine and the recent paper using Sentinel-1 SAR data to study that event (Tavakkoliestahbanati et al., 2024).

References:

Fielding, E. J., M. Talebian, P. A. Rosen, H. Nazari, J. A. Jackson, M. Ghorashi, and R. Walker (2005), Surface ruptures and building damage of the 2003 Bam, Iran, earthquake mapped by satellite synthetic aperture radar interferometric correlation, J. Geophys. Res., 110(B3), B03302, doi:10.1029/2004JB003299.

Gamba, P., F. Dell'Acqua, and G. Trianni (2007), Rapid Damage Detection in the Bam Area Using Multitemporal SAR and Exploiting Ancillary Data, IEEE Transactions on Geoscience and Remote Sensing, 45(6), 1582-1589, doi:10.1109/tgrs.2006.885392.

Tavakkoliestahbanati, A., P. Milillo, H. Kuai, and G. Giardina (2024), Pre-collapse spaceborne deformation monitoring of the Kakhovka dam, Ukraine, from 2017 to 2023, Communications Earth & Environment, 5(1), doi:10.1038/s43247-024-01284-z.

Reviewer #3 (Remarks to the Author):

This is a highly interesting and novel study that utilizes freely available SAR data from the Sentinel-1A satellite, along with the freely available processing capabilities of Google Earth Engine (GEE), to generate time series maps for damage assessment in urban areas. My expertise lies in using repeat-pass radar interferometry to measure land surface displacements associated with slow tectonic deformation, earthquakes, volcanoes, landslides, and crustal fluids. Therefore, remote sensing of building destruction falls outside my field of expertise. Additionally, I am not an expert in machine learning, so my review will focus on the overall readability of the paper and the analysis and interpretation of SAR data.

Regarding readability and presentation, the paper is well-written and easy to understand, even for non-experts. I tested the GEE Rapid Damage Tool, and it worked effectively. Because all Sentinel data are accessible in GEE, this tool is open to everyone. I use GEE in teaching satellite remote sensing, and it always amazes me to have petabytes of satellite data available at one's fingertips. This study takes full advantage of that remarkable resource. The application to building damage during the war in Ukraine makes the study highly relevant to many governmental and humanitarian agencies, as it provides an overview of the spatial and temporal variations in building damage.

As the authors noted, highly accurate damage maps could theoretically be created using high-resolution commercial optical imagery. However, commercial satellites do not always provide full country-wide coverage before a conflict, which is needed for change detection. Moreover, they lack consistent country-wide coverage during a conflict unless acquisitions are paid for. Optical imagery also suffers from data loss due to cloud cover, making winter data recovery spotty.

SAR imagery, on the other hand, can be acquired in all weather conditions, and very high spatial resolution (~1 m) is possible over limited areas with systems like the RadarSat Constellation Mission or COSMO-SkyMed. However, these data are not freely available, and the missions do not offer routine global coverage to provide pre-conflict maps. The Sentinel satellites, part of the Copernicus program, have transformed satellite remote sensing by offering global coverage with a regular cadence of 6-12 days for SAR (Sentinel-1) and 5 days for optical (Sentinel-2), combined with free and open data access and a multi-decadal acquisition plan. Achieving global coverage at a regular cadence comes with the trade-off of lower resolution (10-20 m), but as shown in this study, this resolution is sufficient for assessing damage to large buildings and estimating percentage damage to smaller structures.

Repeated SAR imagery can be used in two ways: incoherent change detection using just the amplitude backscatter, and coherent change detection using both phase and coherence. This study employs the backscatter change approach because the processing is relatively straightforward, and all the amplitude data are available in Google Earth Engine. Coherent change detection is standard in the InSAR community and likely more accurate than using amplitude alone. I believe the paper would benefit from a brief discussion of coherent change detection, along with key references such as Yun et al. (2015) for further context (Yun, S.H., Hudnut, K., Owen, S., Webb, F., Simons, M., Sacco, P., Gurrola, E., Manipon, G., Liang, C., Fielding, E. and Milillo, P., 2015. Rapid damage mapping for the 2015 Mw 7.8 Gorkha earthquake using synthetic aperture radar data from COSMO-SkyMed and ALOS-2 Satellites. Seismological Research Letters, 86(6), pp.1549-1556.).

The study uses changes in radar backscatter to identify building damage. It would be helpful to reference some of the early papers on estimating backscatter variability, such as those addressing persistent scatterers (e.g., Ferretti, A., Prati, C., and Rocca, F., 2001. Permanent scatterers in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, 39(1), pp.8-20).

One element missing from the paper is a brief discussion of the types of backscatter changes related to the destruction of buildings. Intact buildings tend to have flat surfaces and corners that often provide point-like specular backscatter returns, while a completely destroyed building typically produces a more diffuse area of high backscatter. Including a few examples of backscatter time series for fully or partially destroyed buildings would be valuable. For instance, the authors could present a time series of backscatter for the damaged building shown in the left panel of Figure 2. When the building is damaged, does the backscatter increase or decrease, or are both cases observed?

Additionally, it would be interesting to explore how backscatter change depends on the spatial resolution and polarization of the radar. The best azimuth resolution of Sentinel-1 is 14 m, and in this study, 3x3 pixels are averaged, resulting in a pixel resolution of approximately 45 m.

Overall, this is an excellent contribution, and I recommend publication with minor revisions.

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Dietrich,

Please allow us to apologise for the delay in sending a decision on your manuscript titled "An Open-Source Tool for Mapping War Destruction at Scale in Ukraine using Sentinel-1 Time Series". It has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for providing the revised version of your manuscript. I am pleased that my previous comments contributed to improvements in your work. You are entirely correct in noting that my initial assessment of performance relative to UNOSAT results was overly optimistic, and I appreciate the clarification provided in this revision.

That said, I have one significant concern regarding the current framing of the work. You emphasize the importance of using algorithms available within Google Earth Engine (GEE) due to their accessibility for downstream operators—a point I fully understand and agree with. This practical constraint is a valuable consideration.

However, the manuscript does not sufficiently justify this choice from the perspective of an external reader who may not be deeply familiar with GEE or the operational constraints of disaster management. To make the rationale more compelling, I suggest re-titling the paper and reorienting the narrative to focus on *constrained* damage assessment using tools available to operators. This phrasing might better emphasize the pragmatic nature of the approach and its intended real-world applicability. I am not tied to any specific phrasing, of course, but am just providing a suggestion for how to better scope the paper.

Additionally, while the reliance on GEE is a practical limitation, the paper would benefit from exploring how a near-state-of-the-art (SOTA) approach might perform using the same dataset. Including a SOTA baseline could provide valuable context for readers, showcasing what is theoretically possible with advanced machine learning techniques while highlighting the trade-offs inherent in using GEE. This comparison would strengthen the paper by demonstrating both the practical utility and the limitations of the proposed approach. It would also mitigate the risk of the work becoming outdated should GEE be updated to include newer algorithms in the future.

In summary, this is a well-executed and valuable contribution to the field. I recommend the paper for acceptance with minor revisions to address the concerns outlined above.

Reviewer #2 (Remarks to the Author):

It seems that the authors have addressed the concerns that I had with the first submitted version. I think this paper will be of broad interest.

Reviewer #3 (Remarks to the Author):

The authors have done an excellent job of addressing my comments and the comments of the other reviewers and I recommend publication.

An open-source tool for mapping war destruction at scale in Ukraine using Sentinel-1 time series

Response to Reviewers

Dear Reviewers,

Thank you again for the time and effort you invested in evaluating our manuscript and for your valuable feedback. We are pleased that all reviewers acknowledge the improvements made since the first version and support its publication [R2, R3], contingent on a final round of revision [R1]. Below, we provide a point-by-point response to the remaining concerns. For clarity, similar to our first response, the original remarks are presented in bold blue font, and each reviewer is referred to in the third person.

Reviewer 1

Thank you for providing the revised version of your manuscript. I am pleased that my previous comments contributed to improvements in your work. You are entirely correct in noting that my initial assessment of performance relative to UNOSAT results was overly optimistic, and I appreciate the clarification provided in this revision.

We are glad that our revisions addressed most of R1's concerns.

That said, I have one significant concern regarding the current framing of the work. You emphasize the importance of using algorithms available within Google Earth Engine (GEE) due to their accessibility for downstream operators—a point I fully understand and agree with. This practical constraint is a valuable consideration.

However, the manuscript does not sufficiently justify this choice from the perspective of an external reader who may not be deeply familiar with GEE or the operational constraints of disaster management. To make the rationale more compelling, I suggest re-titling the paper and reorienting the narrative to focus on *constrained* damage assessment using tools available to operators. This phrasing might better emphasize the pragmatic nature of the approach and its intended real-world applicability. I am not tied to any specific phrasing, of course, but am

just providing a suggestion for how to better scope the paper.

We thank R1 for this suggestion. While we believe the title sufficiently reflects the scope of our work, we agree that our manuscript would benefit from a stronger emphasis on our reliance on GEE. To address this, we have revised the abstract and multiple sections of the manuscript, including a complete rephrasing of one of our limitations, to better justify this constraint (Lines 130-136, 197-221, 401-427). We let the editors decide if it is enough or if the title should be modified.

Additionally, while the reliance on GEE is a practical limitation, the paper would benefit from exploring how a near-state-of-the-art (SOTA) approach might perform using the same dataset. Including a SOTA baseline could provide valuable context for readers, showcasing what is theoretically possible with advanced machine learning techniques while highlighting the trade-offs inherent in using GEE. This comparison would strengthen the paper by demonstrating both the practical utility and the limitations of the proposed approach. It would also mitigate the risk of the work becoming outdated should GEE be updated to include newer algorithms in the future.

We appreciate R1's suggestion to compare our method with SOTA approaches. While we acknowledge the value of such comparisons, we must clarify that a direct comparison with SOTA methods is not practically feasible, mostly due to limited data availability.
Indeed, most leading SOTA approaches for building damage detection rely on deep learning and very high-resolution (VHR) optical imagery, which provides much more detailed visual information. Unfortunately, we do not have access to VHR optical data for Ukraine – actually one motivation for our work is to enable damage detection with freely available data. Without VHR imagery, a direct comparison is obviously not possible.

To our knowledge, the current SOTA when using freely available satellite imagery is a refined version of the Coherent Change Detection (CCD) method by Scher and Van Den Hoek[1]. While excerpts of their damage maps have been featured in media reports (e.g., for Gaza and Ukraine), the complete dataset and its underlying methodology have not been published in any peer-reviewed venue, thus we can only refer to a conference abstract. In personal communication with the authors, we have learned that their method achieves a true positive rate (TPR) of approximately 60% on UNOSAT labels while maintaining an impressive false positive rate (FPR) below 1%. So far, their approach has, however, not been open-sourced, and it remains difficult to reproduce, since it relies on processing complex Sentinel-1 SLC products, for which there are no easily accessible, open tools (and also no support in GEE).

That being said, several published studies have used freely available satellite imagery for damage assessments in Ukraine. We find that their performance, at much smaller scale, is at best comparable to ours, moreover they follow very different validation strategies. For example, some studies rely on the rapid damage assessments (RDA) maps from UNOSAT, which are generally less accurate than the comprehensive damage assessments (CDA) maps used in our work. A summary of those studies is provided in Table 1 for reference. However, due to the large differences in validation data and evaluation protocols, this is not an apples-to-apples comparison, so we are reluctant to include it in the manuscript.

Study	**Metrics reported**	**Geographic coverage**	**Monitoring period**	**SAR Data used**	**Notes**
Aimaiti et al. (2022)[2]	58% (acc.)	Kyiv and surroundings	16.02.22-08.04.22	Backscatter Intensity	RDA from UNOSAT on 500x500m grid.
Stasolla and Neyt (2023)[3]	61% (F1)	Kyiv and surroundings	20.02.22-31.03.22	Backscatter Intensity	RDA from UNOSAT on 500x500m grid.
Huang et al. (2023)[4]	69% (F1)	Mariupol	28.02.22 - 23.05.22	CCD	CCD with both polarizations. Used manual labels.
Tavakko. et al. (2024)[5]	N/A	Kakhovka dam	June 17 - June 23	CCD	Multitemporal InSAR using persistent scatterers.
Ballinger (2024)[6]	68.4% (F1)	Nationwide	March 22 - February 24	Backscatter Intensity	Re-run with our data to be directly comparable.
Scher and Van Den Hoek (unpub.)[1]	60% (TPR)	Nationwide	March 22 - December 23	CCD	Not published yet, report very low FPR. Randomly split UNOSAT without geographical stratification.
Ours	74.9% (F1)	Nationwide	March 22 - February 24	Backscatter Intensity	

Table 1: Comparison of studies using Sentinel-1 data over Ukraine with their reported metrics.

For completeness, we also explored the application of more sophisticated classification algorithms to the SAR time series used in our study, by running them on local resources independent of GEE. However, we observed no significant improvement when applying a gradient-boosting algorithm (LightGBM) compared to a localized version of our Random Forest approach. This can likely be attributed to the relatively low number of features used in our classification, which simply does not require more complex algorithms.

In summary, this is a well-executed and valuable contribution to the field. I recommend the paper for acceptance with minor revisions to address the concerns outlined above.

We sincerely appreciate R1's thoughtful feedback throughout the review process and hope this final revision meets their expectations.

Reviewer 2

It seems that the authors have addressed the concerns that I had with the first submitted version. I think this paper will be of broad interest.

We are pleased that our revisions have addressed R2's concerns and appreciate their positive assessment and thoughtful review of our work.

Reviewer 3

The authors have done an excellent job of addressing my comments and the comments of the other reviewers and I recommend publication.

We appreciate R3's positive feedback and the effort and time they put into reviewing our work.

We hope that our revisions and explanations satisfactorily address all concerns. Thank you once again for the insightful and constructive feedback, which have greatly improved the quality of our work.

Sincerely,

Olivier Dietrich, Torben Peters, Vivien Sainte Fare Garnot, Valerie Sticher,
Thao Ton-That Whelan, Konrad Schindler, Jan Dirk Wegner

References

[1] Corey Scher and Jamon Van Den Hoek. "Nationwide mapping of damage to human settlements across Ukraine using Sentinel-1 InSAR coherence change detection". In: *AGU Fall Meeting Abstracts*. Ed. by AGU. Vol. 2023. Dec. 2023, GC23A–01. URL: https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1412879.

[2] Yusupujiang Aimaiti et al. "War Related Building Damage Assessment in Kyiv, Ukraine, Using Sentinel-1 Radar and Sentinel-2 Optical Images". In: *Remote Sensing* 14.24 (Dec. 2022), p. 6239. ISSN: 2072-4292. DOI: 10.3390/rs14246239. URL: http://dx.doi.org/10.3390/rs14246239.

[3] Mattia Stasolla and Xavier Neyt. *Rapid Damage Mapping in Areas of Conflict by Means of Sentinel-1 Time Series: The Kyiv Test Case*. July 2023. DOI: 10.1109/igarss52108.2023.10283216. URL: http://dx.doi.org/10.1109/IGARSS52108.2023.10283216.

[4] Qihao Huang et al. "Monitoring Urban Change in Conflict from the Perspective of Optical and SAR Satellites: The Case of Mariupol, a City in the Conflict between RUS and UKR". In: *Remote Sensing* 15.12 (June 2023), p. 3096. ISSN: 2072-4292. DOI: 10.3390/rs15123096. URL: http://dx.doi.org/10.3390/rs15123096.

[5] Amin Tavakkoliestahbanati et al. "Pre-collapse spaceborne deformation monitoring of the Kakhovka dam, Ukraine, from 2017 to 2023". In: *Communications Earth & Environment* 5.1 (Apr. 2024). ISSN: 2662-4435. DOI: 10.1038/s43247-024-01284-z. URL: http://dx.doi.org/10.1038/s43247-024-01284-z.

[6] Ollie Ballinger. *Open Access Battle Damage Detection via Pixel-Wise T-Test on Sentinel-1 Imagery*. 2024. DOI: 10.48550/ARXIV.2405.06323. URL: https://arxiv.org/abs/2405.06323.

An Open-Source Tool for Mapping War Destruction at Scale in Ukraine using Sentinel-1 Time Series

Response to Reviewers

Dear Reviewers,

Thank you for the time and effort dedicated to evaluating our manuscript. We greatly value your insights and constructive feedback. In particular, we note that you recognize the relevance of free and open SAR data for conflict monitoring [R1, R2, R3], acknowledge the novelty [R2, R3] and simplicity [R1] of our approach as well as the effective use of GEE resources [R2, R3], confirm the usefulness of the dashboards [R2, R3], and are satisfied with the clarity of the text and figures [R1, R3]. We have carefully considered all your comments and made significant revisions to the manuscript. Before addressing your points in detail, we first respond to two overarching concerns: the lack of methodological justification and our positioning relative to existing approaches.

Methodological Justification

To support our methodological choices and the robustness of the proposed approach, we have conducted an extensive ablation study (Appendix H). We also display its results below in Fig. 1 for convenience. In the process, we observed that our original version with spatial averaging over a 3×3 window reduced overall performance, despite producing smoother damage maps. Consequently, we have rerun all experiments with 1×1-pixel time series and have updated all figures, performance metrics, and dashboards accordingly.

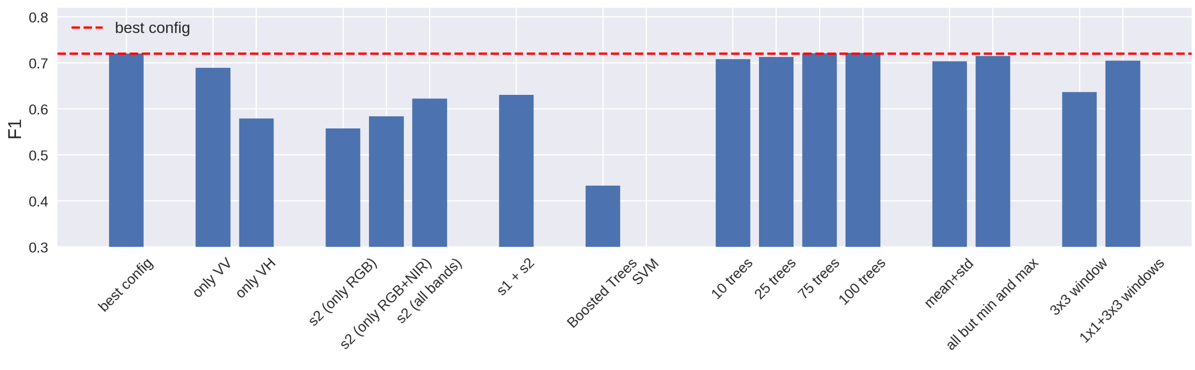

Figure 1: Results of our ablation

Moreover, we agree that choosing the detection threshold via the $F_{0.2}$-score may be somewhat unintuitive for readers. We have therefore switched to a more transparent criterion and set a target precision of 90%. While both criteria serve the same purpose, to reduce false alarms in the vast undamaged areas and keep the workflow manageable for the operators, we believe that the new criterion is more immediate and interpretable. The new configuration leads to a slightly more conservative threshold of 0.655. We would like to reiterate that, in our view, it is a strength of our method to expose the threshold to the user and let them interactively adjust it according to their needs, c.f. lines 902-910.

Finally, we would also like to emphasize that our study focuses on large-scale deployment on platforms like GEE, for the benefit of users not trained in satellite image processing, or without their own high-performance computing resources. This design choice limits what methods we can use. In particular, it rules out interferometric coherence, as platforms like GEE do not offer the functionality needed to process complex SAR data needed for coherence analysis (like for instance the Sentinel-1 SLC product). We agree that incorporating the latter would likely enhance our results, indeed we are currently exploring ways to offer it in an accessible manner.

Positioning w.r.t. Existing Approaches

A second key concern was to more firmly position our work in the context of existing approaches. We have substantially expanded the literature review in the introduction to acknowledge pioneering studies related to ours, *e.g.* [1–10]. We have also included more works that directly relate to the war in Ukraine [11–14]. As stated above, comparisons with coherence-based methods were not feasible due to our focus on large-scale inference on publicly accessible infrastructure. Additionally, we confirmed that traditional amplitude-based methods from the disaster response literature are largely unsuitable; they tend to be tailored for specific legacy satellites (e.g., ERS) and require the event date to be known so as to find pairs of pre- and post-event images. For conflict damages, we do not have access to those dates. To our knowledge, no other method, apart from the PWTT approach [15] already included in the manuscript, matches our requirements. For completeness, we have nonetheless tested our workflow with optical data (Sentinel-2) in our ablation study. As expected, it achieved inferior results; moreover, the combination of Sentinel-1 and Sentinel-2 did not provide any advantage over SAR alone.

We now proceed with a detailed, point-by-point response. For better readability, we include the original remarks in **bold blue** font, and each reviewer is addressed in the third person.

Reviewer 1

The authors present an automated damage assessment mechanism for battle damage in Ukraine using publicly-available data from Sentinel-1 C-band SAR and modeling capabilities on Google Earth Engine. Additionally, the authors make available a dashboard where users can view assessed damage for any location in Ukraine as well as re-run assessment for areas that are not previously assessed.
Strengths:

The paper is well-written and flows well. The inspiration, methodology, and results make sense. The figure are compelling and easy to understand.
The users provide a simple and intuitive mechanism to make use of often-complicated SAR imagery to perform a meaningful task in the real world.
Using SAR for battle damage assessment is still an unmet need. This methodology and write-up could help others build on top of this work to fill this growing need amongst the disaster responses community.

We appreciate the feedback. Indeed, we found that using open SAR data for battle damage assessment was an unmet need, and that was the starting point for our work. With our contribution, we hope to inspire other researchers and provide a foundation for further advances.

Weaknesses:

Why was random forest selected as the model of choice? Did other models have inherent weaknesses or flaws? How does random forest compare to other baselines?
The Random Forest (RF) was selected for several reasons: (1) it is natively implemented in GEE, thus ensuring continuity; (2) it is particularly efficient and suitable for large target areas – specifically, it can be run at country-scale with the compute budget offered by GEE; and (3) by its frequentist nature, it provides well-calibrated uncertainty estimates, which we make good use of in our application. In Appendix H, we have compared RF with two other classifiers available in GEE: Boosted Trees (BT) and the Support Vector Machine (SVM). BT underperformed compared to RF while being much slower (in our experiments $\approx 3\times$ longer inference time). With the SVM, which is inherently even slower, we were unable to obtain results, since the computation exceeds the quota allowed by GEE.

Similarly, how does this SAR-based assessment method compare to other SAR-based damage assessment methods? Or even, EO-based damage assessment methods? The evaluations in the paper are lacking.

As discussed above, we believe that the only amplitude-based method that fits all our requirements is the PWTT approach. Nonetheless, in our ablation study, we also incorporated optical data (Sentinel-2) and observed substantially poorer performance compared to SAR data. As discussed in lines 974-982, our approach was specifically designed to leverage the properties of SAR data, and the underlying assumptions do not hold for optical data. Spatial context is a lot more important with optical data, where an individual pixel holds practically no geometric information. As a thought experiment, imagine having to recognize building damage in a time series of optical reflectance values at a single pixel. We have also experimented with combining SAR and optical data, but for our task, it does more harm than good to inflate the dimensionality of the problem with the fairly uninformative optical features.

The actual assessments output from this method drastically differ from those produced by the World Bank while they agree reasonably with those produced by

UNOSAT. Why? This is not discussed in detail. It would be really important to highlight the assessment choices made by both agencies and how they agree/differ with the assessment choices done by this method.

Thank you for pointing this out. Indeed, we had not interpreted the World Bank assessment correctly. The World Bank considers housing unit , which are not directly equivalent to buildings (e.g. a single building can comprise multiple housing units). Instead of comparing absolute numbers, we now compare the relative damage cost per oblast to our estimates. This is now clarified in Appendix F. Even so, the distribution still differs significantly for "others", i.e., oblasts outside the battle zone. In the spirit of a screening tool, we process those zones, but building changes in them are predominantly not caused by the conflict, and our model is not able to differentiate. The agreement is much higher if, a-priori, we limit the analysis to oblasts directly affected by the war, as for instance done in this NYT article. Fig. 2 corresponds to Figure F4 from the paper, after removing the "others" bar and renormalising to 100%. We can see that both assessments agree rather well, except for underestimates in Kharkivska, and overestimates in Dnipropetrovska and Zaporizka (where we suspect that the World Bank estimates may be too optimistic).

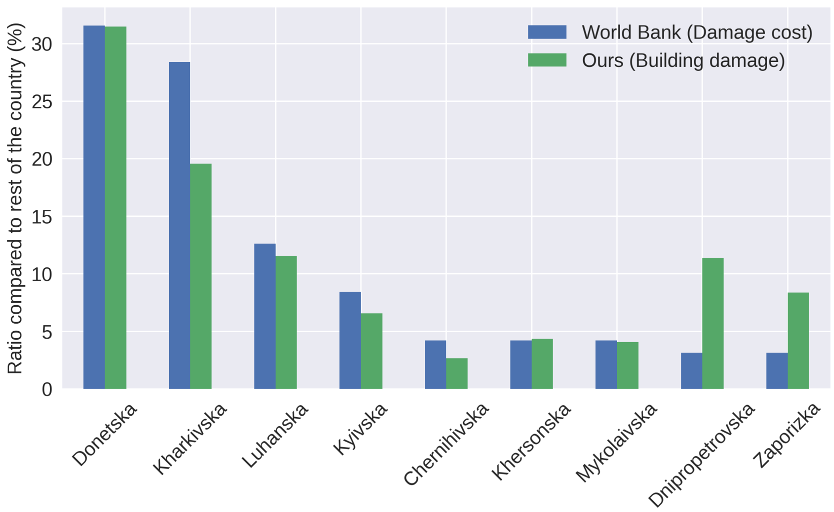

Figure 2: Same as Figure F4 from the manuscript, but without the *Others* category.

The unseen results compared with UNOSAT are not good – is this a limitation of the specific model chosen by the authors and could it be made better by other models, or is this limitation a function of assessment choices, available footprints, or something else? Overall, I would want this paper to dig a bit deeper into *why* the results are the way they are. As a result, this statement "we expect our method to transfer well to other geographical contexts" seems unfounded.

We are not sure what R1 is referring to with the comment “the unseen results compared with UNOSAT are not good”.

If “unseen” implies locations in Ukraine not included in training (i.e., a held-out test set): we have provided quantitative results in Table 1, comparing the output of our method to UNOSAT labels at unseen locations. We find them quite satisfactory for the complexity of the task – of course they are far from perfect, but it would be unrealistic to aim for near-perfect detection, given the 10m GSD of Sentinel-1, the many confounding effects, and the definition uncertainty of when a building is "severely" damaged. Qualitative results are shown in Figure 2 or on the dashboard.

If "unseen results" refers to applying the method to other geographical regions beyond Ukraine: if R1 has conducted independent experiments with our tool, we would be eager to hear their findings. Currently, our model is only meant to be used in Ukraine, but our ultimate goal is to expand it to further countries. In principle, our approach should perform reasonably well in other regions, as it does not rely on country-specific priors and is fundamentally geometrical (unlike, e.g., methods based on spectral indices). Naturally, some fine-tuning will, however, be necessary, as SAR patterns vary depending on local factors such as building density, height, or materials. We also anticipate the performance of the model to drop in regions with dense vegetation, where SAR signals tend to be less consistent.

Reviewer 2

This manuscript presents an interesting and innovative analysis of Copernicus Sentinel-1 synthetic aperture radar (SAR) imagery to map damage to buildings in Ukraine using a machine learning method inside Google Earth Engine (GEE). The main claim of the manuscript is that applying the Random Forest machine learning algorithm to the time series of SAR amplitudes, with training data provided by the UNOSAT mapping of damage and with a database of building footprints, can accurately and efficiently detect major damage to buildings. This claim seems well demonstrated for the application to Ukraine war damage and it should be of interest to a wide variety of scientists and other geographic data users. The use of a whole year of reference SAR imagery is likely a key part of their successful calculations because some areas will have strong seasonal effects on the SAR amplitude, especially in croplands that dominate most of the land area of Ukraine.

We thank R2 for their detailed observations. One small clarification: in our study, we leverage building footprints and limit the processing to built-up areas. Hence, seasonal effects in croplands or deciduous forests do not have a strong effect.

The authors use the Sentinel-1 ground-range detected (GRD) products from Copernicus that have been further post-processed by Google before loading into the Google Earth Engine. The GEE Sentinel-1 GRD products have a 10 by 10-meter pixel spacing, but the authors do an additional averaging of 3 by 3 pixels to do their calculations with a roughly 30-meter resolution. The authors mention the 3x3 pixel averaging in the context of comparing to the building damage mapped by UNOSAT, but do not mention that the final map is similarly smoothed to approximately 30-

meter resolution. This spatial smoothing is likely an important step for reducing the noise in the SAR backscatter amplitude images, but it is important to state clearly in the text. The authors compare their SAR amplitude-based method to the SAR interferometric phase-based coherence method and note that the phase-based coherence requires a calculation over a number of pixels (typically 60 by 60 meters for Sentinel-1), but it seems that this method also requires averaging to 30 by 30-meter resolution to be accurate so the resolution advantage is not so great.

R2 correctly states that we used a 3×3m spatial average when extracting the time series. However, the average is computed densely at every Sentinel-1 pixel, without downsampling. The resulting heatmaps still have the original 10×10m GSD. That being said, since the original submission we have determined that the spatial averaging step is not necessary and we have discarded it altogether. Per-pixel time series are now computed completely independent of the neighbors, still with a GSD of 10××10m. We hope this resolves any possible confusion.

The authors build upon the efficient computation and visualization system of Google Earth Engine, which is a big advantage of their implementation. The GEE system does not yet support the complex SAR pixel values necessary for phase-based computations, so interferometric coherence cannot be calculated in GEE. The Google Earth Engine Sentinel-1 SAR amplitude products include orthorectification but not the radiometric terrain-correction that is important for areas with significant slopes. The cities in Ukraine are all on flat or slightly sloping land, so the use of the GEE Sentinel-1 SAR products works well there. It may not work as well for towns and cities in more hilly or mountainous areas, so the authors should add this to their list of limitations. The NASA OPERA project is now providing radiometrically terrain-corrected (RTC) Sentinel-1 SAR amplitude images globally since March 2024, so there is a new source of RTC products that could improve the accuracy of the SAR amplitude time-series analysis proposed here. The upcoming NASA-ISRO SAR (NISAR) mission will also routinely provide RTC products globally

Thank you for highlighting the NASA OPERA project and the terrain-corrected Sentinel-1 data. This may be very useful once we expand to more mountainous target regions. For now, we have added a paragraph in the "Limitations section" (lines 424-439).

It is very helpful that the authors provide dashboard applications in GEE to view their mapping results and to run their classification code, so readers can run the classifications at the full resolution available for any location in Ukraine. This allowed me to view the effective resolution of the damage probability estimate map. I would recommend that the authors store copies of their final results map and the classification code in a permanent repository, such as Zenodo, in addition to providing the GEE system links that could be removed at any time.

Thank you for the suggestion. We will store our final results in ETH Zurich's research collection as soon as we have the clearance from the admins. We will then share the link in our newly-created, public GitHub repo.

The authors do not mention the long history of using SAR amplitude images to map damage from natural disasters or human-induced effects. For example, Gamba et al. (2007) used multi-temporal SAR images to map damaged buildings after the 2003 Bam earthquake in Iran. The use of SAR interferometric coherence changes or coherent change detection also has a long history, including the Fielding et al. (2005) paper on mapping damage to buildings in the same Bam earthquake. The authors also don't mention the collapse of the Kakhovka dam in Ukraine and the recent paper using Sentinel-1 SAR data to study that event (Tavakkoliestahbanati et al., 2024).

We have significantly expanded the literature review in the section "Satellite-Based War Damage Assessments" section, with a stronger emphasis on SAR (lines 97-136), and on studies related to Ukraine (lines 137-160). We have incorporated the references suggested by R2, as well as further key works that we had previously omitted. We have also clarified the difference between coherent and incoherent methods in more detail, and explained our choice of baselines.

References:

Fielding, E. J., M. Talebian, P. A. Rosen, H. Nazari, J. A. Jackson, M. Ghorashi, and R. Walker (2005), Surface ruptures and building damage of the 2003 Bam, Iran, earthquake mapped by satellite synthetic aperture radar interferometric correlation, J. Geophys. Res., 110(B3), B03302, doi:10.1029/2004JB003299.

Gamba, P., F. Dell'Acqua, and G. Trianni (2007), Rapid Damage Detection in the Bam Area Using Multitemporal SAR and Exploiting Ancillary Data, IEEE Transactions on Geoscience and Remote Sensing, 45(6), 1582-1589, doi:10.1109/tgrs.2006.885392.

Tavakkoliestahbanati, A., P. Milillo, H. Kuai, and G. Giardina (2024), Pre-collapse spaceborne deformation monitoring of the Kakhovka dam, Ukraine, from 2017 to 2023, Communications Earth & Environment, 5(1), doi:10.1038/s43247-024-01284-z.

Reviewer 3

This is a highly interesting and novel study that utilizes freely available SAR data from the Sentinel-1A satellite, along with the freely available processing capabilities of Google Earth Engine (GEE), to generate time series maps for damage assessment in urban areas. My expertise lies in using repeat-pass radar interferometry

to measure land surface displacements associated with slow tectonic deformation, earthquakes, volcanoes, landslides, and crustal fluids. Therefore, remote sensing of building destruction falls outside my field of expertise. Additionally, I am not an expert in machine learning, so my review will focus on the overall readability of the paper and the analysis and interpretation of SAR data.

We thank R3 for their thoughtful review and for taking the time to engage with our work despite the latter being outside their primary area of expertise.

Regarding readability and presentation, the paper is well-written and easy to understand, even for non-experts. I tested the GEE Rapid Damage Tool, and it worked effectively. Because all Sentinel data are accessible in GEE, this tool is open to everyone. I use GEE in teaching satellite remote sensing, and it always amazes me to have petabytes of satellite data available at one's fingertips. This study takes full advantage of that remarkable resource. The application to building damage during the war in Ukraine makes the study highly relevant to many governmental and humanitarian agencies, as it provides an overview of the spatial and temporal variations in building damage.
As the authors noted, highly accurate damage maps could theoretically be created using high-resolution commercial optical imagery. However, commercial satellites do not always provide full country-wide coverage before a conflict, which is needed for change detection. Moreover, they lack consistent country-wide coverage during a conflict unless acquisitions are paid for. Optical imagery also suffers from data loss due to cloud cover, making winter data recovery spotty.

Indeed, clouds are a significant issue in Ukraine, which was a further reason for us not to rely on Sentinel-2 optical imagery. For reference, here is a Sentinel-2 time-lapse of Mariupol for the time period of the invasion between December 1st, 2021 and April 30th, 2022.

SAR imagery, on the other hand, can be acquired in all weather conditions, and very high spatial resolution (1 m) is possible over limited areas with systems like the RadarSat Constellation Mission or COSMO-SkyMed. However, these data are not freely available, and the missions do not offer routine global coverage to provide pre-conflict maps. The Sentinel satellites, part of the Copernicus program, have transformed satellite remote sensing by offering global coverage with a regular cadence of 6-12 days for SAR (Sentinel-1) and 5 days for optical (Sentinel-2), combined with free and open data access and a multi-decadal acquisition plan. Achieving global coverage at a regular cadence comes with the trade-off of lower resolution (10-20 m), but as shown in this study, this resolution is sufficient for assessing damage to large buildings and estimating percentage damage to smaller structures.
Repeated SAR imagery can be used in two ways: incoherent change detection using just the amplitude backscatter, and coherent change detection using both phase

and coherence. This study employs the backscatter change approach because the processing is relatively straightforward, and all the amplitude data are available in Google Earth Engine. Coherent change detection is standard in the InSAR community and likely more accurate than using amplitude alone. I believe the paper would benefit from a brief discussion of coherent change detection, along with key references such as Yun et al. (2015) for further context (Yun, S.H., Hudnut, K., Owen, S., Webb, F., Simons, M., Sacco, P., Gurrola, E., Manipon, G., Liang, C., Fielding, E. and Milillo, P., 2015. Rapid damage mapping for the 2015 Mw 7.8 Gorkha earthquake using synthetic aperture radar data from COSMO-SkyMed and ALOS-2 Satellites. Seismological Research Letters, 86(6), pp.1549-1556.).
The study uses changes in radar backscatter to identify building damage. It would be helpful to reference some of the early papers on estimating backscatter variability, such as those addressing persistent scatterers (e.g., Ferretti, A., Prati, C., and Rocca, F., 2001. Permanent scatterers in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, 39(1), pp.8-20).

As mentioned previously, we have now significantly expanded the SAR-related section in the literature review on "Satellite-Based War Damage Assessments" (lines 97-136). We have added a dedicated discussion on coherent change detection methods, including the references suggested by R3. We have also clarified the differences between coherent and incoherent methods, and explain why we have chosen not to include coherence for this study. We concur with R3 that, from a purely methodological perspective, adding coherence data will benefit our approach, and we are working on how to best do this while remaining accessible to non-expert users.

One element missing from the paper is a brief discussion of the types of backscatter changes related to the destruction of buildings. Intact buildings tend to have flat surfaces and corners that often provide point-like specular backscatter returns, while a completely destroyed building typically produces a more diffuse area of high backscatter. Including a few examples of backscatter time series for fully or partially destroyed buildings would be valuable. For instance, the authors could present a time series of backscatter for the damaged building shown in the left panel of Figure 2. When the building is damaged, does the backscatter increase or decrease, or are both cases observed?

We thank R3 for this valuable suggestion. We have now added a discussion of the type of backscatter changes associated with building destruction, along with illustrative examples, Appendix G. As noted by several authors (see the reviews [16, 17]), SAR amplitude can decrease, increase, or remain relatively stable following a destruction event. Our experiments support these observations and further highlight that even the same destruction event may exhibit different patterns, depending on orbit direction and incidence angle. For example, in a case from Chernihiv (Fig. 3) we observed both decreasing and increasing backscatter patterns, even for two orbits both acquired in ascending direction. This variability underscores the importance of incorporating all available orbits in the analysis.

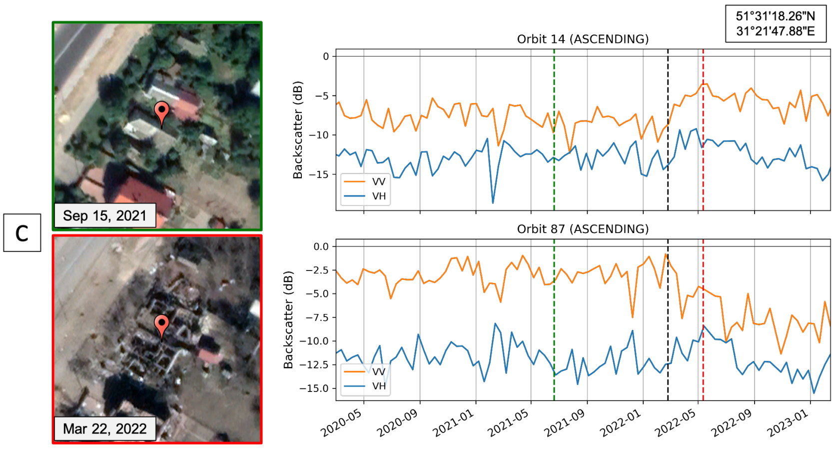

Figure 3: Inset C from Figure G5

Additionally, it would be interesting to explore how backscatter change depends on the spatial resolution and polarization of the radar. The best azimuth resolution of Sentinel-1 is 14 m, and in this study, 3x3 pixels are averaged, resulting in a pixel resolution of approximately 45 m.

Exploring the effect of spatial resolution and polarization on backscatter change would, indeed, be valuable, though we did not test other SAR satellites in this work. We would, however, like to clarify two points: (1) As noted in our response to R2, the spatial averaging that we originally applied was done densely at every Sentinel-1 pixel and did not alter the 10m GSD of the damage heatmaps (for the revised version of the method, spatial averaging has been discarded altogether, but this again has no influence on the GSD). (2) Regarding Sentinel-1's resolution, the 14.1m azimuth resolution concerns the SLC product. The GRD product used in our study is resampled to a 10x10m grid, as defined in the Sentinel-1 product documentation (here, p. 5-2). That said, R3 is correct in pointing out that the true effective resolution sensed by Sentinel-1 remains 14.1m.

Overall, this is an excellent contribution, and I recommend publication with minor revisions.

We hope that our revisions and explanations satisfactorily address all concerns. Thank you once again for the insightful and constructive feedback, which have greatly improved the quality of our work.

Sincerely,

Olivier Dietrich, Torben Peters, Vivien Sainte Fare Garnot, Valerie Sticher,
Thao Ton-That Whelan, Konrad Schindler, Jan Dirk Wegner

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