We would like to sincerely thank the Editor and Reviewers for their time, constructive comments, and valuable suggestions, which have greatly improved the clarity and robustness of our manuscript. We have carefully revised the text throughout to address all feedback.

A detailed, point-by-point response follows, addressing each reviewer comment line by line.

Reviewer Comment (RC); Author Response (AR)

Reviewer #1

RC: *The authors presents a software to process satellite images using image correlation and show a few examples.*

Without entering into the details of the study, which seems good at a quick reading, I think that it is off topic for NHESS, but it should be submitted to more appropriate journals that focus on software like, e.g., Geoscientific Instrumentation, Methods and Data Systems or Computers & Geoscience.

Regards

AR: We thank the reviewer for their comment. We respectfully disagree with the suggestion that this paper is out of scope for NHESS.

NHESS explicitly lists as within its scope "the design, development, experimentation, and validation of new techniques, methods, and tools for the detection, mapping, monitoring, and modelling of natural hazards and their consequences" as well as "databases, GIS, remote sensing, early warning systems, and monitoring technologies". TerraTrack is precisely such a contribution: a workflow designed to detect and monitor slow-moving landslides, hazard covered by NHESS.

Also, our three case studies are not merely software demonstrations but hazard-relevant applications: (i) Landslide detection and monitoring (Slumgullion), (ii) Complementarity with InSAR to obtain a more complete picture of slope instabilities (Tessina-Lamosano), (iii) Generation of displacement time series and failure time estimation to support early-warning systems (Chaos Canyon). Through these examples we also showcase the general applicability of TerraTrack for landslide hazard monitoring and demonstrate its value for operational risk reduction.

Reviewer #2

RC: *The authors present TerraTrack: an open-source, cloud-based processing chain that computes the displacement of slow-moving landslides. They discuss the performance of the different implemented methods through synthetic data and three landslide study sites. The codes are already available on GitHub and seem well documented. The tool implements different methods, offering users flexibility. This is a really nice effort of open-science, which could be usefull for landslides study, and teaching of remote sensing, and possibly more.*

The paper is very well written and the quality of the analysis is good. However, I think the quality of the paper could be improved by addressing a couple of points.

AR: We sincerely thank you for your positive and constructive feedback. Your comments were extremely helpful, and we have carefully addressed each point below.

RC: *The author could add more explanations and references on the different methods they are implementing.*

AR: Thank you for this comment. We have expanded the methodological descriptions and added references where needed and according to your comments. In particular, we clarified the different optical flow families and specified the classification of the Farnebäck method; distinguished TerraTrack's FFT NCC/PCC matching from dense optical-flow approaches such as GeFolki; justified the use of frequency-domain NCC; expanded the description and benchmarking of subpixel refinement methods; added definitions and references for SNR and PKR; and clarified the least-squares time-series formulation, including its conceptual similarity to SBAS and the way temporal resolution is imposed. We also revised Table 1 and the Discussion to improve clarity and transparency of methodological choices and limitations.

RC: *Some choices should be discussed. For now you are not masking shadows : what's could be the impact?*

AR: We acknowledge that shadows can reduce local correlation and affect displacement estimates. In TerraTrack, an anisotropic filter mitigates this by smoothing radiometric variations while preserving feature edges, which limits the impact of unmasked shadows. However, we note that deep or variable shadows may still cause local decorrelation; we now discuss this in Discussion.

RC: *The analysis of subpixel refinement method is bit hard to follow... You mention the benchmark analysis in the case of Slumgullion, but without giving the results of this analysis. Simarly, in the discussion you summarize the results on Slumgullion, then give as recommandation the PCC (without giving a recommandation on the subpixel refinement). Then, you analyse the results on the benchmark to discuss subpixel refinement performances again. It could be clearer to add a small section to present the resultts on synthetic data before the landslides cases. It will help you to explain why you selected the PCC and 4 subpixel refinement methods for Slumgullion. At the end of Slumgullion, you could say that you are selecting os3 for the other landslides. In the discussion, you could discuss in this order : 1) your recommandation for the Feature Tracking algorithm 2) your recommandation for the subpixel refinement method, using the benchmark and Slumgullion case.*

AR: Thank you for this comment. We agree that the structure was confusing. We have added a short section at the start of the Results presenting the synthetic benchmark (controlled subpixel shifts on a Sentinel-2 image; see Supplementary Materials) . In that test, Center of Mass, Parabolic, os3, and os5 performed best, capturing the 0.1-pixel shifts with moderate bias, while the other methods performed poorly. We therefore applied these four methods to Slumgullion. All four delineate the landslide well and are consistent with the spatial pattern reported by Van Wyk de Vries (2024).

In terms of maximum velocity (reference value ≈4.4 m yr^{-1}), os5 underestimates (≈2.4 m yr^{-1}), os3is lower (≈3.2 m yr^{-1}), while Parabolic and Center of Mass are closer (≈4.1 and ≈4.3 m yr^{-1}, respectively). We select os3 because, despite the slightly lower magnitude at Slumgullion, it showed (i) the lowest NMADx and NMADy in the synthetic benchmark, (ii) the lowest bias, and (iii) stable performance across all other landslides. We therefore use os3 as the default for the remaining cases. For transparency, we now report the Slumgullion results for all four methods and note that the main conclusions are unchanged across subpixel estimators.

Finally, we restructured the Discussion to address both the choice of correlation criterion and the subpixel refinement methods. We first discuss and compare these approaches broadly, and conclude with explicit recommendations for each.

RC: *In the abstract you wrote « We validated the workflow on cases with independent displacement measurements ». I was expecting comparison with GNSS or InSAR data. However, even in section 4.2 you are not comparing InSAR and FT results on the points which are in common... Please consider either modifying the abstract or adding more analysis.*

AR: Thank you for this comment. The "independent displacement measurements" mentioned in the abstract refer to results obtained using an external feature-tracking tool and expert based active landslide maps, not GNSS or InSAR data. We agree that the wording could be misleading and have revised the abstract to clarify this point.

It now reads "*We validated the workflow using displacement estimates obtained independently with other feature-tracking tools and expert landslide delineation across the Slumgullion, Chaos Canyon, and Tessina–Lamosano sites.*"

RC: *l.20 : Shugars et al.2021 refers to Chamoli disaster, which corresponds rock and ice avalanche, which was transformed in a debris flow dowstream. It's not really a landslide which fall into lakes causing a GLOF. Could you clarify ? Perhaps, you wanted to mention the Sikkim flood here (Sattar et al., 2025)*

AR: Thank you and we agree. We have replaced the citation.

RC: *l.42 : it could be better to chose between small baseline subset and Small BAseline Subset (SBAS) instead of Small Baseline Subset. Moreover, the paper of reference is usually Berardino et al. 2002 which is the first paper about SBAS. P. Berardino, G. Fornaro, R. Lanari and E. Sansosti, "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms," in IEEE Transactions on*

Geoscience and Remote Sensing, vol. 40, no. 11, pp. 2375-2383, Nov. 2002, doi: 10.1109/TGRS.2002.803792.

AR: Thank you. We have used Small BAseline Subset (SBAS) and replaced the citation with Bernardino et al. 2002.

RC: *l.43 you could derive azimuth and range velocity. Perhaps, you could precise : it's possible to derive 2D displacement field, for example vertical and east-west displacement component (Tofani et al)*

AR: Great point. Thank you. We have rephrased to be more precise accordingly.

It now reads: *"When both ascending and descending satellite orbits are available for a given area, it is possible to derive a 2D displacement field, for example vertical and east-west (EW) displacement components (Tofani et al. 2013)."*

RC: *l.50 FT is also a traditional remote sensing technique now. It could be better here to reformulate, with something like « The gaps left by InSAR and DEM differencing. »*

AR: Thank you and we agree. We have rephrased as suggested.

RC: *Table 1 :*

- *why did you write Subpixel (GPU) for autoRIFT ? It is also a subpixel NCC.*

AR: Thank you for this good point. We initially wrote Subpixel (GPU) to indicate that the implementation runs on GPU, but we agree this is neither relevant nor consistent with the rest of the table. We have now replaced it with Subpixel NCC.

RC: *GDM-OPT also has a service for glacier velocity and earthquake, which are respectively ICE and ETQ. See : https://en.poleterresolide.fr/on-demandprocessing/#/optic*

AR: Thank you for the suggestion. We have changed the purpose to "General".

RC: *If you mention the github of Aati et al 2022 it's more accurate to write COSI-Corr3D, and you should probably remove the (3D) after general. Remember that COSI-Corr is from Leprince et al 2007*

AR: Thank you for the suggestion. We have updated the table accordingly.

RC: *GIV use a NCC FFT no?*

AR: Yes, thank you. We have updated the table.

RC: *Are sure COSI-Corr is not subpixel ? Same for PyCorr.*

AR: Thank you for the suggestion. Yes, they are both supporting subpixel. We have updated the table.

RC: *Could you clarify in the legend what do you mean by partial, and general ? It would be clearer for the reader.*

AR: Thank you for the suggestion. We have updated the caption by adding:

"General" indicates a general-purpose feature tracking framework.

"Partial" refers to tools that are only partly open source or accessible through registration (e.g., via the Geohazards Exploitation Platform or ForM@Ter services) rather than through full public code release.

RC: *L. 60 You are mentioning automated image acquisition and cloud-based processing, but it's not discussed in the Table. You could add a few sentences here to higlight that these algorithms rarelly support these two characteristics.*

AR: Thank you for the suggestion. We have decided to add a column in the table to make this explicit.

RC: *l. 65 « TerraTrack leverages the Google Earth Engine API and processes Sentinel-2 Level-1 data to automatically download and pre-process images before computing displacements using various FT techniques » this sentence sounds weird… could check it ?*

AR: Thank you, we agree. It now reads: *TerraTrack uses the Google Earth Engine API to process Sentinel-2 Level-1 data and to automatically download it and computes displacements using various FT techniques.*

RC: *l. 115 Do you think the Level of the S2 images which have been used could change the quality of the displacement maps?*

AR: Thank you for this comment. We agree that the processing level of Sentinel-2 images could in principle affect displacement quality, as Level-2A products include surface reflectance corrections not present in Level-1C data. However, in our workflow, the use of an anisotropic filtering step and normalization prior to correlation strongly reduces the influence of radiometric differences between image pairs. We therefore expect only minor differences in correlation quality between L1C and L2A inputs.

The main reason we used Level-1C products is their longer temporal coverage (available from mid-2015) which allows us to analyze a longer displacement time series. Level-2A products were generated later and would have limited the observation period.

RC: *Section 3.1 Optical images can be really impacted by shadows, this can introduce seasonal artefacts. How do you deal with that?*

AR: Thank you for this comment. We answer similarly to above. We acknowledge that shadows can reduce local correlation and affect displacement estimates. In TerraTrack, an anisotropic filter mitigates this by smoothing radiometric variations while preserving feature edges, which limits the impact of unmasked shadows.

However, we note and are aware that deep or variable shadows may still cause local decorrelation; we now discuss this in Discussion.

RC: *L.138 Optical flow could be also sparse, see for example : https://docs.prophesee.ai/stable/samples/modules/cv/sparse_flow_cpp.html*

AR: Thank you. We have removed 'dense' from the sentence.

RC: *I think it would be better to explain here that there are different types of optical flow method, see Barron, J., Fleet, D.J., Beauchemin, S., 1994. Performance of optical flow techniques. International journal of computer vision 12, 43–77. Is Farneback method a differential optical flow ? Is the Aperture problem sloved using a local and global regularization term?*

AR: Thank you. We now updated the sentence in the paper to: "Optical flow methods comprise several families, including differential, matching-based, and energy-minimization approaches (Barron et al 1994, Beauchemin et al. 1995)". We also now specify that the Farnebäck method belongs to the differential class. This addresses the aperture problem through local polynomial expansion, which provides local smoothness, but it does not employ a global regularization term.

RC: *It would be helpfull to better understand the differences with GeFolki which has been already used over landslides and glaciers, see for example*

Provost, F., Michéa, D., Mal t, J. P., Boissi r, E., Pointal, E., Stumpf, A., ... & Bally, P. (2022). T rrain d formation m asur m nts from optical sat llit imag ry: Th MPIC-OPT proc ssing s rvic s for g ohazards monitoring. Remote Sensing of Environment, 274, 112949.

Charri r, L., God t, P., Rambour, C., W issg rb r, F., Erdmann, S., & Ko nigu r, E. C. (2020, S pt mb r). Analysis of d ns cor gistration m thods appli d to optical and SAR tim -s ri s for ic flow stimations. In 2020 IEEE Radar Conference (RadarConf20) (pp. 1-6). IEEE.

AR: Thank you for this suggestion. We added a brief clarification on the difference in matching strategies.

GeFolki uses a dense, optical-flow–based co-registration approach in which local displacements are estimated through a multi-scale gradient formulation. In contrast, TerraTrack employs a chip-based FFT NCC/PCC matching scheme with explicit subpixel peak refinement. These are therefore conceptually different correlation strategies: GeFolki solves for a pixel-wise flow field, while TerraTrack performs discrete block matching optimized for medium-resolution Sentinel-2 data. Because our study did not evaluate GeFolki on the selected landslide cases, we limit the comparison to this methodological distinction only.

We clarify this distinction in Discussion.

RC: *l.144. Could you justifiy here why did you not include NCC in the spatial domain, wherease it is probably the most used chip matching technique? I guess it's because of the computational time?*

AR: Thank you. We did not include NCC in the spatial domain mainly due to its high computational cost compared to frequency-domain approaches. Our goal was to optimize processing speed for large datasets, and spatial-domain NCC is typically orders of magnitude slower without significant accuracy gains (Lewis 1995).

RC: *L.168 Could you give more information about SNR and PKR? (references and/or definition)*

AR: Thank you. Yes we now add: "The PKR quantifies the sharpness of the correlation peak as the ratio between the highest and second-highest correlation values, providing a measure of match uniqueness (e.g., Van Wyk de Vries et al, 2021). The SNR represents the ratio between the main correlation peak and the mean background correlation, indicating the confidence of the displacement estimate (Kanade et al., 2002)."

RC: *L.183 Why is it a 1D filter and not 2D?*

AR: Thank you for this comment. We did apply 1D but now updated to 2D as it is more appropriate.

RC: *L. 205 Could you give some reference here : « The resulting masked median velocity map canoptionally be corrected for slope angle effects, under the assumption of a vertical satellite viewing angle. »*

AR: Thank you for this comment. This correction is a simple geometric adjustment based on the assumption of a vertical viewing geometry, intended to project measured horizontal displacements onto the slope surface. It is implemented as an optional post-processing step and does not rely on a specific published method.

RC: *L.215 It's different from the approach developped in GIV, right? Why did you decide not to have iterative approach in this case ?*

AR: Thank you for this comment. Yes, this method differs from the iterative reconstruction used in GIV. The approach described here is intentionally simple: each image pair provides an average velocity over its acquisition interval, which is then distributed in time according to a predefined rule. Because this method does not involve solving an evolving inverse problem, an iterative refinement scheme is not required. For inversion-based reconstruction, TerraTrack provides a least-squares option, and for more advanced temporal modelling the outputs can be exported to external tools such as TICOI.

RC: *L. 221 Is it a SBAS like approach? if yes you should mention it.*

AR: Thank you for this comment. Our least-squares formulation is conceptually similar to SBAS in that each displacement observation is expressed as an integral over an unknown velocity time series, and the resulting linear system is solved for the temporal evolution of motion.

RC: *L. 225 How did you force the solution to be at a chosen temporal resolution ?*

AR: Thank you for this comment. The temporal resolution is fixed directly by how we set up the inversion. Before solving, we define a time grid (e.g., monthly or 6-monthly), and the unknown vector contains one velocity parameter for each of these time bins. The design matrix links each displacement observation to the bins it spans, so the least-squares solution is automatically obtained at the chosen temporal resolution.

RC: *L. 259 you could add « i.e. 49min » : easier to read.*

AR: Thank you. We added it.

RC: *L.305 Is the inverse velocity method implemented ? If yes, it would be great to describe it in the method part, and the Figure 1. It will be logical since it's one of the final goal of the processing chain.*

AR: Thank you for this comment. The inverse-velocity method is implemented as an optional post-processing module and was used here to support reproducibility of the example results. We have added a short description and citation in the Methods (and mention it in Fig. 1 caption) to clarify how it is used within the workflow.

RC: *L. 365 Could you discuss the possibilty to use TerraTrack for other objects such as earthquake and glaciers. It has not been designed for that, but could it still be used ?*

AR: Thank you for this comment.

Although TerraTrack was primarily designed for slow-moving landslides, the feature-tracking framework itself is general. TerraTrack can be applied to glaciers using standard optical feature-tracking workflows. It can also be used to measure coseismic surface displacements: we implemented a dedicated option that constructs image pairs across a user-defined time window, allowing displacement to be computed specifically over the period when rapid motion occurred (e.g., pre- and post-earthquake imagery).

Added in Discussion.

RC: *l. 48 there is a empty parenthesis here*

AR: Thank you. We forgot to add the citation. We now added: *Prokešová et al., 2014.*

Reviewer #3

RC: *The authors present the TerraTrack tool, an open-source workflow based on a cloud processing chain that analyses Sentinel-2 images to identify and monitor the displacements of slow-moving landslides. The tool uses different methods for optical image analysis, and its outputs (velocity maps and displacement time series) are compatible with GIS software for further interpretation. Overall, this tool represents a valuable advancement, providing enhanced support for landslide detection and monitoring efforts.*

The paper is well-structured and well-written; however, some aspects should also be considered.

Please review the attached document for detailed general and specific comments.

AR: We thank you for your very helpful comment. Please find addressed each point below.

RC: *Lines 211-212 – You mention that the output time series is compatible with the 'InSAR Explorer' plugin. However, this is not the case. The files need conversion for this. Please clarify this.*

AR: Thank you but it doesn't need conversion. The csvs can be directly uploaded in QGIS and then opened with InSAR explorer. Is there any specific problem you encountered here?

RC: *The figures are not mentioned in the text at all, except Figure 4. Also, in section 4.1, which is about the Slumgullion case, you refer to a figure about the Chaos Canyon landslide (lines 246-248). This is a bit confusing. Can you fix this or switch the sections if it is more appropriate?*

AR: Thank you for catching this. Now we mention all the figures in the text and we replaced the chaos canyon mention with the slumgullion one.

RC: *It would be better to use the Copernicus DEM rather than the SRTM. COPDEM has a more recent version of Earth's surface, and although it is a DSM that includes buildings, infrastructure, and vegetation, it is often better for calculating morphometric variables, especially if the tool performs poorly in forested areas.*

AR: Thank you for this comment. We considered using the Copernicus GLO-30 DEM, because it offers improved high-latitude availability. However, TerraTrack uses the DEM only for deriving morphometric variables (slope and aspect) for post-processing filters, not for the displacement estimation itself. Because Copernicus GLO-30 is a DSM that includes vegetation and built structures, it can introduce small-scale surface irregularities that affect slope and aspect calculations, particularly in forested areas. For our application, we prefer SRTM because it provides a more terrain-oriented representation and more stable morphometric filtering.

RC: *Did you try comparing the displacement results with the in-situ instruments' recordings? I understand that this approach complements InSAR measurements, but it would be nice to know how much the calculated displacements differ from ground truth. For example, Slumgullion has been very well investigated with in-situ instruments, and such a comparison could be conducted.*

AR: Thank you for this comment. A direct quantitative comparison with in-situ instruments is not straightforward, as TerraTrack provides 10 m pixel-averaged surface displacements over multi-month to multi-year image pairs, whereas ground instruments measure point-scale motion with different temporal sampling and reference frames. In this study, we therefore focus on consistency in spatial patterns and displacement magnitudes using independent remote-sensing products. At Slumgullion, TerraTrack reproduces the characteristic faster central track and peak velocities of ~4 m yr^{-1}, consistent with published remote-sensing estimates (e.g., Hu et al., 2020, Van Wyk de Vries et al., 2024).

RC: *What is the performance of the tool in areas covered by snow for large periods of the year (higher than 4-6 months)? Can you show such an example?*

AR: Thank you for this comment. Chaos Canyon provides an example of an area with seasonal snow cover lasting several months per year. In general, the performance of TerraTrack in snow-covered areas depends on the persistence of trackable surface features. If snow cover remains spatially coherent and retains stable surface texture between image acquisitions, feature tracking can still produce reliable displacement estimates. However, when snow accumulation, melting, or redistribution significantly alters surface patterns between acquisitions, correlation quality decreases. In such cases, low-quality matches are filtered out through SNR and PKR thresholds, reducing the number of valid observations contributing to the final stack. This can increase uncertainty in the median displacement map due to fewer valid pairs.

RC: *Are forests or highly vegetated areas limiting the use of Terratrack? Probably should be mentioned in the discussions section.*

AR: Thank you for this comment. Vegetation can influence the performance of optical feature tracking, particularly in areas with seasonally variable canopy cover. In such environments, changes in vegetation structure between image acquisitions may reduce correlation quality and increase decorrelation noise. However, TerraTrack operates on Sentinel-2 NIR imagery and uses quality filtering (SNR/PKR thresholds) and multi-pair stacking, which help mitigate these effects when surface patterns remain sufficiently stable. Performance therefore depends on vegetation type, seasonal variability, and temporal baseline. We have added a clarification in the Discussion section to explicitly acknowledge this limitation.

RC: *Google Colab limits the analysis of large areas, depending on the plan. I think this point should also be addressed in the discussion section.*

AR: Thank you for this comment. We agree that Google Colab may impose practical limitations for very large areas due to runtime and memory constraints. However, TerraTrack is not restricted to Colab and can also be executed locally on a user's own machine or in alternative cloud environments with greater computational resources. We have clarified this point in the Discussion.

REFERENCES

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