Authors' Response to Reviews of

Sediment aggradation rates in Himalayan rivers revealed through InSAR's differential residual topographic phase

J. Huang, H. D. Sinclair

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RC: Reviewers' Comment, AR: Authors' Response, □ Manuscript Text

AR: Dear Dr. Johannes Leinauer,

> Thanks so much for your interest in our work and your valuable comments. We really appreciate the time you took to share your suggestions. Your insights have greatly helped improve our manuscript, and we're truly appreciate the time you devoted to this manuscript.
>
> Kind regards,
>
> Huang and Sinclair

RC: This is the first time I am reviewing the manuscript entitled: "Sediment aggradation rates for Himalayan Rivers revealed through SAR remote sensing". The authors describe a method to use differential residuals of SAR data to detect mm-scale elevation changes in the range of 20 mm/yr in four seasonally dry rivers of Nepal. They claim to "demonstrate the feasibility of InSAR techniques in geomorphological monitoring". The technical and geomorphological aspects of this study are generally interesting and have potential to bring forward this research field.

As I am not a specialist in SAR analysis, I will focus on the structure and storyline of the paper and the geomorphological implications/ interpretations.

Goal of the paper

First, the general goal or main storyline of the paper is not clear to me. I see two possibilities:

The goal is to prove that the suggested methodological approach can detect sediment dynamics in the selected rivers, or

The measured and processed signals support a geomorphological process that can now be understood or described better.

However, possibility 1) would require some prove that the results of the suggested methodological approach are true or at least reproducible and consistent with other methods.

Possibility 2) would require a clear story/ concept, of which processes should be described and supported. Then, the description of the methods should not be the main focus of the paper but rather be described as a tool to solve the stated geomorphological problem and the observed processes must be discussed in detail.

AR: Thank you for suggesting the two possible storylines for the paper. I prefer the first option, as the majority of the paper focuses on describing this new InSAR approach - DRTP. The results are **reproducible** since we are using open data and open code for signal processing. However, this open code only works with high-quality residual topographic phase data and does not include corrections for the topographic phase ambiguity.

Our immediate next focus is to develop our own open code for DRTP SBAS-InSAR approach, tailored to more complex river systems. All conventional SBAS-InSAR approach is primarily for the line-of-sight displacement phase inversion. While we are adapting it for the differential residual topographic phase processing, we have to develop our own open code with a focus on river sediment mapping. This includes incorporating a machine learning pixel selection method focused specifically the dry river pixels, among other enhancements.

Regarding whether this new InSAR approach is **true**, it builds on the work of Zhang et al. (2019), who inverted all phase components into displacement first and then removed the 'noise'. Fattahi and Amelung (2013) demonstrated that, in the displacement time-series domain, the linear model achieves zero RMSE for the estimated residual topographic phase. Additionally, the mathematical equation describing the residual topographic phase (Bombrun et al., 2009) supports our methodology.

Our new approach is grounded in these previously published foundations, with the key innovation being the modification of the changing in the topographic height in Equation (7) in our paper. It is worth noting that an essential aspect of this approach, as with all other InSAR data processing, is the quality of the input data (high interferogram quality with strong residual topographic phase).

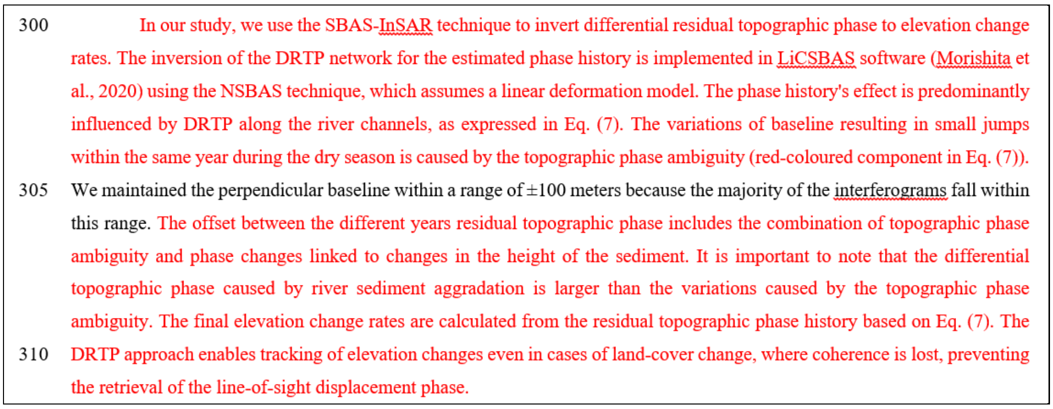
In terms of **consistency** with other methods, since this is the first observation detecting millimeter-scale riverbed elevation changes, there are no existing methods to compare with. One approach is to use the subsidence rate in the adjacent cropland, mapped using the conventional InSAR method based on the line-of-sight phase. Whether the conventional InSAR or the residual topographic phase InSAR from our new approach is used, as long as the input phase data is of a high quality, the results should indicate the same rate. For instance, in Figure 17, point C, which is adjacent to river 3, shows a subsidence rate of -14 mm/year based on conventional InSAR deformation phase. In Figure 14, river 3 near point C indicates a subsidence rate of -12 mm/year, with an uncertainty range of -12% to +8%, corresponding to rates between -13.4 mm/year and -11 mm/year based on the differential residual topographic phase.

The conclusions state that this manuscript develops a "novel approach", provides "detailed, high-resolution geomorphological data", shows a "significant sediment aggradation" (is it statistically significant?) and that "this approach adds a new tool". These statements should be supported clearly be the main part of the manuscript.

AR: Thank you for highlighting the need to emphasise the key points. In the Introduction, we have now clarified the novel aspects of using the DRTP approach, and highlighted this by a change in the manuscript title to 'Sediment aggradation rates in Himalayan rivers revealed through InSAR's differential residual topographic phase'. The DRTP approach introduces a novel method by treating the residual topographic phase as a signal rather than noise. Its phase difference is used to map sediment height changes, as described by Equation (7) in our paper. This new equation is a modified from Bombrun et al. (2009) and Fattahi and Amelung (2013). The DRTP approach allows for the tracking of elevation changes even in cases of land-cover change, where coherence is lost, making it impossible to retrieve the line-of-sight displacement phase. These points are supported in lines 300–311 in the manuscript.

AR: The phase velocity standard deviation mentioned in Section 3.6 demonstrated the statistically significant of the result, which is less than 1 mm/yr of standard deviation. The velocity standard deviation is calculated based on a bootstrapping approach, which uses the cumulative displacement data and repeated bootstrap sampling from original cumulative displacement data, then calculates the velocity. The standard deviation of the velocity tells us how much the estimate velocity estimate varies. The 1 mm/yr of standard deviation is low, which means the displacement time-series is not noisy.

AR:



In our study, we use the SBAS-InSAR technique to invert differential residual topographic phase to elevation change rates. The inversion of the DRTP network for the estimated phase history is implemented in LiCSBAS software (Morishita et al., 2020) using the NSBAS technique, which assumes a linear deformation model. The phase history's effect is predominantly influenced by DRTP along the river channels, as expressed in Eq. (7). The variations of baseline resulting in small jumps within the same year during the dry season is caused by the topographic phase ambiguity (red-coloured component in Eq. (7)). We maintained the perpendicular baseline within a range of ±100 meters because the majority of the interferograms fall within this range. The offset between the different years residual topographic phase includes the combination of topographic phase ambiguity and phase changes linked to changes in the height of the sediment. It is important to note that the differential topographic phase caused by river sediment aggradation is larger than the variations caused by the topographic phase ambiguity. The final elevation change rates are calculated from the residual topographic phase history based on Eq. (7). The DRTP approach enables tracking of elevation changes even in cases of land-cover change, where coherence is lost, preventing the retrieval of the line-of-sight displacement phase.

Structure

In general, the readability of manuscript could benefit from a clearer structure. There are two method sections (methodological background and methods applied in this study). This causes repetitions. The methods should be focused only on things that are needed to solve the focus problem of the study. Starting with the general principal could help non-SAR-specialists to follow. Additionally, some results and interpretations appear in the methods section (which polarization amplitude is higher, the effect of soil moisture, sources of errors and uncertainties…). Vice versa, in the results section, some things are shown that have been presented in the methods before.

AR: Thank you for noting the two methods sections. We have updated the title of Section 3 to 'Methodology for DRTP InSAR application to dry gravel riverbeds.' We have also shortened the section 3.1, and moved most of the text into the supplementary material. After restructuring the manuscript, we have ensured that there is no repetition of text between the methods and results sections, and have given it a simpler structure that hopefully is clearer to the reader.

The introduction and methods sections take 19 pages, results 3 pages, discussion 4 pages and conclusions 0.5 pages. However, the structure of the manuscript should somehow fit the scope of the paper. It might be possible to increase conciseness by re-evaluating, if all 16 figures are necessary to support the main goal.

The discussion about uncertainties appears as an own section before the section "Discussion". The section 8.1 "Validation…" consists of one paragraph giving an outlook on further research and only a brief comparison to other sediment aggradation rates. This could be elaborated in more detail.

Geomorphological processes

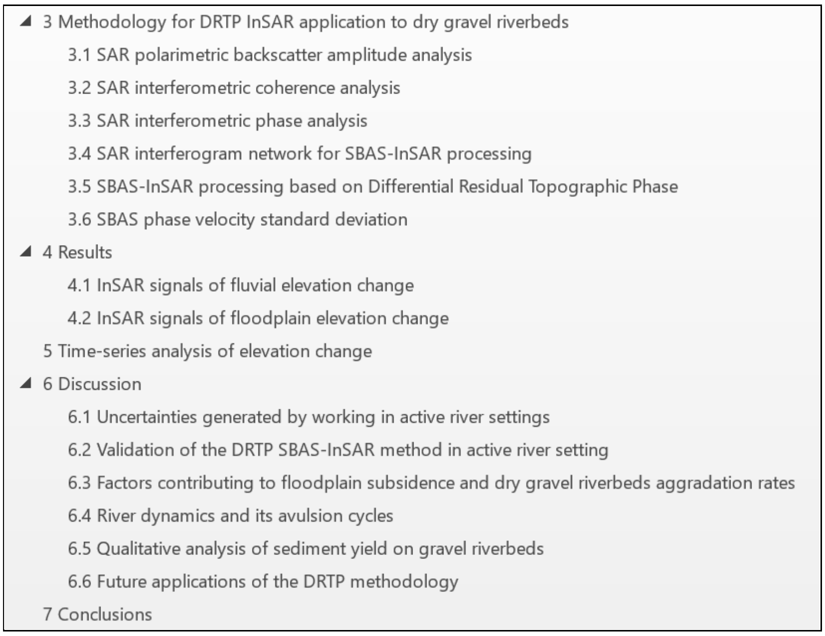
The positive elevation change is highest close to the mountain range. How can you exclude influences of topographic uplift of the mountains also raising the riverbeds? Fig. 17 touches this aspect by comparing the riverbeds to the surrounding areas. How can you make sure that the differences in elevation change are not influenced by the different datasets and processings (20 m vs. 100 m resolution)?

AR: Thank you for highlighting the structural issues in the manuscript. We have restructured it, as illustrated in the figure below.

AR: The reviewer raises a good point here that we are keen to emphasise. Whilst there are localised areas in the Gangetic Plains where blind thrusts may cause structurally driven surface uplift, we can remove this as a signal in this area by demonstrating that the floodplains are subsiding. So the contrast with increasing elevation occurring solely in the channels implies that this process is linked to surface processes of sediment transport in the channels themselves.

AR: The 20 m and 100 m resolution datasets are produced from the same InSAR data, differing only in resolution. The variation in resolution is due to coherence levels: the riverbeds have high enough coherence to achieve a good signal-to-noise ratio at 20 m resolution. Both the 20 m and 100 m resolution results are processed using the same reference point. The differences in elevation change are likely governed by the phase information at the different land-cover (riverbeds and floodplain). At the riverbeds, the phase primarily has residual topographic phase contribution, while at the floodplain, it has both line-of-sight displacement phase and residual topographic phase contributions.

AR:



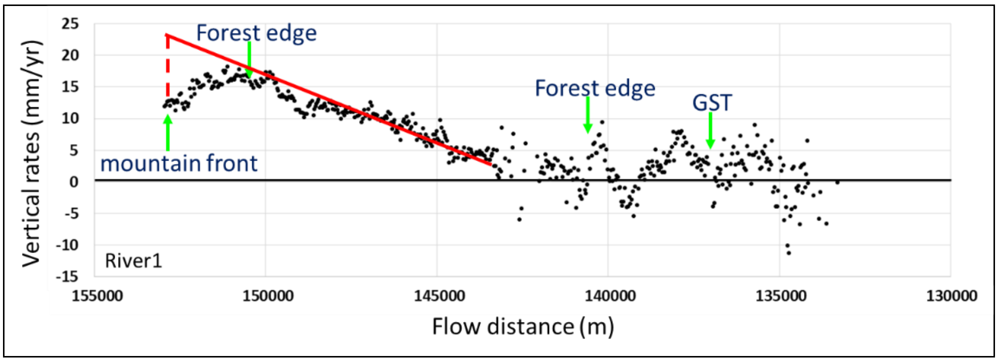
- 3 Methodology for DRTP InSAR application to dry gravel riverbeds
  - 3.1 SAR polarimetric backscatter amplitude analysis
  - 3.2 SAR interferometric coherence analysis
  - 3.3 SAR interferometric phase analysis
  - 3.4 SAR interferogram network for SBAS-InSAR processing
  - 3.5 SBAS-InSAR processing based on Differential Residual Topographic Phase
  - 3.6 SBAS phase velocity standard deviation
- 4 Results
  - 4.1 InSAR signals of fluvial elevation change
  - 4.2 InSAR signals of floodplain elevation change
- 5 Time-series analysis of elevation change
- 6 Discussion
  - 6.1 Uncertainties generated by working in active river settings
  - 6.2 Validation of the DRTP SBAS-InSAR method in active river setting
  - 6.3 Factors contributing to floodplain subsidence and dry gravel riverbeds aggradation rates
  - 6.4 River dynamics and its avulsion cycles
  - 6.5 Qualitative analysis of sediment yield on gravel riverbeds
  - 6.6 Future applications of the DRTP methodology
- 7 Conclusions

Following your analysis, the surroundings close to the mountain margin lowered 60-90 mm over the studied time period and the river channels raised 70 mm. This means that the channel raised 130-160 mm relative to its surrounding. Is there a way to verify this?

AR: For analysing elevation rate changes along riverbeds due to subsidence and sedimentation, we will use river 1 as an example (refer to the figure below). The solid red line represents the projected trend in sedimentation rates for River 1. The dashed red vertical line, showing a rate of approximately 10 mm/yr of the difference between the projected sedimentation rates and the observed elevation change rates at this pixel in river 1. The 10 mm/yr is from the subsidence effect. This indicates that the riverbed at the mountain front pixel raised by 12 mm/yr, while the adjacent floodplain subsided by 10 mm/yr. Both measurements reference to the same point, which is the airport located at the embanked, inactive riverbed.

AR: In addition, we have referred to the cross-validation between the channel and floodplain in our earlier response. We have also discussed more general validation of the results in the response to reviewer 3, and in the discussion section 6.2, lines 488-503.

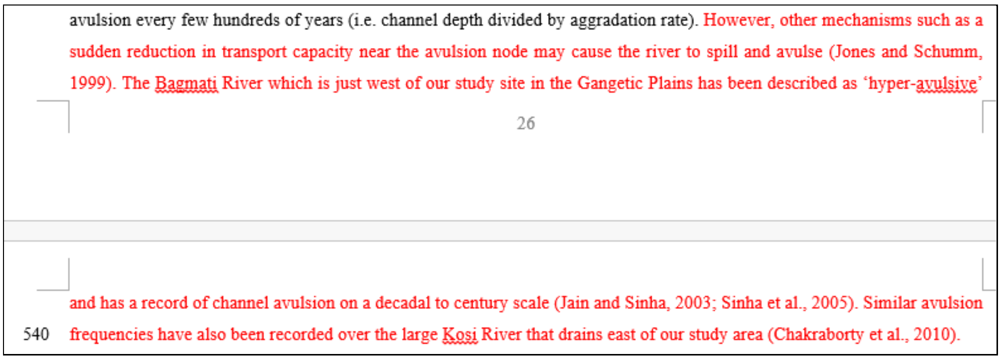
AR:



You interpret a "channel avulsion every few hundreds of years". If this is true, this should be possible to see in the geological record, detectable by geophysics or in outcrop profiles, and it might even be possible to date avulsion layers. Without further proof or discussion, this hypothesis stands alone.

AR: We have added three additional references that discuss rapid avulsion frequencies in rivers immediately east (the Kosi) and west (the Bagmati) of our study site in lines 536-540.

AR:



avulsion every few hundreds of years (i.e. channel depth divided by aggradation rate). However, other mechanisms such as a sudden reduction in transport capacity near the avulsion node may cause the river to spill and avulse (Jones and Schumm, 1999). The Bagmati River which is just west of our study site in the Gangetic Plains has been described as 'hyper-avulsive'

and has a record of channel avulsion on a decadal to century scale (Jain and Sinha, 2003; Sinha et al., 2005). Similar avulsion frequencies have also been recorded over the large Kosi River that drains east of our study area (Chakraborty et al., 2010).

If the riverbed is incised into the surrounding floodplain, there must be an erosive process. How and when does erosion happen? If I understood right, then during monsoon there is aggradation and during the dry season there is no sediment change. If finally, the channel is filled up and avulsion happens, how does the channel erode into the surroundings again?

AR: We are not convinced that there is any evidence of significant incision of the channel into the surrounding floodplain. Our Figure S4 in the supplementary material demonstrates that all of the channels are aggrading, with a few localised patches of net subsidence that may be caused by localised erosion of the channel. Once the channel is abandoned through avulsion, there is no further process to drive erosion.