

# Automatic Delineation of Cracks with Sentinel-1 Interferometry for Monitoring Ice Shelf Damage and Calving

We thank the Editor for its comments and corrections. In the following, the editor's comments are reported in italic bold font. The replies of the authors are provided below each comment in normal font. The line number refer to the corrected manuscript without track change.

## ***Reply to Editor***

***Thank you for submitting your revisions which was positively evaluated in the re-review. The manuscript is now almost ready for publication. Congratulations!***

***Unfortunately, I do not concur with the reviewer's judgement of the high presentation quality. Below you will find many comments regarding language, definitions and layout of the manuscript.***

***In particular, I believe we do not have the same concepts/terminology to describe the different ice dynamic components. Although I understand your desire to differentiate between different mechanisms (e.g. "deformation" and "flow" in equation (1)), I don't think this is correctly done here (cf comment to L457). Also I believe that InSAR cannot differentiate between those components without external knowledge. This must be worked out more clearly.***

We apologize for the inaccurate terminology used for describing ice dynamics. Given the confusion raised by our choice to describe the different phase components, we decided to restrict ourselves to the tide and ice flow contribution, and to remove the deformation/displacement part that may be less relevant for a general ice shelf description. We do believe, however, that such a distinction can be made between ice flow and displacement in some circumstances: when the ice detaches from the shelf, the ice does not "flow", it "moves" (c.f. explanation of the rigid body rotation in section 6.5).

Regarding the InSAR phase, we do not wish, in no instance, to let readers think that InSAR can a priori differentiate between the different phase components. We attempt to clarify this in the manuscript by using words such as "blend", "combination" or "cumulative effect".

***Another example is that "stress", "strain" and "strain rates" appear to be used interchangeably but those are surely not the same things.***

The words "stress", "strain" and "strain rates" have indeed been loosely used and confused with each other. We revised their use throughout the manuscript, which should now be adequate.

***None of my comments challenge the concepts or findings of the paper, but I still urge them to take them seriously so that the paper can be made more accessible to a wider readership.***

- L 56 remove „for the first time“. This also doesn't fit with the reference from 2016.

The paper by Torres et al. (2016) discusses the data availability, coverage and revisit of Sentinel-1. It presents the global observation scenario of Sentinel-1 and it supports the fact that this mission is a gain for continuous monitoring compared to previous missions. We believe that "for the first time" is adequate as such a long-term systematic coverage of Antarctica was never achieved with SAR sensors before Sentinel-1.

- L 68 "about" -> "around" (?)

Both "about" and "around" are correct in this context.

- **L 74 InSAR does not detect “stress field changes”, only if those lead to deformation. Consider rephrasing.**

We rephrased the sentence (L74-75).

- **L 95 I don’t think the abbreviation SWIT is needed.**

The abbreviation has been removed.

- **L 110 Again I don’t think InSAR captures “stress”. It captures strain rates related to stress gradients.**

You are right. InSAR does not directly capture the “stress”, it captures the strain (deformation) resulting from the stress – if the deformation is not spatially constant. The difference between two consecutive interferograms therefore captures the variation of strain pattern. We rephrased the sentence (L111).

- **Figure 1: Add text “Fig 1c,d” to the white dashed box in Fig 1a.**

Figure 1 has been modified.

- **L 140 I don’t see icebergs being treated here. Remove this example.**

Modified (L143).

- **L 140 Somehow, I feel this is described more complicated than needed. How can you differentiate in an interferogram between  $d^{ij}_{LOS}$  and  $v^{ij}_{LOS}\Delta^{ij}$  ? I don’t think you can.**

No, indeed, you cannot differentiate both without further information. As stated in the response to your previous comment, we simplified the description and removed the deformation/displacement component for the general description of an ice shelf (see Equation 1).

- **Fig 2a does not show “tidal bending” (nothing is bend here). Replace with “vertical tidal displacement”. Bending only occurs in the grounding zone.**

We changed “tidal bending” for “tides” (L157).

- **L 166: add “..SAR interferometry captures [the cumulative effect] of spatially...”. Rephrase the stress field component.**

We rephrased the sentence (L166-167).

- **L 168 In order for tides to be visible (rather than a constant phase offset) you require a spatially variable tilting of the ice shelf, correct? I don’t understand how you infer that “...the change of vertical position for a given pair of acquisitions shows smooth spatial variations of only a few centimeters”. The interferometric phase lumps all effects (ice-shelf tilting through tides, horizontal ice flow motion,..) together so how do you infer without external evidence that one of the components is small? I agree that horizontal ice-flow is more important than a residual tidal signal in the vertical but the chain of arguments for this is unclear.**

Yes, the tides are captured by the interferograms if the surface is tilted. That is what we intend to say when talking about “spatial variations”.

It is of course impossible to infer the amplitude of vertical displacements caused by tides directly from the interferogram. This information comes from the same models that we use for tidal correction of

offset-tracking maps, i.e. CATS2008 for tides and ERA-5 for atmospheric pressure. We realized that it may be unclear from the text and we rephrased it (L172-173).

- **L 177 “...crack detection is performed on interferograms containing the information of all three phase components”. This sentence and much of the information in the paragraphs above suggests that you can in theory differentiate between the first three phase components in eq. (1) in an interferogram. I don’t think that this can easily be done (e.g., you would need a model for ice-shelf tilting as a response to spatially variable tides).**

We actually intend the exact opposite. As we cannot discriminate the different phase contributions and we do not know for sure what are the processes involved in the rifting activity, we cannot establish the origin of the interferogram segmentation. Therefore we assume that the discontinuity may arise from each one of the components. We rephrased the paragraph in order to clarify this (L179-183).

- **L 200 Which DEM is used for the topographic phase correction? What is the effect if the DEM does not capture small-scale variability such as cracks?**

The TanDEM-X polar DEM with 90m spatial resolution is used for subtracting the topographic phase. Obviously, surface features such as crevasses and cracks advancing with the ice flow can hardly be subtracted by a DEM.

In practice, the SAR signal sees only some part of the crack depth, if not in the shadowed area, because the crevasse walls are steep and very high incidence would be needed to see the bottom of the crevasse. The subtraction of a DEM that does not capture the crevasse surface roughness will still leave a residual topographic phase and introduce local phase discontinuity. Contrary to rifts and cracks, we do not usually observe phase ramps with different orientations and fringe rate on both sides of the crevasses. We added a short discussion on this effect (L168-171).

- **L 204 “The phase signal in the interferogram is a sum of the ice motion component, the tidal component and the random phase noise...” . Eq (1) lists four terms, here only three are mentioned. Does this mean one component (supposedly  $\phi^{ij}_{flow}$  ) has been removed? I don’t think this is the case. The more I advance through the paper, the less convinced I am that the distinction of  $\phi^{ij}_{flow}$  and  $\phi^{ij}_{defo}$  is needed.**

See our previous reply on the simplified INSAR signal model.

- **L 240 All tuning parameters should be explicitly mentioned so that the study is reproducible.**

All parameter values used for this experiment are clearly stated in Section 5. Since they may change from one test site to another, we prefer not to specify them in the “method” section, as it could make the reader think that those parameters are directly transferable to other cases.

- **L 247 What is the reason that the 50 m contour line of the TanDEM X DEM is used rather than any published grounding line (e.g., the one displayed Fig 1a)? The clipping will be unnecessarily inaccurate.**

Grounding line locations are usually provided as vector lines, very often discontinuous, making it not straightforward to convert into a mask. They also do not necessarily fit the location of the grounding line during period of interest. Given that the region around the Brunt Ice Shelf grounding line is highly crevassed and that a comparison with the NASA MeaSURES’ grounding line location showed no major change of the mask coverage, we decided to stick to the DEM-based mask. This decision was also supported by the fact that the focus of the study is set on the North Rift far from the grounding line location.

- **L 255 Provide numbers for “small” to keep everything reproducible.**

As for the comment on L240, the cutoff length of the dangles is given in Section 5 (L353).

- **L 319 Here the parameters are provided that I asked for previously. I think this can be presented more succinctly by including the “processing” steps directly in the methods.**

As answered to the comment on L240, we prefer to provide the parameter values altogether in a section describing the experiment, as we do not wish the reader to believe that these parameters are necessarily valid for all study cases. We also believe that, if the reader wishes to reproduce the results, it is easier for him/her to have all the parameters listed at the same place rather than looking for them throughout the text.

- **L 363 “As already stated above, ...” no need to start the sentence like this. Either its worth repeating or it is not.**

We rephrased it as: “As observed also in Fig. 8...” (L393).

- **L 428 remove “))” and “see”.**

This has been modified (L460).

- **Figure 10 What does the AA stand for in the title?**

“AA” stands for Antarctica. This has been changed to the full name.

- **L457 “..changes in flow velocity or creep deformation..”. I believe we have different ice dynamic concepts. For me ice-flow has two components one due to internal ice-deformation and one to basal sliding. Both leads to a displacement at the surface. If “creep deformation changes” so does the “ice flow”. I believe what you are trying to distinguish here is “plug flow” (which is the most relevant flow regime for ice shelves with essentially 100% basal sliding and 0% deformation) and other components. Anyway, the way this is written here and also elsewhere repeatedly confuses me.**

As already stated before, we reviewed the ice dynamics terminology throughout the text. For this specific comment, we removed “creep deformation” and left only “ice flow” (L205).

**Later in that sentence only “ice flow” cancels during the doubled differencing. What happens to the “creep deformation” ? Further on in this sentence only the “natural variations...and the deformation” are left in the double differenced interferograms. What do you mean by “natural variations” ? Tides go “naturally” up and down, but this is not what is left in a double differenced interferogram. What is left is the differential tidal signal.**

**How about something like: “The differential phase of double differenced interferograms is composed out of the differential vertical displacement by tides and time-variable components in the horizontal velocities between the two interferograms.**

The sentence has been rephrased (L204-207).

- **Section heading 6.5: Rephrase, InSAR does not see stress field variations. It sees related strain rate patterns.**

The heading has been modified.

- **This entire section starts be reiterating basic concepts of differential interferometry. This should be moved to the methods.**

We re-arranged Section 3 on SAR interferometry over ice shelves and move the first part of Section 6.5 to a subsection of the Section 3.

We choose to move it to Section 3, which is more about “rationale”, instead of Section 5 because this paragraph is part of the result interpretation, not of the detection method.

- **L430 “bulk contribution” seems like an unfortunate term. Define it as “the time-invariant contribution” or something like that.**

As suggested, we replaced it as the “time-invariant core contributions” (L181).

- **L 470 Differential interferometry does not “isolate” the signal caused by rifting activity. As stated in the paragraphs before this differential signal still contains other processes (e.g. differential tides). Maybe “amplify”?**

We changed it to “emphasize” (L473d).

- **L 473 The first interferogram sees the “strain” the second “the stress field” and the third the “fringe pattern”. This is another example where I urge you to use consistent terminology. Please unify the discrepancy of “stress”, “strain”, and “strain rates” throughout the manuscript. Those terms cannot be used interchangeably. I don't think InSAR can pick up any stress patterns.**

As already replied to your previous comments, we review the use of those words throughout the manuscript.

- **L 480 “..the observed phase ramp could either correspond to a vertical deformation or to a horizontal displacement..”. I agree, but what about the deformational component that you introduced in eq (1,12)?**

See our previous reply on the modification of the INSAR phase signal model.

- **L486 Use “the differential phase” when you refer to double differenced interferograms.**

We are not certain to spot the confusion in this case. For the sake of clarity, we have specified “double difference interferograms” and added “differential phase” throughout the paragraph. In order to avoid confusion, we decided to switch from “differential interferograms” to “flattened interferograms” throughout the text.

- **L502 “dominates..” -> “..that is larger than the differential tidal displacement in the vertical.”**

Corrected (L514-515).

- **L526 “iceberg drift”? Icebergs are fully disconnected from the ice sheet. I don't think this is the case here. Rephrase.**

We rephrased it as “...the displacement of the future iceberg as it separates progressively from the ice shelf after the opening of the North Rift over the full ice thickness and its consequent widening” (L525-526).

- **Acknowledgements: Consider thanking the reviewers.**

The acknowledgment has been added.