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

We thank the reviewers for their comments and corrections. We tried to respond in a relevant and concise way to all the comments. In the following, the referee's comments are reported in italic bold font. The replies of the authors are provided below each comment in normal font. We first address the comments of Referee #1 and then those of Referee #2.

Please mind that, resulting from the review process, one figure has been added and the numbering of the last two figures has therefore been shifted by one (Fig. 12 -> Fig 13 and Fig. 13-> Fig. 14). Some equations have also been added.

Reply to Referee #1

Overall a well-written paper, which is generally easy to follow, although there are some minor points that should be clarified.

- ***P.5, L116: "cracks at the scale of the pixel resolution". I think "spatial resolution" is a better term, as this is a lower limit (pixel size is often smaller).***

We agree and changed "pixel resolution" to "spatial resolution" (L114).

- ***P5, L116 to L123: Please provide numbers for the resolution, wavelength, and revisit time of the sensor, as this helps in interpreting the results and may not be known by everyone.***

We have added a table with the main sensor characteristics specific to S-1 SLC acquisition in IW mode (see Table 1).

- ***P5, L131, "we assume the phase noise is negligible". Although it is not relevant exactly for the discussion here, the temporal decorrelation should be briefly discussed somewhere in the introduction or theory section.***

We briefly introduced temporal decorrelation and the main factors causing it in L151-154.

- ***P6, L139: The sign of $Dtidesij$ used in equation (3) is not defined – is it positive for an upwards motion? In that case, the sign in the equation seems wrong. Since it is a purely vertical motion, perhaps it would be better to define it as a scalar.***

Indeed, in this case, there is an error in equation (3). We changed the vector $\vec{D}_{tides}^{ij}$to a scalar parameter D_{tides}^{ij} and specified that upward motion corresponds to positive values of the parameter. This corresponds to a negative change in slant range when projected on the LOS and therefore a negative phase component. We change the sign in equation (3) accordingly.

- ***P8, L193 "The wrapped interferogram is geocoded". Would it not be easier and more precise to calculate the gradients and edge detection in the original radar geometry, where the resolution in each dimension is known and can be accounted for, and no geocoding of a wrapped phase is required? Then just the final result could be geocoded. Please comment on this.***

The phase gradient and derived products could indeed be calculated in the original radar geometry. However, for the following reasons, we prefer the geocoded approach:

1) Pixels usually do not have the same dimensions in the slant range and azimuth directions and it is therefore necessary to apply a scaling factor for calculating the gradient (i.e. calculate the

phase variation per meter or per degree, not per pixel). In this case, one can easily consider different length scales for calculating the spatial gradient in both directions, which should be avoided. In the geocoded case, pixels are usually and easily squared, making it straightforward to work at the same scale in both directions.

2) Although we do not use the phase gradient direction in this context, it seems more natural to calculate it in geocoded geometry and provide an angle relative to a projection axis, rather than to calculate it in radar geometry and provide an angle relative to the satellite flight path. Generally speaking, it should allow to work with gradients calculated along different orbits.

- ***P8, L201: "The discrete phase derivatives are computed by averaging the phase differences between adjacent pixels along the x- and y-directions over a square window". The windows applied in eq 6 and 7 are not square, they are one-dimensional.***

There was indeed a mistake in the mathematical description of the phase gradient calculation. A second summing sign, accounting for the second dimension of the window, has been introduced in equations (6) and (7) for describing adequately the calculation that is performed in practice (L217-218).

- ***P10, L224: "we neglect the phase gradient direction". Of course, the gradient direction is not meaningful when the magnitude is low and should not be used in this case, but could it not be useful in a situation where the magnitudes on two sides are equal, but the directions differ? Please comment on this.***

One could imagine a situation where the fringe rate is similar on both sides of a crack, but fringes have a different orientation, in which case, yes, the phase gradient direction would be useful. However, exploiting the phase gradient direction would require an edge detector that would be able to deal with the wrapping of the angles and would still be as efficient as, for example, the Canny edge detector. Ideally, the information from both phase gradient magnitude and the phase gradient direction should be combined in order to exploit the comprehensive fringe information. Such investigations are ongoing but are still at an early stage. For the study case presented in this paper, the phase gradient magnitude seems to already provide an added value.

- ***P11, L254 "uncompensated tidal displacements". These have no component in the along-track direction so they should not lead to phase jumps at the burst overlaps?***

That is right and the sentence has been removed.

- ***P13, L291 "all areas above 50 m height". Is this a general rule or does it only apply to this dataset?***

It is specific to this dataset. The mask could also have been derived from the grounding line location, as elevation drops clearly in this region.

- ***P17, Section 6.4: Could the interferometric coherence perhaps show some of the fractures more clearly than just the backscatter image? Please comment on this, and maybe provide an example if this is so. Maybe also comment on whether the interferometric coherence could add some value to the processing, other than just the thresholding.***

The North Rift can be observed clearly in some coherence images. Other cracks like Chasm 1 or Halloween crack, not necessarily well-captured by the phase gradient, appear also clearly in coherence images. We provide a sample of coherence examples in Figure 1. Depending on the viewing geometry, the crevasses appear also highly contrasted.

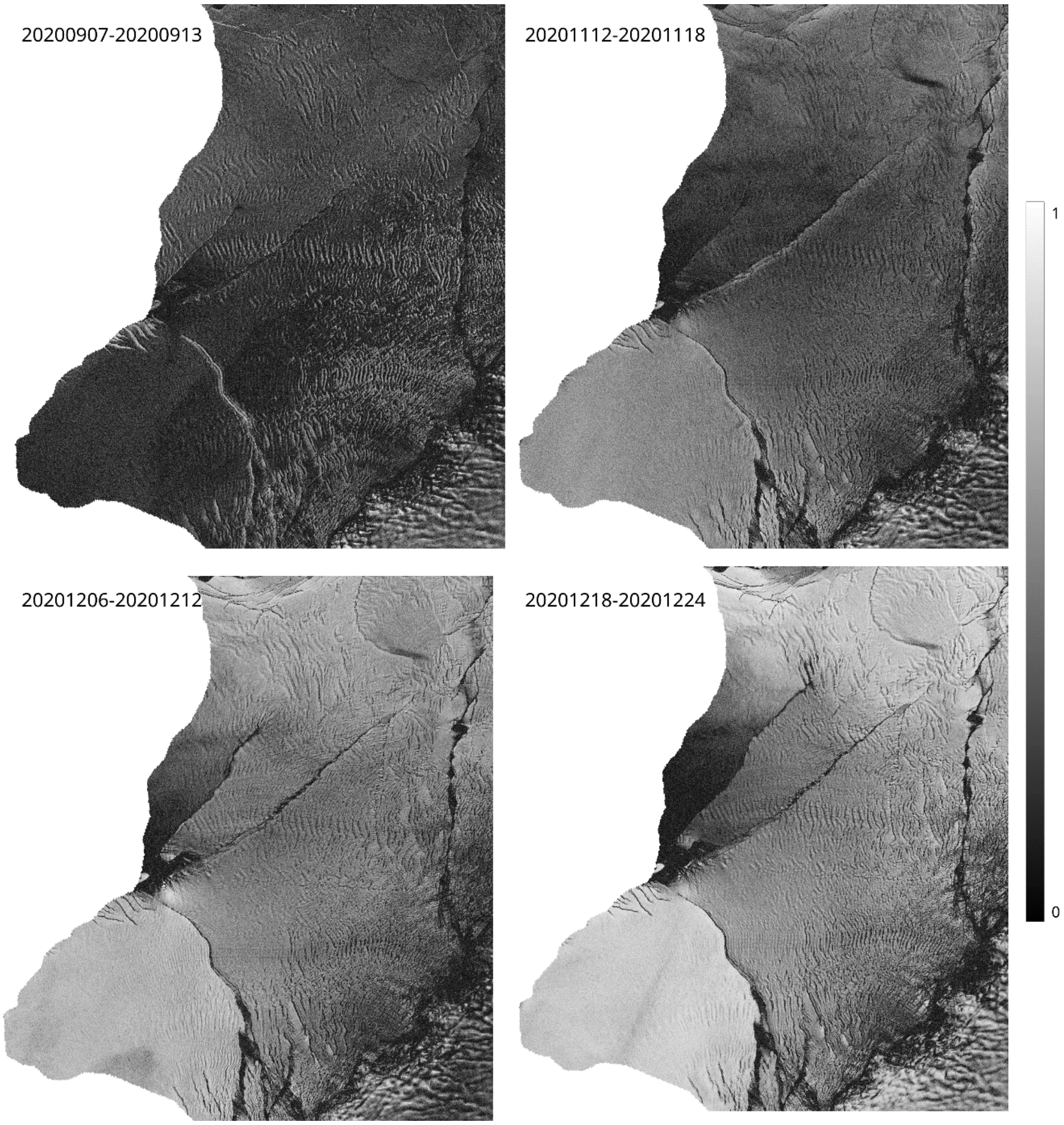

Figure 1: Sentinel-1 coherence over Brunt Ice Shelf. Acquisition dates are annotated in the upper left corner of each image.

In practice, while interferometry may accommodate with coherence levels of about 0.4-0.5, which are quite often encountered, such coherence values reduce strongly the contrast between the ice sheet background and the crack in the coherence image. We observe it around the North Rift, e.g. for the acquisition of 12-18 November 2020. In the few examples provided here, we also observe that a crack may sometimes result in a positive contrast, and sometimes in negative one (see the Chasm 1 on 7-13 September compared to the other dates), depending on the changing conditions (snow, melt, wind, etc.) on the ice shelf. The variations of contrast level and contrast sign make it challenging to use coherence for crack detection and would require further characterization of the coherence behaviour.

In Section 6.4, we aim at comparing the information held by interferometric phase against imagery and show the benefit of the first over the latter. Since coherence is a measure of the interferometric phase quality, it basically holds the same information as the phase and displaying coherence images instead of backscatter images would not meet our purpose. However, following the suggestion of the referee #2, we added a comparison with Landsat-8 optical images for validating the tip of the crack (see Figure 12).

- ***P19: Figure 12: The figure comes before it is referenced in the text. The same goes for Figure 13.***

We change the position of these figures and we have no doubt that this kind of formatting issue will be handled properly by the editor, if the paper is accepted.

- ***P20, L398 and 402: "Differentiation" implies finding a derivative. Please use the word "differencing" or "difference between"***

This has been corrected (L454 and L458).

- ***P20, L411: "This number of fringes corresponds to a displacement of about 35 cm in the direction of the line-of-sight". Isn't it technically a change in LOS displacement, changing along the fringe belt? What is the direction of the change (negative or positive in LOS)?***

Yes, in the double difference interferogram, the amount of fringes corresponds to a change in LOS displacement between the two interferograms, relative to the point where you start counting the fringes (in this case, the origin of the crack) and this relative displacement change has the same magnitude for all the points along a given fringe. We agree that the sentence might be misinterpreted and we modified it to make it clearer.

Positive phase corresponds to a motion (or change in displacement) in the direction away from the satellite. In the double difference interferogram along track 50, on the region north of the rift, the phase increases from the expanding tip towards the origin of the crack (MIR). South of the rift, between the North Rift and the Halloween Crack, we observe a phase decrease in the same direction. This actually indicates distinct stress field variation on both sides of the North Rift.

As a response to your comment and those of the second referee, we clarified the sign of the phase in the double difference interferograms and lengthened the discussion in section 6.5.

Some minor typos:

- ***P1, L.10: "These unprecedented ... enable" should be "The unprecedented … enables"***

Corrected (L10).

- ***P2, L.33 "results into" should be "results in"***

Corrected (L33).

- ***P2, L.43 "iceshelves is" should be "iceshelves are"***

Corrected (L43).

- ***P2. L.56 "wide SAR images" should be "wide swath SAR images"***

Corrected (L61).

- ***P5, L105 "November 2021" should be "November 2020"***

Corrected (L106).

- ***P5, L120 "deramping or burst stitching" should be "deramping and burst stitching"***

Corrected (L121).

- ***P7, L180: “hence” should be deleted***

Corrected (193).

- ***P7, L184 “account for” should be “accounting for”***

Corrected (L197).

- ***P12, L274 “REMA DEM” should be “the REMA DEM”***

Corrected (L305).

- ***P21, L417: “opposite”, please use another word, like. Opposite suggest a 180° change of the LOS direction.***

We change it for “… a line-of-sight rotated by about 60° with respect to track 50” (L482).

Reply to Referee #2

Libert et al. map the growth of a rift on the Brunt Ice Shelf, making use of the high frequency of Sentinel-1 imagery to provide a time series of crack evolution. Their interferometric method using edge detection of phase gradient magnitudes has an advantage over interferometrically-derived strain fields in that it does not rely on phase unwrapping, however, it has a disadvantage over other rift detection techniques (for example backscatter contrast or edge detection in optical imagery) in that it requires multiple images, with good coherence between image pairs. The method accurately tracks the location of a rift on the Brunt Ice Shelf. It also approximates the timing of rift growth. The timing is not validated by other observations, so it is currently difficult to assess the accuracy in detection of the rift tip itself.

The delineation of the rift is dependent on multiple (presumably tuned) threshold parameters, various stages of filtering and line cleaning to reduce unwanted noise. This appears to be a careful balance between keeping real cracks and removing artefacts. It would be valuable if the authors explained how the parameters are determined.
The paper is well written and provides a useful dataset for this particular ice shelf, but whether it would be valuable to apply to automatic crack detection on other ice shelves, given the added complexity and data processing requirements associated with interferometry and the lack of evidence that there is any improvement in positional accuracy, or detection success, is not clear.

Specific comments:

- ***Line 23: I don't think you should link fracturing and damage development to climate warming here. The large independent rifts you observe on the Brunt Ice Shelf are not related to climate warming and I have some doubts that your method would work well in areas where this is the case, for example where these is dense damage / cross-cutting cracks or complex shear margins.***

We agree that this is not demonstrated in the paper and that the method might not be applicable for any type of damages, especially over fast-flowing ice shelves with complex disintegration pattern at the calving front. A typical non-working example would be Pine Island Glacier. The reference to climate warming has been removed, both in the abstract and the conclusion.

- ***Line 43: sp '…the majority of ice shelves are routinely monitored…'***

Corrected (L43).

- ***Line 54-55: There is published work that suggests that SAR backscatter imagery can be used to detect narrow cracks under the right viewing geometry (e.g. Thompson et al., 2020, 10.1016/j.coldregions.2020.103128)***

Publications like Thompson et al. (2020) or Marsh et al. (2021, 10.1016/j.coldregions.2021.103284) do indeed suggest the possibility of identifying crevasses and cracks up to only a few centimeters wide (much smaller than the sensor resolution) using very high resolution TSX Stripmap (resolution of 1.2 m x 3.3 m) and Spotlight (resolution of 1.2 m x 1.7 m) mode imagery. However, these data are typically not acquired operationally and only cover small areas (e.g. 10x10 km for TSX Spotlight, 30x50 km for TSX Stripmap). Both studies also underline that crack/crevasse visibility is strongly dependent on the viewing geometry (look direction, incidence angle) and the crack orientation. Another strong dependence arise from the water fraction in the snowpack, that reduces signal penetration when increasing and masks deeply buried features, especially during the melt season. Though these two publications highlight the potential for identifying crevasses with SAR backscatter imagery, they do not propose a detection method and the crack identification is performed in these studies by visual inspection. Moreover, the focus of our paper is set on active rifts, not on the detection of crevasses that may or may not be active.

For improving the state of the art, we have added the two references mentioned above in the introduction and described the pros and cons of SAR backscatter imagery for damage detection (L46-54).

- ***Line 107: It is not necessary to repeat what you are about to say in the next section***

The sentence has been removed.

- ***Line 223: I expect that in the event of a crack opening in pure mode I extension parallel to an ice shelf front, while the velocity may be different on either side of the crack, the phase gradient may not show a significant difference. In this case, edge detection on your offset tracking output may work better. Have you compared this to the interferometry?***

We have tested the edge detection on the velocity magnitude derived from offset-tracking. Doing so, the delineation results are less noisy and the North Rift can be detected, but not necessarily the other cracks. For example, Halloween crack is not always nor completely detected for the dates that we have considered. Though we acknowledge that the timing of the INSAR-based detection is not fully validated, it seems that interferometry captures a more advanced location of the crack tip compared to offset-tracking. This is in agreement with the higher spatial resolution of SAR interferometry and its better sensitivity to changes.

- ***Line 249 – 258: The method appears to suffer both from false positives and false negatives. The Halloween Crack was active during this period (continuing to widen by almost 0.5 m / day in the center).***

Most of the "false detections" (false positives), e.g. close to the grounding line, originate from crevasses. We attempt to clean them because we aim primarily at mapping fractures and they make the detection results noisy, but these detections still picture actual damage. Discriminating between one type of damage and another is obviously challenging.

Regarding the Halloween crack, it is not fully delineated, but part of it is detected for some dates. A possible reason for missed/partial detection of Halloween crack could be that the widening does not introduce as much change in the strain field as the propagation. From the backscatter images, we observe no advance of the Halloween crack over this time period. Let us also mention that the test performed with offset-tracking did not allow to detect the Halloween crack either.

In order to avoid confusion, we rephrased the sentence at L288. Instead of "inactive", we say that the Halloween crack was "not propagating" at this time period.

- ***Line 288: Does this 9 x 9 refer to the value for 'w' in the previous section? It would be useful to restate here (i.e. w = 9).***

It refers indeed to the *w* parameter of the previous section. We restated it, as suggested (L319).

- ***Paragraph 288: As the method is described as automated it is important to explain how these values were determined. What is the sensitivity of the results to these values? Do these parameters need to be changed if the velocity is different, or if the coherence is worse, or under a different viewing geometry, or on a different ice shelf?***

Detection parameters were determined by testing different sets of values on a given pair of acquisitions, and fine-tuned for a balance between detections and false alarms. The upper threshold is critical for detection, as it is the main driver for selecting edges. The value of the lower threshold is less critical, as it mainly allows the connection between the lines corresponding to the strong edges. The value of the detection parameters may need to be adapted in other cases.

The value of the detection threshold mostly depend on:

- Temporal baseline
- Velocity and global orientation of the velocity with respect to the viewing geometry (LOS)

To clarify this, we have added a paragraph (L263-278), showing that the Canny edge detection performs the thresholding on a quantity that is proportional to the temporal baseline, the incidence angle and the local absolute variations of the strain rate. If the expected strain rates are known or can be estimated, an approximation of the thresholds can be obtained. We have also added a sentence L325-329 for stressing that our choice our parameters was an empirical one.

- ***Figure 10: There are only 7 points on this graph, but you say that 32 interferograms were generated (including 9 not used due to coherence issues). It would be useful to add the other 16 points, even if the detected crack length does not change between interferograms. The crack moves in discrete jumps and any periods of no movement are also of interest. This would also help readers to assess the uncertainty in the method.***

For a better summary of the overall results, we have added a panel to Figure 9 that shows the delineation results at the ice shelf scale for all coherent pairs of acquisitions. We have updated figure 10 with the corresponding points. For some pairs, negative propagation rates are measured due to the inaccuracy of the method. In this case, we do not provide the estimated rate values since they are not relevant. We have also updated the text of Section 6.3 accordingly.

- ***Line 363: While it may be difficult to delineate the rift in Sentinel-1 backscatter, it was visible in Landsat-8 at a similar location to the interferometry on 19th January and almost fully visible to the Stancomb-Brunt Chasm by the 6th February, suggesting there is not necessarily a significant information gain using this InSAR method, relative to optical imagery.***

We have analysed these two Landsat-8 images and decided to add them to the discussion in section 6.4. The rift is indeed well visible in those images and the comparison provides a real added value to the paper.

We compared the InSAR detection of 17-23 January with the North Rift location in both Landsat-8 images. This InSAR detection is coincident with the Landsat images of 19 January. The InSAR-based detection shows an agreement within 200 m over most sections of the rift. It is however longer than what is observed in the Landsat-8 images. Comparing the InSAR detection of 17-23 January with the Landsat images of 6 February that shows that crack at a later stage of expansion, we observe that the tip of the rift agrees with the curvature of the rift. This demonstrates the increased sensitivity of InSAR compared to imagery, since it captures the tip location a few days ahead the optical image.

These results have been added (see Figure 12) and the discussion of Section 6.4 has been completed with the analysis of the Landsat-8 images (L405-422).

- ***Line 366: This sentence is a bit odd, consider rephrasing.***

We rephrased the sentence, as suggested (see L424-425).

- ***Fig 12 (a-c): As the fringes are fairly close, it is not immediately obvious from the figures that the color order of fringes is reversed on one side of the crack with respect to the other. This is an important point to highlight that the change in velocity is opposite on either side of the crack (particularly given that the fringe frequency is similar). This could be mentioned in the text to draw the readers' attention.***

Indeed, the color order is reversed on both sides of the cracks. North of the crack, the phase increases from the tip of the crack towards the McDonald Ice Rumples, while the phase behaviour is reversed on the other side of the crack. This indicates distinct responses on both sides of the crack.

Following your suggestions and in response to the other referee's comments, we clarified the phase sign, discussed the phase behaviour in the double difference interferograms in more details and lengthened section 6.5.

- ***Line 410: You should probably refer to strain rate (as they are being measured) rather than stress.***

We modified stress for strain in the text (L473).

- ***Line 443: What do you mean by 'could be misinterpreted as ice flow acceleration by offset-tracking'?***

We aim at distinguishing between a drift motion of the entire chunk of ice, as a whole body, and the speedup of the fluid ice flow. Both would be physically different, especially in terms of vertical gradient (no gradient in the first case, shearing in the second one) that we cannot capture with interferometry or offset-tracking, but they would result in a similar signal since we see only the speed of a single horizontal layer. We attempt to clarify it in L512.

- ***Line 449: The derived rift growth pathway agreeing with the final calving pathway does not fully demonstrate the suitability of the approach for understanding the timing of rift growth. Would it be possible to validate the derived rift tip via other means (e.g. optical imagery)?***

The comparison with final calving pathway aims at validating the spatial extent of the crack, though we know that it cannot account for e.g. secondary branches. Without in situ observations, the timing of the rift growth remains challenging to validate, especially for the tip of the rift, as different delineation methods (based on remote sensing) may have different sensitivities.

In order to strengthen the validation, we exploit optical imagery as suggested (the Landsat-8 images mentioned previously). We compare the crack delineated manually from the Landsat-8 figure and measure the distance between this reference and the edges delineated with INSAR at the same date. The results are provided in Figure 12 and discussed in Section 6.4.

- ***Line 456: Again I am not sure what you are referring to here with respect to ice flow speed up vs ice drift.***

See the reply to the previous comment.