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

Reply to comments of Anonymous Referee #1

We thank the reviewer for its comments and corrections, as well as for raising some fruitful discussions on the analysis. We tried to respond in a relevant and concise way to all those points. 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. 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).

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.

- ***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.

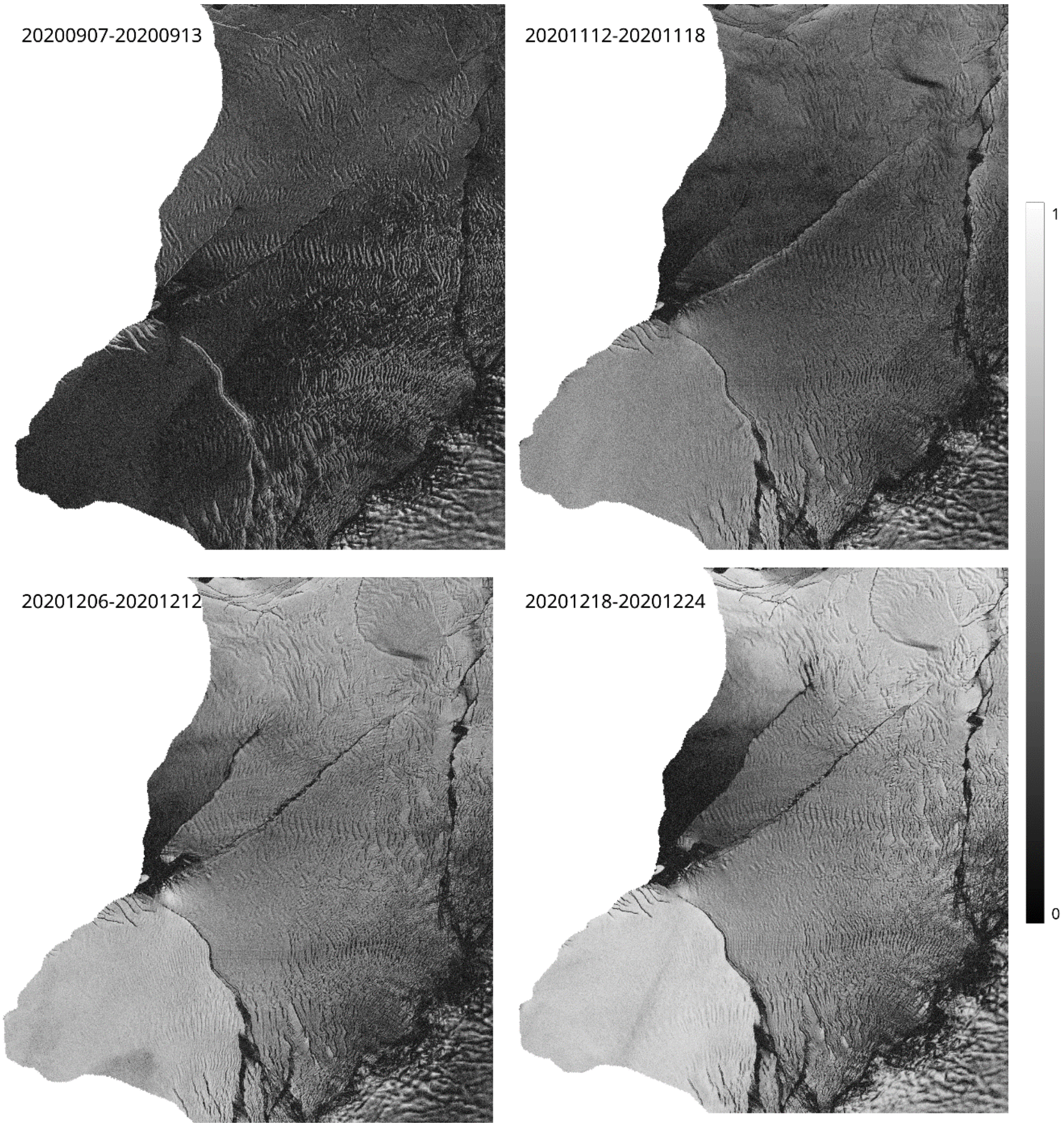

Figure 1: Sentinel-1 coherence over Brunt Ice Shelf. Acquisition dates are annotated in the upper left corner of each image.

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 (L438 and L442).

- ***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.

<u>Some minor typos:</u>

- ***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.

- ***P7, L184 "account for" should be "accounting for"***

Corrected (L197).

- ***P12, L274 "REMA DEM" should be "the REMA DEM"***

Corrected (L290).

- ***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" (L457).