Dear Reviewer,

Thank you very much for providing your valuable comments that helped us to significantly improve our manuscript. Below we provide our detailed responses to your questions in italic font.

Best regards,
Sergey Samsonov, Kristy Tiampo and Ryan Cassotto

This draft proposes a novel method for 3 -D velocity mapping of glaciers using modern spaceborne SAR measurements. Instead of using surface parallel flow constraint, this method combines speckle offset tracking and MSBAS , which is also assisted with regularization. It is further validated with Sentinel-1 data over 5 glaciers in Alaska. The draft is generally well written and the methodology is reasonable. However, there are couple of issues that need to be resolved/expanded in detail.

Major comments:

1. Study area description is better to be extracted from Section I, together with the dataset description in Section 2, to form a separate section, named “Area and Data”

Reply: Thank you. We are prepared to address this issue in the revised manuscript.

1. The model description in Section 2 needs to be clearly rewritten and expanded in detail. If sufficient details do not fit the section, they could be added to an appendix then.

Reply: We are prepared to address this issue in the revised manuscript. In the past, the first author had reviewers telling him not to repeat information that can be cited.

Detailed comments:

Line #13: this is the same sentence as included in the abstract, thus redundant

Reply: Our understanding is that an abstract should stand on its own. We will modify the redundant sentences.

Line #26: SAR-based correlation algorithms not only operate on radar backscatter, but also radar backscatter and phase (complex-valued correlation).

Reply: That is correct. We will correct this in the revised manuscript.

Section I: you introduced multiple methods for velocity mapping (SPO, DInSAR, MAI), but did not mention what specific one you use in this work and why you chose that one. It is clear later in Section 2 that you used SPO, but would be better to motivate it in Section 1

Reply: We will add a statement in the introduction to clarify this.

Line #74: the last sentence is also the same as that included in the abstract, i.e. redundant
Reply: We will amend to remove redundant statements.

Line #83-84: the number of pixels also need to be converted to distance in m. I see you want a square sampling interval on the ground by choosing 64 x 16 for Sentinel-1 images.

Reply: Will do.

Line #84-86: why isn't the correlation window (256 x 256) a square window on the ground to be consistent with the sampling interval. Also, the numbers you chose are equivalently 1km x 4km on the ground. With the 2km wide median filter, you essentially got a spatial resolution around 2km or at least on the order of km. Even though you resampled the products into 200m, this does not justify the spatial resolution is 200m. That said, the spatial resolution is too coarse over fast-moving glaciers, and the resulting spatial pixels are strongly correlated.

Reply: We recognize the benefits of having high-resolution results. Unfortunately, in this area, the application of a small window produces measurements that are too noisy, and if we only select pixels with high SNR the spatial coverage reduces to nothing. Likely this happens because of the warm regional climate and wet glacier surface (in comparison to Greenland or the Arctic or the Antarctic). Therefore, we are limited to using a large window of256x256 pixels.

We consulted the developers of GAMMA processing software that is used to compute speckle offsets. We were advised that the window that is used to compute the offsets is not uniform, pixels in the center have large weights than pixels on edges. The effective resolution is about four times higher than the window size. The process of extraction of offsets, as it is implemented in the software, is not linear. We acknowledge that the spatial resolution is reduced by using such a large window. However, this is necessary for extracting temporal information. Note that the computation of offsets, in general, is not specific in any way to the presented here technique.

To confirm this we computed offsets for a single pair using 64x64, 128x128, and 256x256 windows. In figure 1 we present these results before and after filtering. As you can see, while there are differences, overall the signal is consistent. We will add this figure to the revised manuscript. Note that filtering does not reduce the resolution significantly. Again, we found that these processing parameters are optimal for our purposes, it does not mean that they would be optimal in other areas.

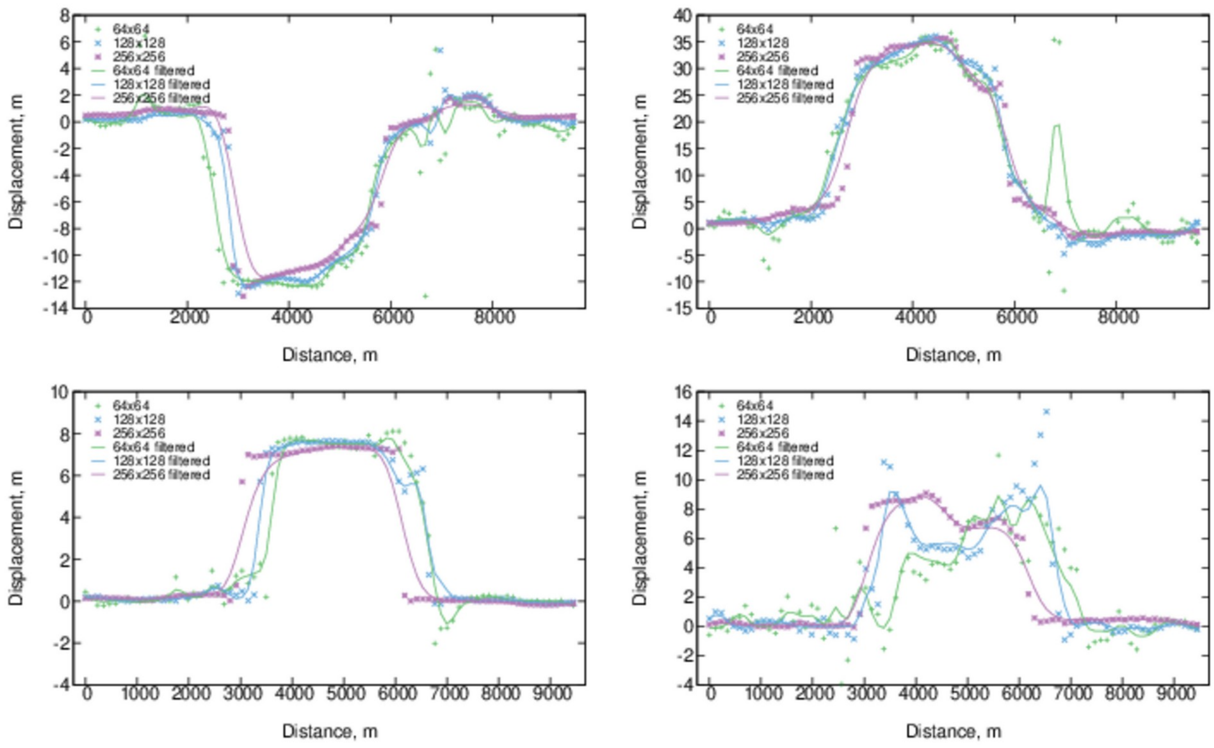

Figure 1: (top-left) Seward range, (top-right) Seward azimuth, (bottom-left) Klutlan range, (bottom-right) Klutlan azimuth.

Eq. 1: you should either cite a reference or explicitly show the proof of this equation. The way it current shows is introducing the equation out of the blue. When details of the proof is involved, you can also put that in an appendix if necessary.

*Reply: It is a basic equation with a meaning similar to V*t =D. We will clarify it in the revision.*

Eq. 1: the matrix/vector notation should be clearly defined by providing the dimension, which should then be related to the number of ascending/descending acquisitions.

Reply: Will do.

Eq. 3: this simplified example is not clear. First of all, it is not clear how the Sa and Sr components are coupled in that way. To do so, you probably need a separate graphic illustration besides Fig. 2 or an appendix. If you can find a citation that does exactly the same thing, that would work too. Second, the notation of the rho and alpha elements in the column to the right of the "=" sign were never introduced since they are different from those described in Line #96 -101. Third, the last three elements in the velocity vector only show the northing of velocity at t3 and easting/vertical of velocity at t4. Why is that and what happened to the missing other components at t3 and t4, and what happened to t5?

Reply: We will clarify the notation and make it consistent.

Line #112: “any phenomenon” This is to vague. You need to be specific what type of phenomenon

Reply: We meant to say any surface motion.

Line #114: the dimension is 609 x 1014 for the matrix to be inverted. As mentiond above, how to relate these numbers to your total ascending/descending acquisitions. After Eq. 1, you should add a symbolic equation that relates the matrix dimension to the number of radar acquisitions

Reply: Sounds good, we will clarify that.

Line #116: please report the specific computer setting and runtime for your case

Reply: We will do. For us, it takes about 24 hours of processing time on a single node with 44 cores. An MPI version of msbas software is on its way. The processing time in an MPI version will be reduced proportionally to the number of nodes.

Line #117-120: add a sentence explaining why regularization is needed, and what happens if not included. Any comparison of the horizontal velocity results derived from the 3-D approach with regularization to those from the 2-D methods? Please add some simple analysis

Reply: Will do.

Line #121: what do you mean by “mean linear flow velocity” especially the word “linear”? Regarding “mean”, is the 3-year mean value meaningful for those fast-moving glacier terminus? It is expected that such glaciers should have strong seasonal/interannual changes. Probably 1-year mean value is better

Reply: With the technique presented here, we compute velocities between consecutive SAR acquisitions. Sentinel-1 data is acquired with either a six or 12 day revisit cycle, and velocities are computed for every revisit cycle interval (so-called instantaneous velocities). The flow displacement time series are then reconstructed from these instantaneous velocities. Assuming a 12 day Sentinel-1 revisit cycle, our technique produces about 365/12 = ~30 4D velocities per year. Since all these data cannot be presented in a single publication (30 velocities per year x 4D x 4 years ~ 480 figures), as a simplified representation of our results that require only four figures, we choose to compute mean velocities by fitting a line to the flow displacement time series. Along with the mean velocities for each of the four components, we compute their standard deviations and coefficients of determination (R2), which help us understand if the linear model provides a good approximation. For some regions, a linear approximation cannot capture all the complexity of the motion. For these regions, we plot flow displacement time series, which describe instantaneous velocity at each moment in time. Annual or any other duration (monthly, quarterly) velocities can also be computed from our flow displacement time series by aggregating time series at different intervals.

Concerning selecting the length of time to estimate mean flow, a shorter period could certainly be used; however, our aim for this manuscript was to demonstrate the technique used and the overall trends that occurred over 4 years. The flow displacement time series and text in the discussion address the benefits of short term analyses such as seasonal and interannual variability.

Line #123: how much coarser resolution is the horizontal one resampled to? And also why is <5m/yr removed? Velocity estimates over slow-moving areas (e.g. < 15m/yr) are usually used to tie the products and calibrate the estimation bias. How did you calibrate your Sentinel-1-derived velocity products?

Reply: The resolution and masking out is performed only for improving visualization, otherwise, the image gets oversaturated with details. We use precise orbits downloaded from the ESA website. We calibrate the offsets by fitting and removing the polynomial model. This approach works well in this region where most areas do not show any motion. The entire Sentinel-1 scene is processed as a whole, and it is cut into small sub-regions only for visualization in the manuscript. Note that the entire Sentinel-1 scene extends far beyond the area shown in the manuscript. The software provides alternative methods of calibration that can be employed in other, more complex, regions (e.g. calibration against multiple reference regions, Z-score).

Line #180: "every single range and azimuth offset maps must be coherent at every pixel" what does it exactly mean?

Reply: This means that if a pixel is incoherent on one of the offset maps (e.g. 20190201-20190213) it will be excluded from the processing and all results will have NaN value at that pixel. In general, our processing software can handle partially incoherent pixels (it will be filled by the regularization); however, in this study, we choose to utilize only pixels coherent in all offset maps so their precision is identical. The technique that utilizes partially coherent pixels will be discussed in the follow-up publications.

Line #181: "large correlation window followed by strong filtering" gives you much lower resolution and spatially correlated pixels. Isn't that problematic for fast-moving glacier terminus? Please comment and justify.

Reply: That is correct. However, it is a necessity to use a large window and filtering as processing with a low correlation window produces very noisy results in this region. This has already been discussed above. It will be addressed in the revised manuscript. Also, in the revised version we will be using a filter with the Gaussian window, we found that it performs better for small and large glaciers. Finally, none of the glaciers in our study area is tidewater and thus do not experience the rapid flow that typifies tidewater glacier termini.