We thank the authors for their response and revising the manuscript according to our comments.

1. There are still some parts of the manuscript (such as the equations/notations in Section 2) that are confusing or misleading.
2. Also, for some responses, the authors only replied to us but did not reflect any changes in the manuscript which may still be misleading or confusing to other readers. Please be sure to both address the reviewers' comments and reflect (even if the comment may sound simple) any possible changes in the manuscript.
3. The revised manuscript still lacks a section on formal error/accuracy analysis (by comparing to other reference velocity measurements) and a discussion section about current limitations and how to improve.

Below we attached the authors' response and only added highlighted comments to those questions that were not fully addressed.

Dear Reviewer 3,

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. Here is a quick summary of changes:

- *Addressed reviewers' comments to the best of our knowledge;*
- *Added recent Sentinel-1 data, mainly to investigate what is happening at region P1 at the Malaspina Glacier;*
- *Recomputed offset maps using smaller 128x128 window and the Gaussian filter with 1.3 km 6-sigma width;*
- *Detected another surging Kluane Glacier and analyzed it in-detail;*
- *Used OGGM software to extract flow lines and performed all analysis for selected flow lines;*
- *Simplified interpretation by removing reference to kinematic waves, which require more attention and, which possibly will be addressed in a separate publication.*
- *Provided animations for four AOIs.*

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: We followed your advice and created a separate section "Study Area and Data".

2. 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 rewrote the section "Model" entirely.

The equations/notations in Section 2 have been rewritten and also additional references have been added. It looks a bit better however, there are still places that look confusing or unclear. For example,

1. please rewrite the 1st sentence of 4th paragraph in Section 2 to use notation of M x N to represent the dimension of matrix A. You could explain what M or N means using the number of unknowns/observables, e.g. number of SLC images.
2. You did not answer our comment why the velocity vector in Eq. 3 only included V_n^3, V_e^4, V_v^4. What about the other missing terms at t_3, t_4, t_5?
3. The RO and AO vector definitions using rho and alpha elements need a vector transpose as they are column vectors.
4. Define right after Eq. 3 what those vector/matrix mean and note clearly the dimension using the above-mentioned number of unknowns/observables.
5. You now added the total dimension of 666 x 1109 in Section 2. However, 666 actually corresponds to the column dimension and 1109 the row dimension, which is opposite to the convention of the using row x column. Please reverse the order unless there is a reason for it. Also, you need to put your response to our comment about how these numbers are calculated based on the number of unknowns/observables into the main text.
6. In Fig. 1, and also the simplified example of Section 2, you have 3+4=7 SLC images, so according to the statement (1st sentence of 4th paragraph in Section 2), the number of columns should be (7-1)*3=18, which is not equal to the actual number (12) in Eq. 3.
7. Please also put your response to our comment about regularization into the text.
8. It also seems that the actual value of the regularization parameter, lambda, does not matter. Because it got cancelled out in each regularization equation, where there are only two non-zero terms (both terms have lambda's that will be cancelled out) and all zero values for the other terms. Not sure why your reported value of 0.1 matters.

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

Reply: We rewrote the redundant sentence in the Introduction.

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

Reply: Corrected.

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 commented in the second paragraph of the Introduction that we use the SPO technique and in the first paragraph of the Model section explained reasons (no need for phase unwrapping, produces range and azimuth results).

We only found one sentence in Section 2 and did not see that you chose to use SPO in Section 1.

Line #74: the last sentence is also the same as that included in the abstract, i.e. redundant

Reply: Corrected.

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: This is approximately equal to 200x200m. This information is now provided in the last paragraph of Study area and Data section.

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: Such a large window was required to obtain a distinct, statistically-significant peak of the 2D cross-correlation function; its square shape produced similar precision in range and azimuth directions in radar coordinates, and azimuth precision four times lower than range precision in geocoded products. We found that 128x128 (as in the revised version of the manuscript) is sufficient. If we chose to reduce the number of pixels in the azimuth direction M (to make square window on the ground) we would need to increase the number of pixels in the range direction N to keep M*N=128*128, but that would affect the precision in an unpredictable way.*

In the revised version we reduced the correlation window to 128x128 pixels and used a Gaussian filter with a width to Gaussian 1.3 km (6-sigma). 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. Therefore, we are limited to using a larger window.

We consulted the developers of the 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 centre have larger weights than those pixels on edges. The effective resolution is about four times higher than the window size. The process of the 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 technique presented here.*

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

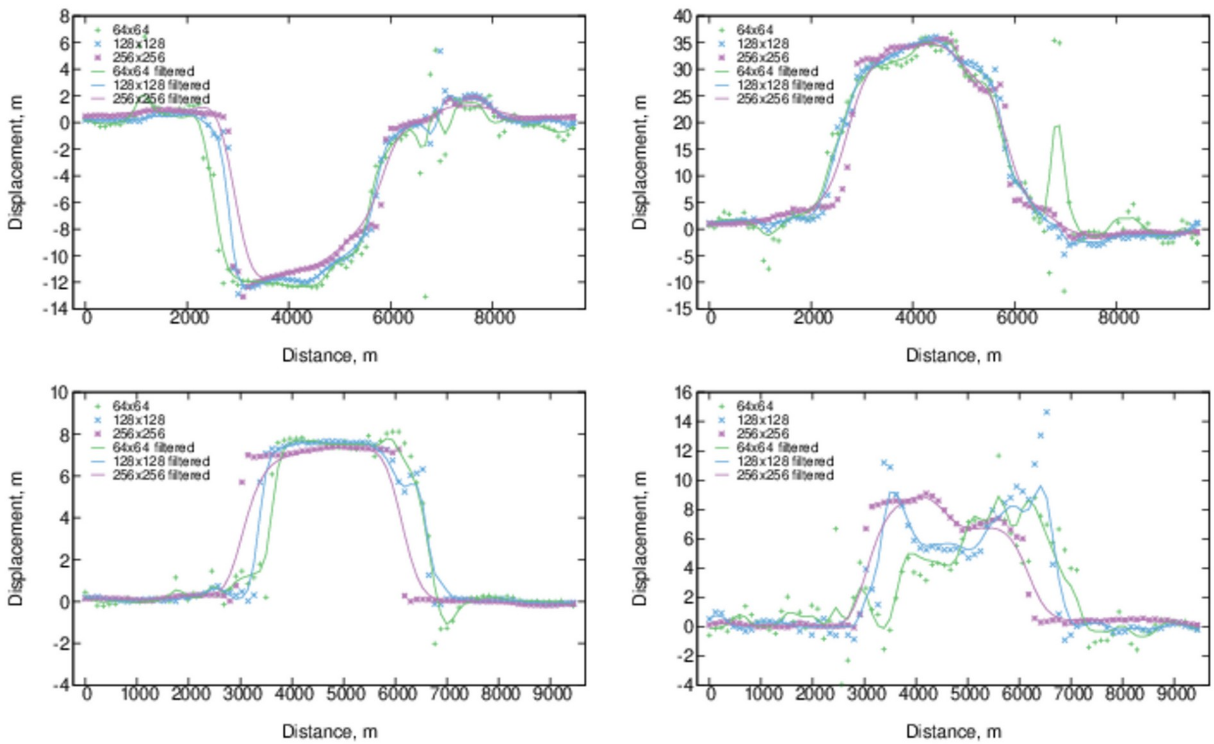

Figure 1: (top-left) Seward range, (top-right) Seward azimuth, (bottom-left) Klutlan range, (bottom-right) Klutlan azimuth.

1. Based on what you clarified, using a large window might be okay for your area. But using a filter with larger width (km) is not recommended. Are you saying you replaced the previous median filter (2km width) with a Gaussian one (1.3km 6-sigma)? If so, 3-sigma Gaussian is roughly 650m, which might be okay but still a bit large.
2. From above figure (bottom right), it seems using your new window of 128 x 128 with filtering gives quite different results compared to 64 x 64 without filtering. So the question arises: the large window might be insufficient for this area and also the filter width might be too coarse.
3. You probably want to mention this as a limitation of the current processing and discuss how to improve the results in the future.

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: While it looks unconventional, it is a basic equation with a meaning similar to V*t =D, that we believe does not require further derivation. It is used in many SBAS and MSBAS publications and its explicit representation can be deduced from the example (equation 3). We provided clarifications about this equation in the third paragraph of the Model section. Also, the Fialko et al., 2001 paper is cited that explains in detail how azimuth and range offsets are used to solve for the 3D deformation.*

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: We provided the following clarification. "In matrix A the number of columns is equal to the number of available SLC images minus 1 multiplied by three, and the number of rows is equal to the total number of range and azimuth offset maps computed from those SLC images." We also explained the size of the matrix in this particular case.

Please refer to our above comments on rewriting this sentence and also the problem of applying this sentence in calculating the dimension for the particular case.

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: This comes from the geodetic analysis of seismic events and it is very well described in (Fialko et al., 2001; Bechor and Zebker, 2006), which are now referenced in our manuscript. We now explicitly show RO and AO in our simplified example (lines 85-90). Each row in A represents one range or one azimuth offset map. We believe it is now clearer.

As mentioned above, you did not answer our comment why the velocity vector in Eq. 3 only included V_n^3, V_e^4, V_v^4. What about the other missing terms at t3, t4, t5? Also, as mentioned above, please denote number of unknowns/observables (e.g. number of SLC images as N) and use N to express each vector/matrix dimension right after Eq. 3. This is pretty standard way of introducing vector/matrix notation in writing scientific articles.

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.

Please reflect that change not only in the current response but also in the revised manuscript, otherwise it is still confusing to others.

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: After adding the most recent Sentinel-1 data to the revised version of the manuscript (we wanted to see what is happening at Malaspina Glacier at region P1) the dimensions of matrix became 666×1109. This means that we have 223 SLC images (223-1)*3=666 and 108 ascending range and azimuth offset maps and 115 descending range and azimuth offset maps = 108+108+115+115=446 and the regularization rows are (223-2)*3= 663. The total amount of rows is 446+663 = 1109. This now is explained in the Model section.*

As mentioned above, you need to move your response to the revised text as well. Once you define number of unknowns/observables as N or M as suggested above (e.g. number of SLC images as N), it is pretty straightforward to make this calculation by substituting N=223.

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

Reply: For us, it takes about 24 hours of processing time on a single node with 44 cores. An Message Passing Inteface (MPI) version of msbas software has also been developed. The processing time in an MPI version is 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: It is a somewhat specific and complex issue from the field of linear algebra, which most users probably do not want to know unless they want to develop their own software. There are three theoretically possible cases: the number of equations is less, equal or greater than the number of unknowns. In the equal case, the matrix is square and no regularization is required. In the greater case, the least square solution is found using SVD – this is common in 1D MSBAS (more interferograms than SLCs). In the lesser case (as always in 2D and 3D MSBAS), the solution is found using the truncated-SVD, which is identical to the zeroth-order Tikhonov regularization. If we want to fill the temporal gaps, we need to apply higher order regularization (first and second-orders work equally well in this case). From the computational point of view there is no difference between the 2D and 3D problem. The need for regularization arises because SAR images from different tracks are acquired at different times, which results in more unknowns than equations, producing a rank-deficient, under-determined problem.

Even though only some readers might be interested in this topic, you still need to include it in the text to be complete. Also it is not trivial and widely used in the literature on ice velocity mapping.

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 3D velocities per year. Since all these data cannot be presented in a single publication (30 velocities per year x 3D x 4 years ~ 360 figures), as a simplified representation of our results that require only three figures, we choose to compute mean *velocities by fitting a line to the flow displacement time series, which we then divide by the length of our record. 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 (particularly Figure 11) and text in the discussion address the benefits of short term analyses such as seasonal and inter-annual variability. Also four supplementary animations show instantaneous velocities for each of the studied glaciers.

It is now clear to us. However, it is strongly recommended to rename the term "mean linear flow velocity". Alternatively, you should add a few more sentences from the above response to the main text otherwise, the readers might still feel confused and thought it was a statistical averaging mean value.

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 (after processing is finished), otherwise, images in the figures get 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). You can see an example of the complete data set at the original resolution in Figure 5 and in supplementary files.

Please objectively report your above calibration approach and clearly state that this is a limitation of the current processing chain in the main text. It seems too empirical and will be problematic for fast moving glacier areas. We would like to see some validation of the velocity results by comparing to other reference velocity measurements with some accuracy or error analysis, which is completely missing in this work.

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. This approach ensures we used only the highest quality results. 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.*

It is the term "coherent" that sounds confusing to us. Please define the coherence you are referring to here or use another word to convey the exact idea.

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.

In the revised version we use smaller window and a filter with the Gaussian window, we found that it performs better for small and large glaciers. Finally, with the exception of a handful of tidewater glaciers (Hubbard, Tsaa, Guyot, and Taan), the majority of glaciers in our study area are land terminating and thus do not experience the rapid flow that typifies tidewater glacier termini.

As mentioned above, although it seems to work for your area (note it is not convincing without a formal error analysis), you should explicitly add this as a limitation of the current processing routine, and explain how to improve it in the future for fast glacier outlets. The current revision of the manuscript still lacks a formal discussion about current limitations and how to improve.