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Response to Referee # 3

'Open-source sea ice drift algorithm for Sentinel-1 SAR imagery using a combination of feature-tracking and pattern-matching'

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Dear Referee # 3,

Thank you very much for helping us improving our paper.

Please find here the **answers** to your comments and the corresponding ***changes in manuscript***:

General comment

A general impression after reviewing this manuscript is that it requires more work and provision of additional details before being ready for publication in TC. The authors are thus invited to revise their manuscript before a new version is submitted. Specifically, the following items should be addressed.

We increased the level of detail and added new figures to improve the manuscript.

1 Description of the algorithm

The 'pattern-matching' step is not well enough described and many questions are still open at the end of section 3.2.

The pattern-matching description has been rewritten and more details have been added.

1.a) The ordering of the sub-sections (I. Feature-Tracking, II. Pattern-matching, III. Combination) is maybe not optimal as you spend some of Section III to describe the rotation by angle beta (that should really go into II). Maybe it would be easier to follow if the sub-section followed the steps of the algorithms (feature-matching, fitting of polynomial for first-guess, filtering, patter-matching, etc...).

We changed to order according to this comment. The new subsections are: 'I Feature-tracking', 'II Filter', 'III First guess', 'IV Pattern-matching' and 'V Final Product'. We added Figure 3 incl. flow chart to illustrate the steps and the respective products.

1.b) It is unclear if your pattern-matching step features a series of x,y shifts to maximize the cross-correlation in addition to the rotation by beta, or not. If you combine both x, y, and beta shifts, what is the relative order and does it matter?

The pattern-matching description has been changed according to this comment. The matrix NCC(x,y), containing all normalised cross coefficient values for all possible x,y shift, is calculated several times: one for each rotation β. The highest cross coefficient value is found considering all NCC matrizes.

1.c) As you recall in I. 'Feature-Tracking', the ORB algorithms also gives an information about the rotation angle (delta between centroid-based orientation of the matched features). Is this feature-matching first-guess of the rotation used at all? If yes, how; and if no, why not?

This is a good point and we adjusted the algorithm according to this comment. We included the usage of the feature-tracking rotation: a filtered rotation field based on the rotation found for the individual features serves now as initial rotation for the pattern-matching step.

1.d) What is 'the initial rotation between the two Sentinel-1 image' (line 194) and how is it computed? Is it the same value across the image?

The 'initial rotation between two Sentinel-1 images' was derived as angle between the left edges of the images. It was calculated by re-projecting the left edge of the second image onto the projection of the first image. This is the same value for the entire scene. However, after including the feature-tracking rotation (see above), the algorithm is not using this rotation anymore, but rather a rotation field, that varies over the image (see α in Figure 5), based on the rotation of the individual features.

The 'initial rotation between two Sentinel-1 images' is still calculated since it allows to exclude the different projections of the two scenes and derive the actual rotation of the sea ice at each point of interest.

1.e) In subsection II. 'Pattern-matching' you write the NCC formula for 'two equally sized windows'. But later you seem to use two unequally sized windows (size t1 in SAR1, size t2 in SAR2). What is the NCC formula do you then use? Of is size t2 related to the size of the search window while t1 is the size of the pattern? The questions above are mostly to give an impression of the level of details expected when you re-formulate this section. Your first manuscript contained quite some details on the methodology, and this new one requires at least as many details.

We changed the pattern-matching description according to this comment and included a more detailed formulation of the NCC equation.

2 Validation against GPS data

2.a) The choice of validation metric (the distance between the end points of the reference and estimated vectors) is not peculiar. Virtually all other studies use the RMSE along two components (e.g. u and v). And the logarithmic distribution of the errors is not discussed or exploited. Please also discuss the RMSDs in u and v components and compare your results with that of other investigators.

We changed the validation procedure and fitted a logarithmic normal distribution to the histogram. We did not see any specific pattern when considering u and v component separately, but we added plots to further investigate the systematic and random error (Figure 11). To our knowledge, we are currently the only ones using this GPS dataset for validation. It is hard to compare these results with other drift products, since they resemble a different resolution and we don't have drift estimates at the buoy locations. However, we tried to make our validation procedure similar to the regular validation of the CMEMS ice drift to improve the possibility for future comparison.

2.b) The N-ICE campaign deployed many buoys, but very much in the vicinity of the vessel Lance. How many different buoys enter your validation database, and what is the average distance between them? Are we sampling more than few kilometres in each SAR pair?

The Norwegian Polar Institute provided us with data from 32 buoys. Based on that dataset, we automatically searched for fitting Sentinel-1 image pairs that provided more than 300 feature-tracking vectors and had a time differences of less than three days. We added a map with the resulting buoy trajectories (Figure 8) to illustrate location, spread and drift distance.

2.c) N-ICE data should offer the possibility to discuss the accuracy when inside the pack versus at the marginal ice zone. Please see if you can segment your validation database to cover this. As you point out yourself, the added value of rotation should be most visible in the marginal ice zone.

To describe the ice conditions during the collection of the validation data, we added the following to Section 2:

The ice conditions during the N-ICE2015 expedition are describe on the project website (http://www.npolar.no/en/projects/n-ice2015.html) as challenging. The observed ice pack, mainly consisting of 1.3-1.5 m thick multiyear and first-year ice, drifted faster than expected and was very dynamic. Closer to the ice edge, break up of ice floes has been observed due to rapid ice drift and the research camp had to be evacuated and re-established four times. This represents a good study field, since these challenging conditions are expected in our area and time period of

interest.

The automatic search algorithm, that allows to perform the validation on a high number of image pairs, is only comparing location and timing of buoy and satellite data and does not include any information on ice condition. To segment the validation dataset according to ice condition, we would need to describe the ice conditions for each validation vector individually. Unfortunately However, future work will cover experiments of the algorithm performance in different ice conditions.

2.d) Can you convince the reader (and the reviewer!) that the value of the maximum NCC indeed constitutes a quality measure (your Abstract)? Are matchups with lower NCC values really father away from GPS truth, than those with high NCC? Hollands et al. (2015) did not find any relation between the two. Is your threshold at 0.35 related to a significant drop in the documented accuracy against the buoy drift? (Hollands, T. , Linow, S. and Dierking, W. (2015): Reliability Measures for Sea Ice Motion Re?trieval From Synthetic Aperture Radar Images , IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8 (1), pp. 67-75 . doi: 10.1109/JSTARS.2014.2340572)

We removed the term 'quality measure' throughout the manuscript. However, we found that the probability for a high error decreases with increasing maximum cross coefficient value (Figure 11) and added the following to the validation section:

We found that the probability for a large D value (representative for the error) decreases with increasing maximum cross coefficient value MCC. Therefore we suggest to exclude matches with a MCC value below a certain threshold MCC_{min}. This option is embedded into the algorithm, but can easily be adjusted or turned off by setting $MCC_{min} = 0$. Based on the findings shown in Figure 11, we recommend a cross coefficient threshold $MCC_{min} = 0.4$ for our time period and area of interest.

A corresponding statement was added to the method section.

After changing the recommended size of the smaller template t_1 to 34×34 pixels (to be consistent with the feature-tracking resolution and the aimed accuracy of the drift product), we also adjusted the cross coefficient threshold to 0.4.

2.e) You use a maximum velocity of 0.5 m/s for your feature-based results (line 171). Is this limit high-enough in view of your validation dataset in the Fram Strait region?

To discuss the maximum velocity limit of 0.5 m/s, we added a general drift assessment to the Introduction and the following to Section 5:

The current setting of the feature-tracking algorithm applies a maximum drift filter of 0.5 m/s. We found this to be a reasonable value for our time period and area of interest. However, when considering extreme drift situations in Fram Strait and a short time interval between image

acquisitions, this threshold should be adjusted.

As mentioned above, we deployed three GPS tracker in Fram Strait and they recorded their positions with a temporal resolution of 5-30 min between 8th July until 9th September 2016 in an area covering 75° N to 80° N and 4° W to 14° W. Considering the displacements with 30 min interval, we found velocities above 0.5 m/s on a few occasions, when the tidal motion adds to an exceptionally fast ice drift.

The GPS data from the hovercraft expedition FRAM2014-2015 (https://sabvabaa.nersc.no), that was collected with a temporal resolution of 10 s between 31st August 2014 until 6th July 2015, did not reveal a single 30 min interval during which the hovercraft was moved by ice drift more than 0.45 m/s. The hovercraft expedition started at 280 km south from the North Pole towards the Siberian coast, crossed the Arctic Ocean towards Greenland and was picked up in the north-western part of Fram Strait.

We removed the validation procedure with the considered image pair over Fram Strait, even though it did not include velocities above 0.5 m/s.

Finally, it would be good if the revision of the paper could include a thorough discussion of the robustness of the combined method to the success of the feature-matching step (not in terms of computation cost, but of introduction of artefacts).

We did not find any artefacts in the test images that we considered so far. However, we would like to increase the number of image pairs significantly and produce large drift field datasets (and corresponding divergence, shear and total deformation datasets) to further evaluate the algorithm performance and investigate its robustness in terms of artefacts. To do that, we recently established a cooperation with TU Wien to embed our algorithm into their super-computing facility and learn from their experience with handling large Sentinel-1 datasets. The aim of this paper is mainly the presentation of the methodology and our next goal is the application on large datasets for further testing. To specify our next steps, we added the following to Section 5:

Our next step is to embed the algorithm into a super-computing facility to further test the performance in different regions, time periods and ice conditions. The goal is to deliver large ice drift datasets and open-source operational sea ice drift products with a spatial resolution of less than 5 km.

Thanks again for your comments. We are looking forward to your reply!

Best regards,

S. Muckenhuber and S. Sandven