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Response to Referee # 2

'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 # 2,

Thank you very much for helping us improving our paper.

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

1 Major comments

Introduction, P2: The manuscript should include some additional background information on the sea ice drift in the study area (with possible references): what are the magnitudes of typical ice drift in the study area and whole Arctic (e.g. cm/s and daily) and in which areas they are located and which are their causes?

We added references and the following to Section 1:

Early work from Nansen (1902) established the rule-of-thumb that sea ice velocity resembles 2 % of the surface wind speed with a drift direction of about 45° to the right (Northern Hemisphere) of the wind. This wind driven explanation can give a rough estimate for instantaneous ice velocities. However, the respective influence of wind and ocean current strongly depends on the temporal and spatial scale. Only about 50 % of the long-term (several months) averaged ice drift in the Arctic can be explained by geostrophic winds, whereas the rest is related to mean ocean circulation. This proportion increases to more than 70 % explained by wind, when considering shorter time scales (days to weeks). The wind fails to explain large-scale ice divergence patterns and its influence decreases towards the coast (Thorndike and Colony, 1982).

Using GPS drift data from the International Arctic Buoy Program (IABP), Rampal et al. (2009) analysed the general circulation of the Arctic sea ice velocity field and found that the fluctuations follow the same diffusive regime as turbulent flows in other geophysical fluids. The monthly mean drift using 12 h displacements was found to be in the order of 0.05 to 0.1 m/s and showed a

strong seasonal cycle with minimum in April and maximum in October. The IABP dataset also revealed a positive trend in the mean Arctic sea ice speed of +17 % per decade for winter and +8.5 % for summer considering the time period 1979–2007. This is unlikely to be the consequence of increased external forcing. Instead, the thinning of the ice cover is suggested to decrease the mechanical strength which eventually causes higher speed given a constant external forcing (Rampal et al.; 2009b).

Fram Strait represents the main gate for Arctic ice export and high drift velocities are generally found in this area with direction southward. Based on moored Doppler Current Meters mounted near 79° N 5° W, Widell et al. (2003) found an average southward velocity of 0.16 m/s for the period 1996–2000. Daily averaged values were usually in the range 0–0.5 m/s with very few occasions above 0.5 m/s.

Method/Feature tracking, P5: It is mentioned that 'The best match is accepted if the ratio of the two shortest Hamming Distances is below 0.75.'. Explain why this is done and how the threshold was selected. Probably to reduce possibilty of similarization errors? What is magnitude of typical Hamming distances? If they are small, then 0.75 has quite different meaning than for larger values. I assume that the ratio is the ratio of the shortest and second shortest Hamming distance (also write this in the text).

The Hamming distances are embedded in the feature-tracking algorithm and are not returned during application of the algorithm. This makes the evaluation of the value distribution difficult. However, based on visual interpretation of drift results using different Hamming distances, Muckenhuber et al. (2016) found a suitable value for our time period and area of interest. We added the following to Section 3:

The best match is accepted if the ratio of the shortest and second shortest Hamming distances is below a certain threshold. Given a suitable threshold, the ratio test will discard a high number of false matches, while eliminating only a few correct matches.

Muckenhuber et al. (2016) found the most suitable parameter setting for our area and time period of interest, including a Hamming distance threshold of 0.75, ...

Method/Combination, P6: To filter outliers each vector is simulated using two functions which are LS solutions... This need more explanation. Why third degree polynomial has been used and which data are used in the LS fit? Also in the extrapolation is also performed using a LS solutions. Also describe this in more detail. How is the traingulation constructed (Delauney?) in interpolation?

Section 2 has been changed according to this comment. We included more detailed descriptions of LS solutions and triangulation. Equations were added to specify the procedure. The

Parameter Tuning/Validation, P10: It is not exlpicitly mentioned which data were used for the parameter tuning. Were all the vlaidation data used for this? Then the validation with this data set is not fair as the algorithm has been tuned for this data. Then only the buoy data can be used for independent validation. Or if separate sets are used for parameter tuning and validation, indicate this in the manuscript.

The Parameter Tuning Section has been removed and validation is now only done against buoy data.

2 Detailed comments

P1L2: 'computanional' -> 'computationally'

Agree, we changed the manuscript accordingly.

P2L33: '90s' -> '90's'

Agree, has been changed.

P2L38: In the case of ENVISAT, rather give the name of the instrument i.e. ENVISAT ASAR, could also mention that RADARSAT was an instrument of CSA and ENVISAT ASAR of ESA.

Agree, has been changed.

P3L88: '((' -> '('

Agree, has been changed.

P3L88: '...dual polarization support...' '..also in wide swath mode'. Also earlier instruments had a possibility to measure multiple polarizations but the covered area was small. This has been changed by RADARSAT-2 and SENTINEL-1.

We changed the sentence to:

The mission includes two identical satellites, Sentinel-1A (launched in April 2014) and Sentinel-1B (launched in April 2016), each carrying a single C-band SAR with a centre frequency of 5.405 GHz and dual-polarisation support (HH+HV, VV+VH) also for wide swath mode.

P3L90: Give also the acronyms for the mode i.e. EW GRDM (thes are generally used by ESA in documentation and file names).

Agree, has been added.

P4L125: You can remove 'of 93m range x 87m azimuth', this information has already been given earlier.

Agree, has been removed.

P6 eq. 3: Here You give the formula for NCC. Also give the drift (dx,dy) detection as a formula, something like: $(dx, dy) = argmax_(k,l)inWNCC(x+k, y+l)$ Is NCC computed according to this equation or by applying FFT and IFFT (which has been applied in many algorithms to fasten the computation)?

The matrix NCC is computed according to the new Equation 8 and FFT and IFFT are not applied. The used python function is matchTemplate from OpenCV (http://docs.opencv.org/2.4/modules/imgproc/doc/object_detection.html). We changed the pattern-matching description according to this comment and added the following:

The highest value in the matrix NCC, i.e. the the maximum normalised cross coefficient value MCC***, represents the location of the best match and the corresponding location adjustment is given by*** dx ***and*** dy***.***

$$(\frac{1+t_{s2}-t_{s1}}{2}+dx, \frac{1+t_{s2}-t_{s1}}{2}+dy) = argmax(\textbf{\textit{NCC}}(x,y) \quad (1)$$

P6 Eq. 4: Define 'side' in the text.

This phrase has been removed and replaced by t_{1s} **and** t_{2s}**.**

P7 Fig 1 and Fig 2. Use a, b, and c for the subfigures and to refer to them.

We added titles to the subfigures to refer to them and make the algorithm description easier understandable.

P7 L195: Explain here what is denoted by 'beta'. It is is also in Fig. 2 caption.

The algorithm description has been changed according to this comment and the following has been added:

To account for rotation adjustment, the matrix NCC is calculated several times: template t_1 ***is rotated around the initially estimated rotation*** α ***from*** $\alpha-\beta$ ***to*** $\alpha+\beta$ ***with step size*** $\Delta\beta$***. The angle*** β ***is the maximum additional rotation and represents therefore the rotation restriction. The NCC matrix with the highest cross coefficient value*** MCC ***is returned.***

P7 Fig.2 (and text): Why rectangular/square templates has been used? A circular template would be much easier (symmetric) to rotate. Consider using a circular templates instead.

We agree with this comment. Regarding t_1 **however, the current version of the used OpenCV function matchTemplate does not allow circular templates and work-arounds would influence the result and the computational efficiency. We hope that a later version of matchTemplate will allow to use masks. Regarding** t_2**, we included a circular mask for the matching result to**

limit the search area to a circle rather than a square.

Logarithmic scaling P8-9: I think logarithmic scale is the typical presentation of SAR sigma0 and often a fixed scaling to gray tone imagery is used for SAR imagery, e.g. scaling between -30dB -> 0 dB. You could mention this fact on the manuscript. This also leads to the question if any other 'scaling' would produce even better results, e.g. applying some king of histogram derived image mapping (e.g. simple histogram equlization etc.). This could be one topic for further development.

We agree. The corresponding section has been removed and the logarithmic scaling description has been moved to Section 3 and adjusted according to this comment. Muckenhuber et al. (2016) tested different scalings procedures on four representative image pairs to retrieve the best possible feature-tracking results. We apply the same scaling for pattern-matching for both computational efficiency and because we assume that a scaling that is preferable for feature-tracking is also preferable for pattern-matching. This assumption however, has not been proven and is certainly a topic for further development.

P10/Computational efficiency: You give a time of less than 3.5 minutes here. Is this a typical execution time or just execution time for a randomly selected example. Could you give average execution times and deviations or maybe estimate for the worst case? Does the execution time increase linearly as a function of the number of vectors or is there some other kind of relationship?

The given time is representative for an image pair with large overlap, good coverage with feature-tracking vectors and the given resolution of the final product. We adjusted and extended the Section Computational efficiency according to this comment. The step 'II Pattern-matching and III Combination' is proportional to the number of chosen points of interest, i.e. the number of drift vectors of the final product. The first two steps can be seen representative for all Sentinel-1 image pairs with 400×400 km coverage. We added a corresponding analysis of the different steps and the influencing parameters.

P12 L270-271: also give the average D. 'peak' is not a correct word here, the histogram/distribution has many peaks, possibly You could use 'mode' here and also in the caption of Fig. 7.

We agree. The error estimation has been changed accordingly. We now fit a logarithmic normal distribution to the histogram and found a median $e^{\mu} = 341.9$ m.

P12 L276-277: The DTU method has not been documented very well in any publications I think. Also the reference given does not say much. I suppose there is not better reference for this?

The comparison with the DTU drift field in Fram Strait has been removed. The DTU product however, is still mentioned in Section 1. We did not find any better reference than

Pedersen et al. (2015), http://www.seaice.dk/ and http://marine.copernicus.eu.

P12 L279: '...used the nearest neighbors...' -> '...used the nearest neighbors (NN's)...' then NN can be used in Table 4.

We agree. However, the corresponding comparison using image pair Fram Strait has been removed.

P13 Fig. 6: Would it be possible to indicate the location of the detail in the coarse-scale image (without causing too much damage for the image)?

We agree. However, the corresponding image has been removed.

P14 Table 4: 'Average distance' -> 'Average NN distance' or something like that. Are the values after +- sign standard deviations or some multiples of standard deviation or something else? Include this information in the table or caption.

The +- sign indicated one standard deviation. However, the corresponding comparison using image pair Fram Strait has been removed.

Discussion: What is the possible error magnitude of the manually estimated drift (is it assumed to be sub-pixel, one pixel or more and what kind of possible error sources these vectors include?)?

The estimated error is in the order of several 100 m. However, the corresponding comparison using image pair Fram Strait has been removed.

P15 L319-320: Also ESA is going to improve their thermal noise removal by including more measurements along the azimuth direction. Probably this also could be mentioned. If necessary you can get more information on this from Nuno Miranda at ESA (nuno.miranda@esa.int).

Thank you for this information. We contacted Nuno Miranda from ESA and added the following to Section 5:

The European Space Agency is also in the process of improving their thermal noise removal for Sentinel-1 imagery. Noise removal in range direction is driven by a function that takes measured noise power into account. Until now, noise measurements are done at the start of each data acquisition, i.e. every 10-20 minutes, and a linear interpolation is performed to provide noise values every 3 seconds. The distribution of noise measurements showed a bimodal shape and it was recently discovered that lower values are related to noise over ocean while higher values are related to noise over land. This means, that Sentinel-1 is able to sense the difference of the earth surface brightness temperature similar to a passive radiometer. When the data acquisition includes a transition from ocean to land or vice versa, the linear interpolation fails to track the noise variation. The successors of Sentinel-1A/B are planned to include more frequent noise

measurements. Until then, ESA wants to use the 8-10 echoes after the burst that are recorded while the transmitted pulse is still travelling and the instrument is measuring the noise. This will provide noise measurements every 0.9 seconds and allows to track the noise variations in more detail. In addition, ESA is planning to introduce a change in the data format during 2017 that shall remove the noise shaping in azimuth. These efforts are expected to improve the performance of the presented algorithm significantly.

We thank Nuno Miranda in the Acknowledgement for the provided informations.

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

Best regards,

S. Muckenhuber and S. Sandven