RETRIEVAL OF SEA ICE DRIFT FROM SAR DOPPLER SHIFT

Morten Wergeland Hansen, Kjell Kloster, Knut-Frode Dagestad, Stein Sandven, and Johnny A. Johannessen

Nansen Environmental and Remote Sensing Center, Thormøhlens gt. 47, 5006 Bergen, Norway

ABSTRACT

The Doppler shift of single antenna Synthetic Aperture Radar (SAR) signals is related to the line-of-sight velocity of the moving ocean surface. In this paper, the Doppler shift is applied to measurements of sea ice drift. This is performed over a sea ice eddy in the Skagerrak Sea from February 2010, and a sea ice eddy in the Fram Strait from November 2008. Cross-eddy velocity variations are detected at about 1 m/s. A number of SAR images over the Fram Strait have been studied to retrieve ice drift velocities across 79° North. In many cases, it is very challenging to properly calibrate the SAR Doppler shifts. However, 115 images of Doppler shift derived range oriented sea ice drift velocities have been compared to ice drift velocities based on feature tracking in SAR backscatter images. During winter, the comparison is promising with regards to this usage of the Doppler method. The summer season, however, is more difficult to monitor, probably because of high water content in the ice and large open water areas. This causes the measurements to be mainly influenced by wind generated (ocean) surface waves.

Key words: Sea ice drift; Fram Strait; ASAR; Doppler shift.

1. INTRODUCTION

Ice drift estimation from satellite is traditionally made from subsequent images by spatial correlation or by feature tracking in Synthetic Aperture Radar (SAR) backscatter, optical imagery, and passive microwave imagery. For example, Kwok & Cunningham (2002) and Kwok (2008) used SAR and passive microwave imagery to study ice production and outflow from the Arctic ocean. Such observations, in combination with air-sea-ice dynamical models (Smedsrud et al. 2008), moored upward looking sonars (Vinje et al. 1998), and ice drifting buoys (Inoue & Kikuchi 2007), constitute a fundamental component of studies on the Arctic sea ice cover.

The SAR instrument also provides a measure of the Doppler shift from the moving ocean surface. Chapron et al. (2003, 2005) demonstrated that the Doppler shift contains a geophysical component generally dominated by wind generated surface waves, but also related to sea surface current. The European Space Agency (ESA) therefore made the Doppler shift available in the Envisat Advanced Synthetic Aperture Radar (ASAR) Wide Swath Mode (WSM) data product in mid 2007.

This data also provides a new and independent method for direct estimate of range oriented sea ice drift. At certain satellite passes in ascending configuration, the range Doppler shift aligns with the mean (southward) sea ice drift in the Fram Strait. The Fram Strait is a main corridor for ice exiting the Arctic and is, as such, an important region for this new application. We will assess ASAR Doppler shift data for sea ice applications by comparison to ASAR backscatter based sea ice drift measurements in the Fram Strait, and investigate velocity variations across sea ice eddies.

In Section 2 we will briefly present the method used to retrieve range oriented sea ice drift based on the Doppler shift. Section 3 presents the method used to retrieve sea ice drift velocities from feature tracking. In Section 4, we present the first results of ASAR Doppler shift based sea ice drift velocity variations across ice eddies, and a comparison to drift velocities based on feature tracking. Section 5 summarises the paper and presents our concluding remarks.

2. ASAR RANGE DOPPLER VELOCITIES

Since May 2007 the beam centre Doppler frequency estimate (the Doppler centroid) has been included in the Envisat ASAR Wide Swath Mode (WSM) products. The pixel size of this data is about 8.5 km in near range (cross track direction) and 3.5 km in far range, and 8 km with 30% overlap between adjacent pixels in azimuth (along track direction), with an estimated Root Mean Square (RMS) error of 5 Hz. Over the ocean, the Doppler centroid measured by SAR is found to differ from the frequency predicted from the a priori known motion of the satellite and the Earth rotation (Chapron et al. 2005). The difference between measured and predicted Doppler centroid frequency (the Doppler anomaly, f_{Dca}) is calculated by subtracting, from this grid, Doppler centroid data based on the relative velocity of the satellite and the rotating earth, using Envisat mission analysis software provided by ESA.

However, some unwanted noise partly mask the geophysical information in the Doppler anomaly: (1) a bias along range caused by antenna pattern variations, and (2) a bias along azimuth caused by gradients in the radar backscatter along the same direction. The range bias is removed by calibrating the scenes using land reference. This is done in two steps. First, a sinusoidal variation is removed using land from scenes over the Amazon and Greenland ice sheet. This correction leaves an offset from zero Doppler anomaly which must be corrected by the mean Doppler anomaly over land in the given scene.

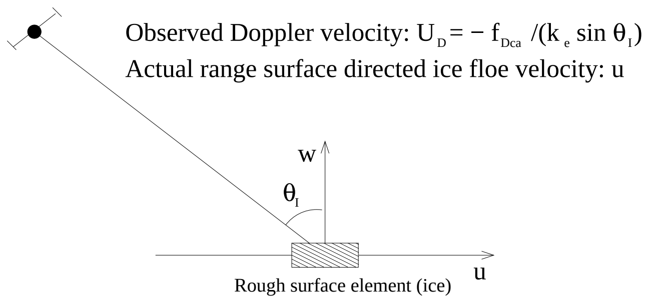

Figure 1. Interaction between a rough surface element (in this case ice), and the radar signal at incidence angle θ_I with ice floe velocities u and w in ground range and vertical direction, respectively. The Doppler velocity (U_D) is a function of the Doppler anomaly (f_{Dca}), the electromagnetic wave number (k_e), and the incidence angle (θ_I).

In case there is not sufficient land in the given scene, we can only calculate relative range Doppler velocities. A correction for the azimuthal bias is found by calculating the gradient of radar backscatter along azimuth, and fitting a linear relationship with the corresponding variation in the Doppler anomalies. This relation is then subsequently used to correct the Doppler anomaly values based on the corresponding radar backscatter gradients.

The calibration of the instrumental biases is challenging, and adds uncertainty to the 5 Hz accuracy estimate.

Figure 1 shows a simplified sketch of the relation between the Doppler anomaly and the surface range Doppler velocity, where θ_I is the radar incidence angle and k_e is the electromagnetic wave number. Generally, the Doppler anomaly relates to ground range and vertical surface velocities, weighted by the radar backscatter of each surface element (Chapron et al. 2005) as:

$$\frac{f_{Dca}}{k_e} = -\frac{\overline{(u \sin\theta_I - w \cos\theta_I)\sigma_0(\theta_I)}}{\overline{\sigma_0(\theta_I)}}, \qquad (1)$$

where σ_0 is the radar backscatter, and u and w are velocities in ground range and vertical direction, respectively. It is thus evident that the ice floe velocity in range direction, u, is not necessarily equivalent to the surface range Doppler velocity, U_D. Chapron et al. (2005) showed that the largest wave contributions arise from the high-frequency waves, proportional to the third moment of the surface elevation spectrum. These short waves are closely related to the wind, and any swell should be insignificant. Thus, ignoring vertical motions away from the marginal ice zone and assuming the ice moves uniformly within a Doppler pixel (≈ 4 by 8 km), Equation 1 reduces to

$$U_D = -\frac{f_{Dca}}{k_e \sin\theta_I} \approx u. \qquad (2)$$

The result is a measure of the Doppler shift from the moving ocean surface in range direction which, when applied to sea ice, is assumed to result directly from ice floe drift.

Figure 2. ASAR backscatter images from the 3^{rd} and 6^{th} January 2009 at 21:01:32 and 21:06:58 UTC, respectively. Red boxes indicate an ice floe drifting along the red arrow.

3. SEA ICE DRIFT ESTIMATES BASED ON FEATURE TRACKING

The Nansen Environmental and Remote Sensing Center (NERSC) has been monitoring ice drift using feature tracking in subsequent ASAR scenes (usually 3 days interval) in the Fram Strait since summer 2004.

Figure 2 shows ASAR backscatter images from the 3^{rd} and 6^{th} January 2009 to illustrate the estimation of sea ice drift based on feature tracking. Individual ice floes are manually detected and geo-located in both images, displacement vectors are measured, and the average speed is calculated under the assumption of constant drift velocity.

4. RESULTS

The use of ASAR Doppler shift data for estimation of sea ice drift is first assessed by investigating measurements of sea ice eddies with known orbital motion characteristics. A systematic study of the ice drift retrievals in the Fram Strait is then carried out with consistent comparison to results from feature tracking in ASAR backscatter across 79°N in the Fram Strait. The compared ice drift data is smoothed by a 90 days averaging window in order to more clearly exhibit seasonal variations.

4.1. Sea Ice Eddies

In February 2010, the Norwegian Meteorological Institute (`met.no`) published the observations of a distinct anti-cyclonic sea ice eddy in Skagerrak. The eddy was persistent in time, and had a similar geophysical signature with snow and ice along the Norwegian coast. Observations at various electromagnetic wavelengths further confirmed this icy nature.

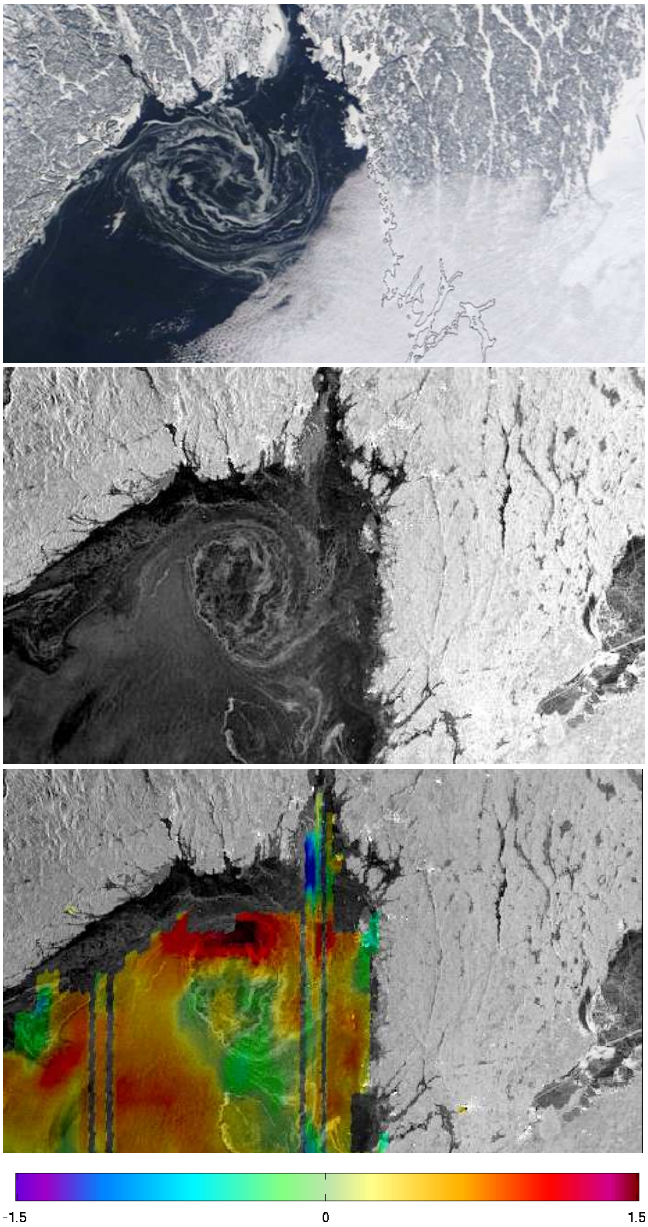

Figure 3. Ice eddy in the Skagerrak Sea from MODIS (top, exact date unknown), ASAR backscatter, and ASAR range Doppler velocity (positive to the right) on the 8^{th} February 2010 at 20:54:30 UTC.

The top panel of Figure 3 shows the ice eddy as observed with the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. The same eddy was observed with ASAR on the 8^{th} of February, 2010, captured in radar backscatter in the centre panel and by Doppler shift in the lower panel. The wind from the NCEP model was low (< 5 m/s) and homogeneous over the ice eddy area, and hence the Doppler signature of the eddy is believed to reflect mainly the ocean circulation. The difference in Doppler velocity of the upper and lower part of the eddy, which should be the circulation velocity, is about 1 m/s. This confirms the anti-cyclonic orbital motion of the eddy.

Figure 4 shows a similar sea ice eddy observed in the Fram Strait on the 5^{th} of November 2008 in ASAR backscatter (top), range oriented Doppler velocity (centre), and a profile of the velocity variation (bottom) across the stippled line marked in the centre panel. Due to poor land coverage, the observations can only be interpreted relatively. However, the data demonstrates nicely the cross-eddy velocity variation of about 1 m/s.

All in all, this clearly suggests that the Doppler shift from SAR is feasible for determination of range directed sea ice drift.

4.2. Ice Drift Across 79° North

Figure 5 shows the northward ice drift velocity component in the Fram Strait across 79° North, based on feature tracking in ASAR backscatter at 3 days interval and averaged within a 90 days moving window. The purple region indicates one standard deviation within the averaging window.

The seasonal variation is evident with, expectedly, minimum southward ice drift during summer months and maximum in winter. The summers of 2008 and 2009 show average southward drift velocities around 5 cm/s. Winter averages reach 20 cm/s towards south in 2007/2008 and 2009/2010, with slightly lower ($\sim$ 18 cm/s) drift in 2008/2009.

We have compared Doppler measurements of sea ice drift in the Fram Strait across 79° North with drift velocities based on feature tracking. Many ASAR Doppler scenes were rejected because of missing land and poor calibration, leaving 115 acquisitions for further analysis. Areas with less than 90% ice cover, based on AMSR-E passive microwave data (Cavalieri et al. 2004 (updated daily)), were then excluded. Figure 6 shows radar backscatter and Doppler based (ASAR ascending pass configuration) range directed velocity variations with time between September 2007 and March 2010 (directed towards southwest (negative) and northeast (positive), respectively). The radar backscatter based velocities are selected only at times for which valid Doppler shift data is available, and both datasets have been smoothed with a 90 days moving average. This helps to clarify seasonal trends, and makes it easier to compare the data. On the contrary, direct comparison could also be useful, but is considered less valuable due to the different measurement methods, more noisy data, and thus less clear (scatter) plots.

Despite a rather small dataset, we see similarities between the two measurement methods. During winter 2007/2008, the ASAR velocities are mostly within one standard deviation of the radar backscatter based drift measurements. During summer 2008, however, there were some ASAR measurements with large deviations from the radar backscatter based data with positive values meaning drift towards northeast. After October 2008, the rest of the comparisons show a noticeable positive bias between the feature tracking and Doppler based range velocities.

During summer, the ice cover in the Fram Strait is reduced considerably. The ice floes may also be covered by wet snow or water ponds. As pointed out in Section 2, the method of ice drift estimation using Doppler shifts is not generally valid in the marginal ice zone. The influence from water waves is thus expected to significantly change the characteristics of the radar Doppler shift data acquired in the summer season. This may explain the deviations in summer 2008.

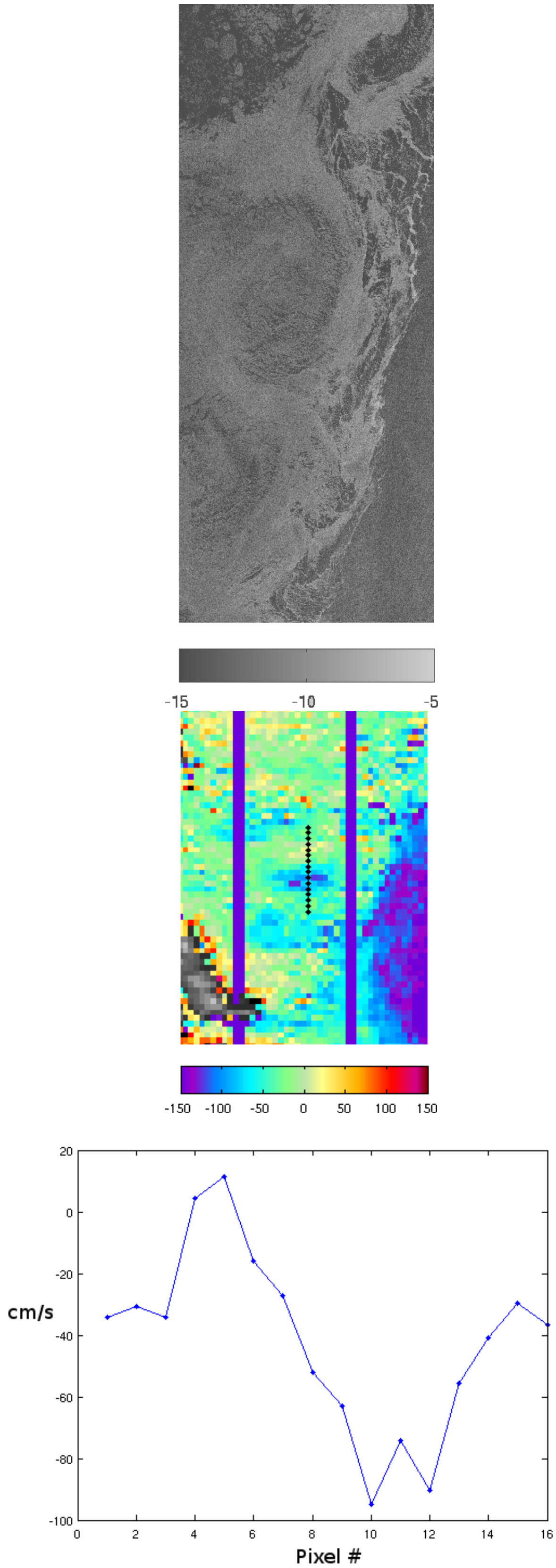

Figure 4. Sea ice eddy observed from ASAR backscatter in the Fram Strait on the 5^{th} of November 2008 at 12:01:02 UTC (top), corresponding range oriented velocity measured by Doppler shift (centre), and a profile of the velocity variation (bottom) across the stippled line marked in the centre panel. The distance between pixel centres is 3.2 km, and the Doppler shift only provides relative velocities because of missing land cover in the imaged scene.

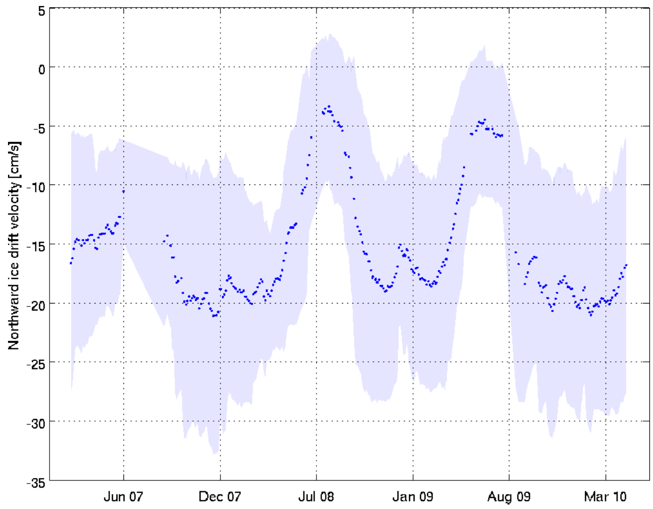

Figure 5. Ice drift velocity component (positive northward) in the Fram Strait across 79° North between 15° West and 5° East, based on feature tracking in ASAR backscatter at 3 days interval and averaged within a 90 days moving window. The purple region indicates one standard deviation within the averaging window.

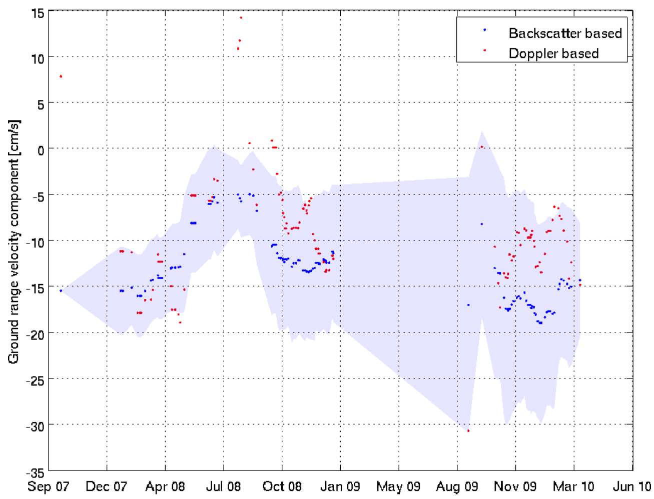

Figure 6. Ground range velocity components across 79° North between 15° West and 5° East based on feature tracking in ASAR backscatter (blue), and ASAR Doppler shift (red). The dataset is smoothed with a 90 days averaging window, and the purple region indicates one standard deviation of the radar backscatter based data within this averaging window.

The biases from October 2008 to January 2009 and from October 2009 to March 2010 in Figure 6, are not further analysed in this paper. However, the difference may be due to different measurement methods, although it should be expected that the instantaneous Doppler velocities were larger than the averaged feature tracking based velocities. This is a task for further studies.

5. SUMMARY AND CONCLUSIONS

A new method for direct estimation of range oriented sea ice drift has been presented and compared to traditional measurements by feature recognition in SAR backscatter. This method retrieves instantaneous range oriented velocities, in contrast to traditional methods which provide temporal averages.

For two sea ice eddies, we have demonstrated cross-eddy velocity variations measured with SAR at about 1 m/s. The seasonal ice drift variation across 79° North in the Fram Strait was also evident, with minimum ice drift ($\sim$ 5 cm/s on average) during summer and maximum ice drift ($\sim$ 20 cm/s on average) during winter. This is seen in both backscatter and Doppler shift based data.

During winter, the comparison is promising with regards to using the Doppler method for sea ice drift retrieval. The summer season, however, is more difficult to monitor, probably because of high water content in the ice and large open water areas. This causes the measurements to be mainly influenced by wind generated (ocean) surface waves.

Finally, much work still remains with calibration methods to improve and enlarge our dataset. Provided these possible improvements, the SAR Doppler shift data therefore seems to be promising for measurement of sea ice drift.

ACKNOWLEDGMENTS

This work has been supported by the Nansen Fellowship Fund at NERSC in Bergen, Norway, and by the ESA Dragon-2 program under ESRIN contract number 22494/09/I-LG. In addition, the ESA Changing Earth Science Network Initiative and the Research Council of Norway, under contract number 177441/V30, have supported the study.

REFERENCES

Cavalieri, D., Markus, T., & Comiso, J. 2004 (updated daily), AMSR-E/Aqua Daily L3 12.5 km Brightness Temperature, Sea Ice Concentration, & Snow Depth Polar Grids V002, [2007–2010]

Chapron, B., Collard, F., & Ardhuin, F. 2005, Journal of Geophysical Research (Oceans), 110, 7008

Chapron, B., Collard, F., & Kerbaol, V. 2003, in Proceedings of the Second Workshop on Coastal and Marine Applications of SAR, ed. L. H., European Space Agency (ESA Publications Division)

Inoue, J. & Kikuchi, T. 2007, Journal of Meteorological Society of Japan

Kwok, R. 2008, Journal of Climate

Kwok, R. & Cunningham, G. F. 2002, Journal of Geophysical Research – Oceans, 107

Smedsrud, L. H., Sorteberg, A., & Kloster, K. 2008, Geophysical Research Letters, 35

Vinje, T., Nordlund, N., & Kvambekk, A. 1998, Journal of Geophysical Research – Oceans, 103, 10437

ABBREVIATIONS AND ACRONYMS

ASAR Advanced Synthetic Aperture Radar

ESA European Space Agency

MODIS Moderate Resolution Imaging Spectroradiometer

NERSC Nansen Environmental and Remote Sensing Center

RMS Root Mean Square

SAR Synthetic Aperture Radar

WSM Wide Swath Mode