INverting consistent surface CUrrent fields from SAR (INCUSAR)

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Introduction

Ocean current is one of the key parameters needed for ocean monitoring and forecasting, and to better understand the climate system. Unfortunately, it is also one of the most challenging parameters to measure from satellite. The only operational method in use today is the indirect approach of altimetry, where measured sea surface heights used to derive geostrophic currents under assumption of balance between pressure and Coriolis forces. Limitations of this approach are rather coarse resolution of 30-50 km, and that the geostrophic assumption excludes retrieval of converging and diverging currents, which have a strong impact on setting up vertical motions in the upper layer and that in turn influence primary production.

The primary goal of this project is to develop a novel surface current retrieval technique based on Synthetic Aperture Radar (SAR). The suggested approach, if successful, will map the instantaneous current at a resolution on the order of a few kilometres, avoiding the limitations of the geostrophic assumption. Accurate knowledge of the wind conditions is a necessary precondition for this approach, and therefore the first part of the project is dedicated to improving a newly developed and promising method for SAR wind retrieval. Thus, this project will directly contribute to the following target challenges of the ESA Living Planet Program:

- Provide reliable model- and data-based assessments and predictions of the past, present and future state of the ocean.
- Understand physical and bio-chemical air/sea interaction processes.
- Understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.

Background

The SAR instrument measures ocean surface roughness linked to e.g. wind, waves and currents, sea ice, and surface contaminants and surfactants. In particular, current shear and convergence zones can affect the waves resulting in wave steepening and enhanced SAR-detectable roughness changes. By this mechanism, detailed structures of mesoscale current dynamics have been observed and studied during the last decades, but successful quantitative measurements of ocean currents have not been possible, except for very simple and idealised cases (e.g. Romeiser and Alpers, 1997; Lyzenga and Bennett, 1988). However, in addition to the surface roughness, the SAR instrument also provides a measure of the Doppler shift from the ocean surface, which has recently been demonstrated to be a highly useful source for retrieval of both surface current and wind (Chapron et al., 2003, 2005). Over the ocean, the beam centre Doppler frequency (Doppler centroid) measured by the 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. (2003, 2005) demonstrated that this difference, the Doppler centroid anomaly, is a useful quantitative measurement of the ocean surface velocity in range direction (range Doppler velocity). This velocity is induced by the combined action of near surface wind speed, wave motion and surface current. It complements the Normalised Radar Cross Section (NRCS) measurements, and facilitates better quantitative interpretation of the relationship between the usual complex roughness pattern and upper ocean dynamic conditions.

The measured range Doppler velocity relates to a geometrical mean of the surface element velocities weighted by the local NRCS (Chapron et al. 2003, 2005) as

$$V_D = \frac{\pi f_D}{k_R} = -\frac{\overline{(u\sin\theta - w\cos\theta)\sigma_0(\theta+\Delta\theta)}}{\overline{\sigma_0(\theta+\Delta\theta)}}, \qquad (1)$$

where f_D is the Doppler anomaly, k_R is the radar wave number, u and v are the horizontal and vertical velocity components of the radar scattering elements in the plane of the SAR look direction. θ is the incidence angle with associated wave induced tilt ($\Delta\theta$) which modulates the NRCS (σ_0). The overbars indicate averaging over the area over which the Doppler frequency shift is calculated.

The velocity components u and v depend on orbital motion of wind waves and longer waves (swell) and the surface currents in a very complicated and nonlinear manner.

However, as a rough first order approximation it can be assumed that the contributions from wave orbital motion and surface currents can be linearly added. Based on this approximation, the one dimensional (range directed) surface current can be estimated by subtracting the contributions of wave orbital motion from the range Doppler velocity. Using collocated ECMWF wind fields and Envisat ASAR Wide Swath data, Collard et al. (2008) have developed an empirical model (CDOP) to reproduce the dependency of the Doppler anomalies on the wind speed and direction, and radar incidence angle. This model is thus the Doppler-counterpart of the CMOD-models (e.g. Stoffelen and Anderson, 1997; Quilfen and Bentamy, 1994), which relate the NRCS to the same parameters. By taking modeled wind field as input to CDOP, the contribution of wind waves to the Doppler anomaly can (at first order) be estimated and removed from the total Doppler anomaly of a given SAR image.

Only the component of the surface current field which is perpendicular to the SAR travel direction can be retrieved by this method. The NRCS is however sensitive to current gradients in both horizontal dimensions, but gives no direct measure of the magnitude of the surface current. The innovative methodology proposed in this project, is to combine both the Doppler velocity and the NRCS for a full retrieval of the 2D surface current, with consistent wind and wave fields. The central tool of this algorithm is a radar imaging model (Kudryavtsev at al., 2003ab, 2005; Johannessen et al., 2005, 2008), which is developed to predict both NRCS and Doppler velocity for given fields of wind, waves and current. The idea is then to input qualified first guess fields, and iteratively modify these fields until the simulated radar parameters are consistent with the observed counterparts.

A bottleneck of the outlined method is that the wind field taken from a numerical model might not be an accurate description of the actual wind at the acquisition time of the SAR image, thus leading to an inconsistency. Calculating the wind from the NRCS based on a CMOD-model and model wind direction does not give an improved wind direction as output, and further the NRCS is also affected by non-wind features, such as the surface current itself, and other phenomena such as rain cells and surface films. A hybrid approach was suggested by Portabella et al. (2002), where model and SAR-based winds were combined in a Bayesian minimisation approach. This method was extended by Kerbaol et al. (2007) by adding also wind direction estimates based on “wind streaks” and Fourier analysis, and by Mouche et al. (2008) by including the Doppler centroid anomaly which relates to the wind through the CDOP model. Promising results have been demonstrated, but the approach still contains much room for improvement.

Work done and progress towards attaining objectives

The project is divided into two work packages (WP), where the first WP focuses on improval of the Bayesian SAR wind retrieval principle, and the second WP covers the 2D surface current inversion scheme as outlined in the previous section. The first WP has been the main focus of the first project year, whereas the work of WP2 is in preparation.

Bayesian wind retrieval scheme

The first task performed was to implement a basic Bayesian wind retrieval software, based on the approach described in Mouche et al. (2008), but with some modifications as follows. The minimization problem is highly computationally expensive, as the optimal wind speed and direction must be searched for over a range of possible solutions for each pixel of collocated model wind and SAR NRCS and Doppler. In Mouche et al. (2008) the speed of this algorithm was highly improved by only searching for solutions which matched perfectly the CMOD-relation between NRCS and wind, thus implicitly neglecting errors and influence of other factors than wind on the NRCS. In the implementation of this project this criteria was let, and the code was optimized to provide wind fields with a spatial resolution of the same size as the Doppler centroid (i.e. around 5 km) in less than 20 minutes, which is adequate, at least in a research-mode, and could probably be further improved with respect to eventual operational near real time implementation. The performance of the scheme has been validated against two buoys off the Norwegian coast. Sensitivity tests were performed, by comparing the correlation with in situ measurements for various choices of the parameterized errors of the model, NRCS and Doppler, respectively. More details about this work are given in Dagestad et al. (2010), and will not be repeated here (see link in reference list, including a presentation given at the ESA SeaSAR workshop in January 2010). One should be careful to draw conclusions, since various errors (also of the in situ measurements) might be compensating others, but it was quite clear that in the overall case (several hundred collocations), the use of the Doppler anomaly did not improve the accuracy of the scheme. This is a bit surprising and disappointing, as several case studies with challenging and interesting cases (cyclones, fronts and topographically steered winds) show that the Doppler anomaly is highly useful to get the correct wind direction, and hence correct speed. This conclusion is however consistent with recent unpublished work by Alexis Mouche (personal communication), and the preliminary explanation is that whereas the Doppler is useful in cases where the model wind is totally wrong (i.e. close to fronts), the large calibration uncertainties of the Doppler act as noise and degrade the performance in the general case when model wind and NRCS are both very accurate. Calibration of the Doppler anomaly was an implicit and complementary subtask of this project, and has consequently needed more attention than initially planned. This is also necessary since a well calibrated Doppler is also critical for a successful implementation of the inverse current retrieval scheme. The work on the Doppler calibration is described in the following section.

Calibration of the Doppler centroid anomaly

Included in Envisat ASAR Wide Swath files since June 2007, is a grid of Doppler centroid frequencies of 100 pixels in range, and a given number in azimuth depending on the length of the scene. This grid is regular in slant range time, and thus the pixel size varies over the scene, around 4km in range and 8km in azimuth. The Doppler anomaly is not provided in the files, but must be calculated by the user by subtracting a predicted Doppler shift from the relative velocity of the satellite and the rotating earth. This predicted Doppler shift is calculated at NERSC with the CFI c-code library provided by ESA (http://envisat.esa.int/earth/www/object/index.cfm?fobjectid=1646). The principles of the calibration steps described below were introduced by Dr. Fabrice Collard from CLS in France to Knut-Frode Dagestad and Morten W. Hansen at NERSC. The method has then been implemented independently at NERSC, and further developed and refined. The processing software has been written from scratch in Matlab, containing no third-party code, except for the CFI software.

Examples of measured and predicted Doppler centroid values for a scene covering the South-African coast are shown in Figure 1.

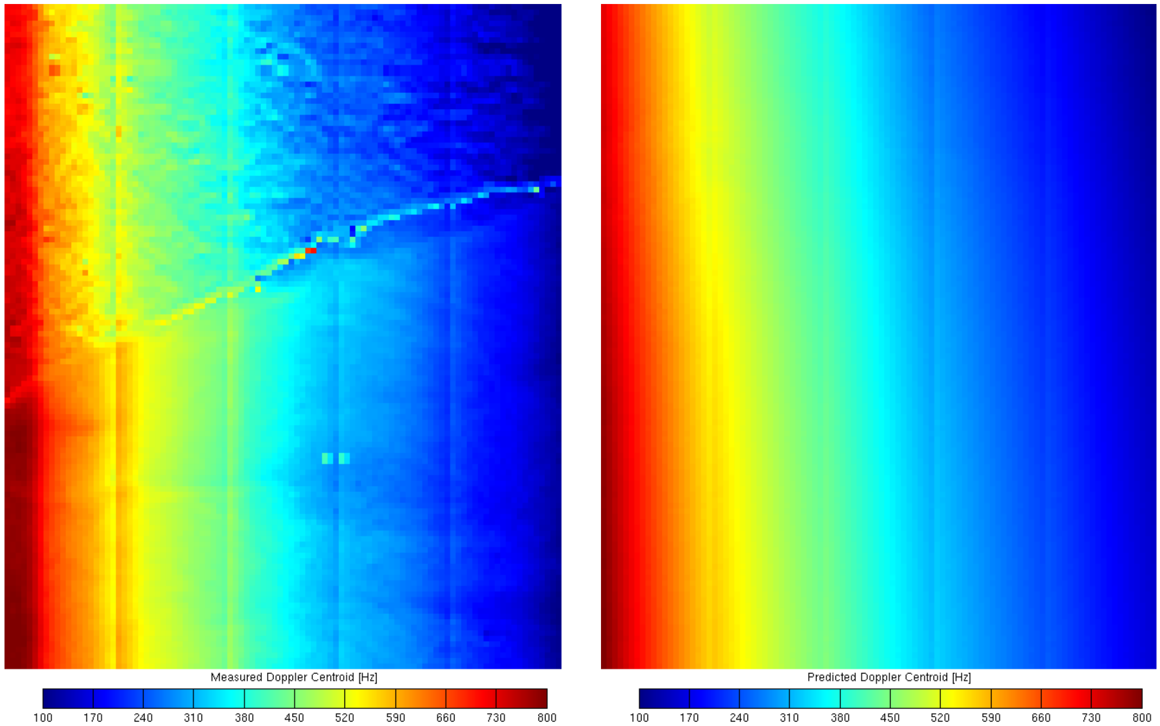

Figure 1: The left figure shows the Doppler centroid frequency grid for an Envisat ASAR Wide Swath scene acquired over the coast of South Africa on 27 May 2010 20:34 UTC. The right figure shows the Doppler centroid predicted for the same scene using the Envisat CFI software.

The Doppler anomaly of this example scene is shown in Figure 2. The anomalies are small compared to the Doppler centroid values, of the order of 30 Hz compared to more than 700 Hz corresponding to Earth rotation velocities of several hundred m/s. Since two large numbers are subtracted to create a small anomaly, accuracy is here of great concern. Consequently, this is considered carefully in the developed software when calculating and interpolating quantities such as the Doppler coordinates (slant range time and zero Doppler times), and incidence angles and latitudes and longitudes. For the predicted Doppler over land, the topography is input to the CFI-software to account for the modulation of incidence angle due to topography (layover-effect). The Doppler anomaly contains quantitative information on the velocity of the surface relative to the earth. However, as is illustrated in Figure 2, some unwanted biases partly mask this geophysical information. Two independent effects are identified, termed “range bias” and “azimuth bias”, to be described in the following subsections.

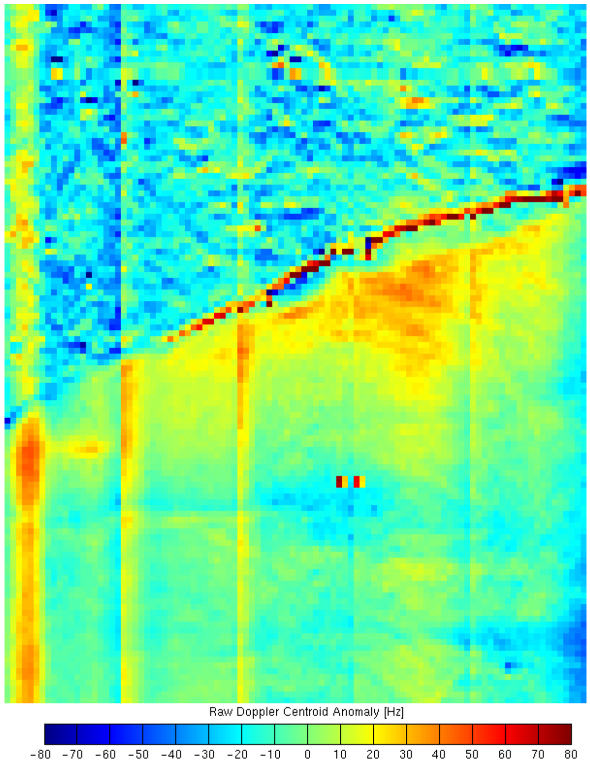

Figure 2: A (raw) Doppler centroid anomaly, calculated by subtracting the predicted from measured values (Figure 1, right and left respectively).

Range bias removal

The range bias is clearly visible on Figure 2 as vertical stripes of enhanced/reduced Doppler anomalies. Taking the average of the Doppler anomalies for each range line (vertically), a pattern resembling the ASAR antenna pattern becomes visible. This is also the case when averaging only over land, where the Doppler anomaly is expected to be zero (see Figure 4). This bias is a result of mispointing of the ASAR antenna due to improperly working pixels of the phased array antenna, as confirmed by a modeling study performed by Davide D'Aria from Aresys in Italy (communication with Fabrice Collard). Ideally, this bias pattern could be estimated by averaging pixels over land, and then subtracted for the whole scene. However, as learned by experience, the land is not always a good reference source, for three reasons: 1) For many scenes there is not (enough) pixels over land for each range line; 2) The topography modifies the incidence (elevation) angle which again modifies the Doppler frequency and leads to additional uncertainties, and 3) the "azimuth bias", to be discussed below, is very strong over land and leads to further uncertainties. Several methods to correct for the range bias have been developed and tested. The current implementation is a hierarchy of methods described below:

- Over the Amazon rainforest the NRCS is relatively uniform, and the topography is relatively flat, making this suitable for calibration of the Doppler. We have ordered and downloaded from ESA a number of Wide Swath scenes for two fixed selected ascending and descending tracks, where some examples of descending tracks are shown in Figure 3. The azimuth-averaged anomalies are very smooth, but are found to vary strongly with time. Possible reasons for this may be varying antenna mispointing or squint angle (antenna is not exactly side-looking). The calibration image closest in time to the given SAR image is then used to correct the given wide swath image.

- As an alternative method, two scenes from the same or adjacent orbits with sufficient land coverage with topography below 200 meters are used to determine the variation of Doppler anomalies with incidence angle, which is then subtracted.
- Whether the variation of Doppler anomaly with range is determined from the first or second approach above, an offset is still found, which is nearly constant for each swath, and also normally varies little from swath to swath, as illustrated in Figure 4. This remaining offset may be due to variation of antenna squint angle with time. If there is enough low-lying land pixels for each range line number of the scene, then this offset can simply be averaged over this land, and subtracted. Alternatively, the ocean part of the scene is used for a dynamic offset-correction: the average the Doppler anomaly of each range line (incidence angle) is subtracted, and then averaged Doppler calculated from the CDOP-function with model wind input, also averaged over the same range line, is added. The latter approach is more dangerous, since an average wind (direction) error over the swath, as well as persistent current direction along the range line, will lead to a new bias.

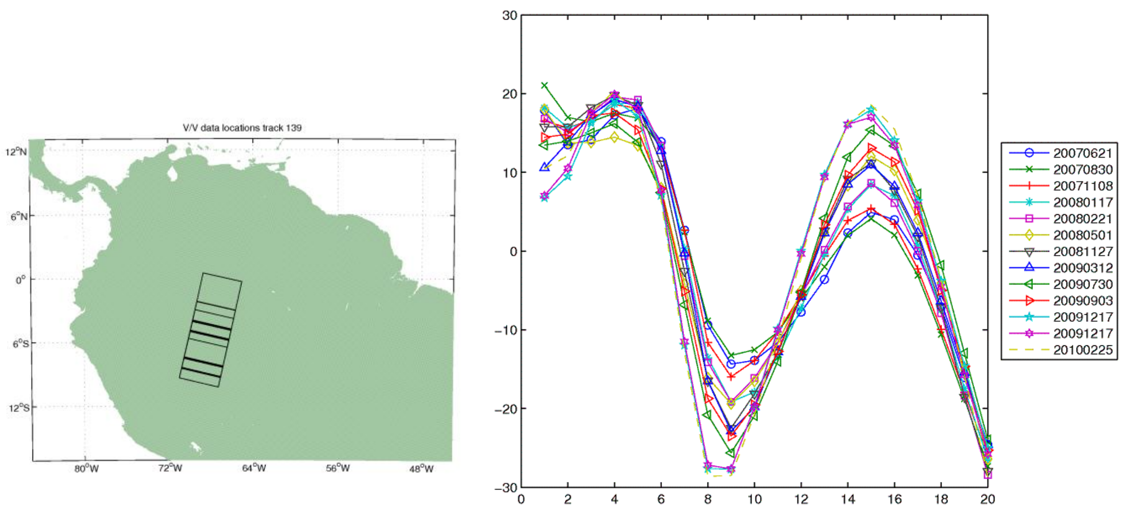

Figure 3: Coverage of a selection of ASAR Wide Swath images over the Amazon forest (left), and corresponding azimuthal average of Doppler Centroid Anomaly for the first swath (right) plotted versus range pixel number (incidence angle), with acquisition time (YYYYMMDD) of each scene indicated on the legend.

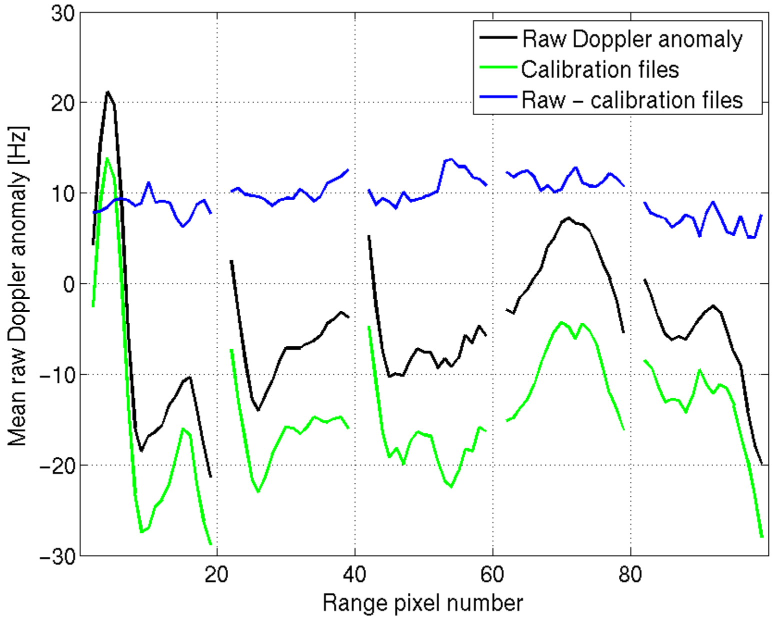

Figure 4: Mean Doppler

The Doppler anomaly of the example scene after performing this range calibration is seen in Figure 5, left.

Azimuth bias removal

In the processing algorithm used for the ASAR Wide Swath scenes (SPECAN algorithm), the Doppler centroid is first calculated, and secondly used to focus the SAR scene to provide a high resolution NRCS. Hence, at the stage of calculation of the Doppler centroid, the sub-Doppler-pixel variations of NRCS are not known, and are assumed homogeneous. However, an azimuthal gradient of NRCS within the area over which the Doppler centroid is calculated will lead to a bias of the Doppler, as seen from the impulse response function of the SPECAN algorithm (e.g. Cumming and Wong, 2005). An empirical correction for this is found by calculating the sub-Doppler-pixel linear gradient of NRCS over land-pixels, and fitting a linear relationship with the corresponding Doppler anomaly. This relation is then subsequently used to correct the Doppler anomaly values over both land and ocean, from the corresponding NRCS-gradients. Figure 5 shows the Doppler anomaly of the example scene before and after applying this correction. As seen over land, most of the artificial Doppler variations are removed. Some bias remains, and also over ocean Doppler values are flagged as invalid if the NRCS-gradient within the pixel area is larger than a given threshold.

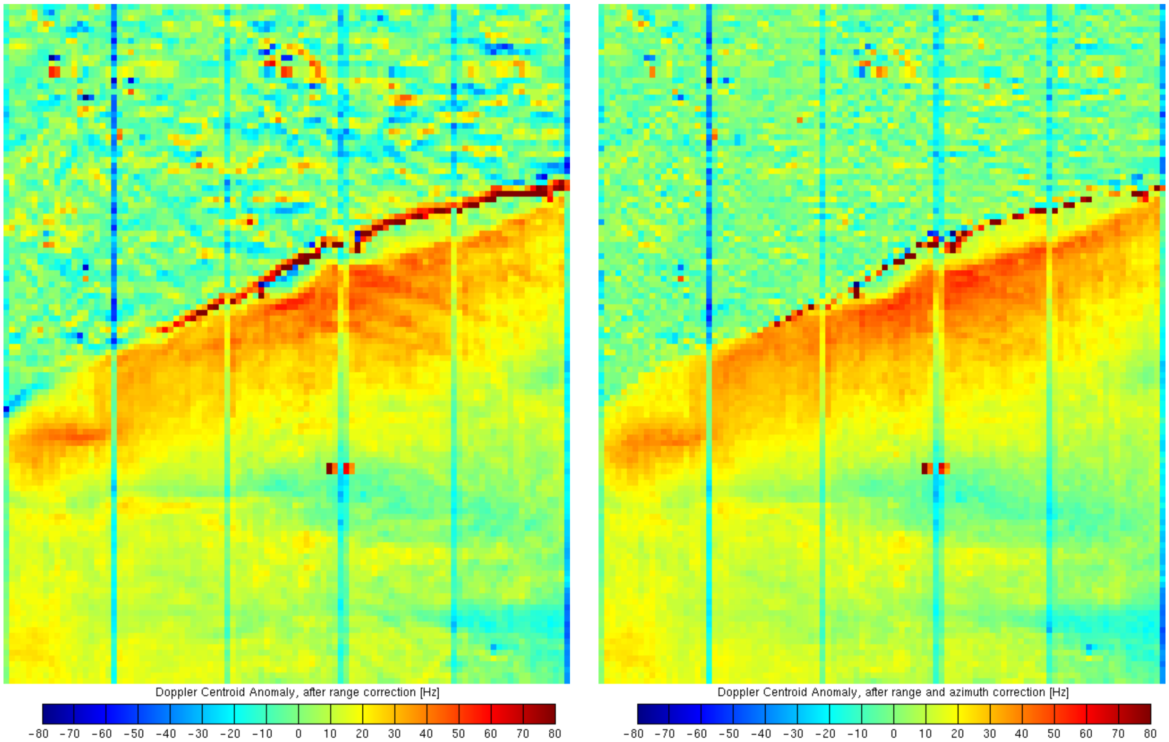

Figure 5: Doppler anomaly of the same scene as above, after applying range correction (left), and subsequently the azimuth correction (right). See text for the description of these corrections. The lines with discontinuities between the swaths are overlapping in slant range time, and are removed before the Doppler is eventually interpolated to another spatial grid.

Finally, the corrected Doppler centroid anomaly is converted to velocity from the Doppler relationship, and projected to the horizontal surface, as seen in Figure 6.

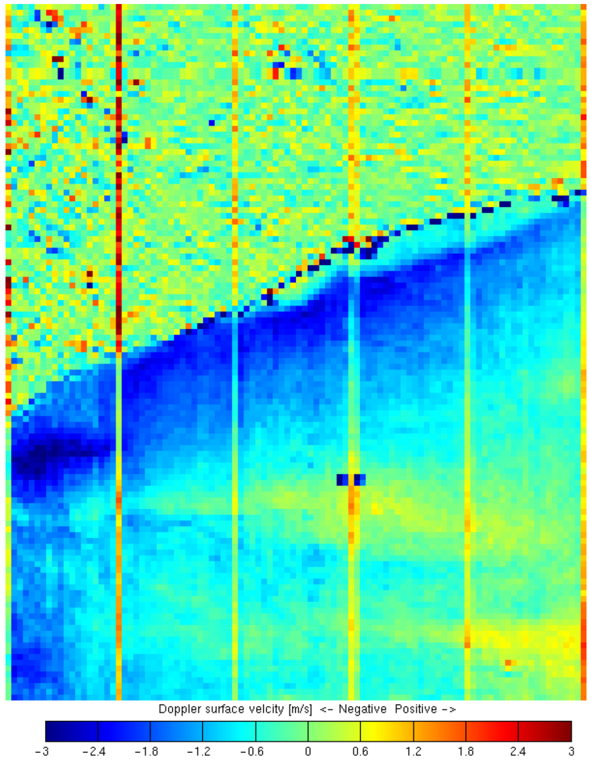

Figure 6: Range- and azimuth corrected Doppler centroid anomaly converted to velocities and projected to the horizontal surface. This is termed the "Doppler surface velocity", and by convention positive values are here chosen to be towards the right of the scene.

As mentioned in the Background-section, this Doppler surface velocity is due to both ocean surface currents and the orbital motion of waves ("sea-state contribution"). As described in Collard et al. (2008), Johannessen et al. (2008) and Hansen et al. (2010), the CDOP function may be used to subtract the sea-state contribution for a first order estimate of the range directed component of the ocean currents.

Conclusions and further work

A Bayesian wind retrieval scheme has been implemented, based on an approach outlined by Portabella et al. (2002) and Mouche et al. (2009). The use of the Doppler anomaly is seen to be highly useful to retrieve a realistic wind speed and direction for interesting cases with sharp wind fronts, such as for cyclones and topography-steered winds. In the general case, however, the Doppler in fact degrades the performance over the traditional SAR wind retrieval scheme based on NRCS and model wind. This is found to be due to uncertainties from the calibration of the Doppler centroid anomalies. Since a precisely calibrated Doppler shift is also necessary for the implementation of the second work package, much effort have been directed towards improving this calibration. Empirical corrections are applied, which compensate for errors/uncertainties from unknown satellite antenna pattern and mispointing or squint. Ideally, such effects should be considered already in the stage of the SAR processing. At Norut IT in Tromsø, an improved Doppler estimator software is being developed, following an approach described in Pedersen et al. (2004). It is believed that this method has potential to provide Doppler centroid anomalies with a significantly higher accuracy than the present, default processing algorithm used for ASAR WSM Level-1b data. 20 Wide Swath scenes in raw-format (Level 0) have been ordered and downloaded in order to test this approach as soon as this software is completed.

After the sea state contribution has been subtracted with the CDOP model, the surface velocity as calculated from the Doppler anomalies is a first order estimate of surface current. Only the component perpendicular to the SAR travel direction is however detected, and the task of the second work package will be to retrieve a full 2-dimensional surface current field based on this, a first order wind field (based on the Bayesian approach or taken from a model), and the RIM model, eventually supported by auxiliary data. The RIM code, although proven very powerful, has no simple user interface, and is presently not adapted to simulate spatially varying 2-D fields of wind, current and incidence angle. In the coming months, this model needs to be updated to be suitable for simulation of NRCS and Doppler shift from such 2-dimensional input.

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