Backscatter and Doppler signals of surface current in SAR images: A step towards inverse modelling

by

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Abstract

Recently, two new and independent methods for quantitative studies of SAR imaging of current features were presented in the July 2005 issue of Journal of Geophysical Research-Oceans. They are the Doppler shift approach and the radar imaging modelling (RIM) approach. It is therefore timely to combine these two approaches for more comprehensive and quantitative studies of SAR imaging of current features. In this paper we present and examine the preliminary results obtained with this new “DopRim” model, which also features an independent wind-wave SAR retrieval tool. Forward simulations of SAR images using this DopRim model have been conducted for two test areas around the French coast at the entrance to the English Channel. The 3D current fields are taken from numerical ocean models, while the wind and dominant wave field are retrieved from the respective SAR images. These products serve as the input for the forward DopRim module. Extensive testing and validation of this method is currently ongoing. Preliminary results show that surface current velocities and estimation of current deformation such as zones of convergence and current shear can be derived in consistence with the SAR backscatter anomalies, near surface wind and wave fields, and the measured Doppler shifts. The inverse module, when fully tested and validated, is expected to significantly advance the use of SAR imagery in quantitative studies of mesoscale features such as fronts, eddies and filaments. In the longer term, it may also open up for routine application of SAR image data in operational oceanography.

1 Introduction

For more than a decade, spaceborne radar instruments have been observing a wide range of ocean surface phenomena, including wind features (even the eyes of hurricanes and typhoons), waves, oil spills, natural film, meandering frontal boundaries and eddies. Now, employing the same principle as police speed guns, satellite radar has also begun to enable direct measurements of the speed of the moving ocean surface itself.

The oceans cover 71% of the Earth’s surface and are constantly in motion. Ocean surface currents can strongly interact with wind and waves, and in turn influence the weather. The dynamic range in the mesoscale is broad, with features such as current eddies, occurrences of filaments and jets, frontal dynamics associated with divergence and convergence, and wind driven coastal upwelling and downwelling. It is very difficult to obtain high-resolution surface current observations on a large scale, although satellite altimeters permit monitoring of sea level anomalies that in turn are inverted to surface geostrophic currents. Additionally, sea surface temperature and ocean colour measurements throw light on ocean circulation characteristics, but only in the absence of clouds.

Synthetic Aperture Radar (SAR) sensors register microwave radar backscatter that is related to patterns of surface roughness in (practically) all weather conditions, day and night. Over the ocean these patterns are linked to varying surface winds, waves and currents, as well as the presence of surfactant material and oil spill. In particular current shear and varying convergence zones can focus wave energy, resulting in wave steepening and enhanced radar-detectable roughness changes. Due to a general lack of sufficient high-quality in-situ observations, the quantitative understanding of how these dynamic features contribute to the complicated surface roughness modulation pattern often manifested in SAR images has usually been incomplete.

Recently, [2], [3], [6] demonstrated the potential capability to derive more direct estimate of the surface currents from SAR images by respectively utilizing the Doppler shift information embedded in the radar signal and an advanced radar imaging model (RIM). In this paper, we combine these two methods in order to obtain a more consistent
estimate of the surface current from SAR images. In section 2, we briefly introduce the new method. Section 3 presents the new and preliminary results, while section 4 contains the summary.

2 The new DopRim method

The Doppler shift is introduced by the relative motion between the satellite platform, the rotation of the Earth and the velocity of the facets of the sea surface from which the backscattered SAR signal originates. The initial two former effects are well known, particularly for Envisat with its very stable satellite orbit and attitude, and can be subtracted to extract the sea surface velocity information. This surface velocity, in turn, is composed of contributions from the wind-wave induced motion, and the background surface current. Following the Doppler shift equation, an estimate of the surface current can be obtained, providing the contributions from wave- and wind-induced motion are first quantified and removed. This is feasible by the use of the RIM; a forward model that simulates radar cross-section signatures from given fields of wind, surface current and boundary layer stratification. As such, RIM provide both wave- and wind-induced ocean surface motion, which are necessary for the subtraction. The remaining shift must then come from the surface current in the line-of-sight of the radar instrument. In short, this new achievement is based on complementary use of the classical radar backscatter intensity signal and the partitioning of the Doppler shift.

2.1 The approach

The Doppler frequency \( f_D \) of the radar backscatter from a moving target is defined as: \( \pi f_D = -k_R v \), where \( k_R \) is the radar wavelength, and \( v \) is the radial velocity of the target. The Doppler frequencies result from the surface current and orbital velocities in the presence of random wind waves. In geophysical applications, statistical characteristics of the Doppler frequencies are described within the frame of the two-scale approach (e.g. [1], [9]).

Present analysis is focused on the mean Doppler frequency shift (the Doppler centroid anomaly). Following [2], it is suggested that the sea surface NRCS (\( \sigma_0 \)) can be represented as a sum of surface facets scattering radiowaves. In this case the Doppler centroid anomaly can be estimated as a mean, weighted over all scattering facets

\[
\frac{\pi f_D}{k_R} = \frac{(u \sin \theta - w \cos \theta)\sigma_0(\theta + \Delta \theta)}{\sigma_0(\theta + \Delta \theta))}
\]

Here \( u \) and \( w \) include the horizontal and vertical velocity of the scattering facets and the surface current velocity. \( \Delta \theta \) is the local modification of the incidence angle \( \theta \), determined from the scalar product of the local normal to the surface and the unit vector along the incident direction. We assume that the scattering facets experience vertical and horizontal movements by longer surface waves. Each term can be split as \( y = \bar{y} + \tilde{y} \), where bar denotes mean quantity (averaged over these long waves) and tilde means correlated with the long wave quantity. Wave-induced quantities \( \tilde{y} \) are of order \( \varepsilon \) (\( \varepsilon << 1 \) is the steepness of long surface wave). In the second order of \( \varepsilon \) this equation gives the following mean Doppler velocity \( V_D = \pi f_D / k_R \sin \theta \):

\[
V_D = \bar{c} + u_S - \frac{1}{\tan \theta} \left( \bar{w} \frac{\sigma_0}{\sigma_0} + \bar{u} \frac{\tilde{\sigma}_0}{\sigma_0} \right)
\]

where \( \bar{c} \) is the mean velocity of the scattered facets, \( u_S \) is the surface current velocity (which includes Stokes drift), and \( \bar{w}, \bar{u} \) are the orbital velocities of long surface waves. In order to calculate the last terms in eq.(2), it is suggested that modulations of NRCS are caused by both a change of the local surface tilt \( \Delta \theta \) and the hydrodynamic modulations of the scattering facets roughness:

\[
\tilde{\sigma}_0 = \Delta \theta \frac{\partial \sigma_0}{\partial \theta} + \tilde{\sigma}_0^h
\]
where $\Delta \theta = \cos q_R \cdot \xi_x + \sin q_R \cdot \xi_y$, $q_R$ is the radar look direction, $\xi_x, \xi_y$ are the components of the sea surface slopes, and $\sigma^h_0$ is the hydrodynamic modulations. If $\xi = a \exp(i \Phi)$ is the surface displacement and $\Phi = k \cdot x - \omega t$ is the phase function, then the wave quantities are:

$$w = -i \varepsilon e^{i \varphi}$$
$$u_j = k_j \varepsilon e^{i \varphi}$$
$$\frac{\partial \xi}{\partial x_j} = k_j \varepsilon e^{i \varphi}$$
$$\sigma^h = \sigma_0 e^{i \epsilon}$$

where $k_j = k_j / k$ is the unit wavenumber vector, $\varepsilon = ak$, and $M$ is the modulation transfer function (MTF), assumed to be a real number (small scale waves are enhanced on the crests of longer waves). When long surface are not monochromatic but represented by a “wide” spectrum, equations (4) are related to each spectral component. In this case equation (2) reads:

$$V_D = \overline{v} + u_S = \frac{1}{\tan \theta} \frac{\partial \sigma_0}{\partial \theta} \int_{k < k_x} \cos(q_R - q) c B(k) d \ln k d \varphi$$
$$+ \int_{k < k_x} \cos(q_R - q) c B(k) M d \ln k d \varphi$$

where $B(k)$ is the 2D saturation spectrum, linked to the surface elevation spectrum $F(k)$ as: $B(k) = k^4 F(k)$. If one assumes that longer waves are quasi-monochromatic and travel along radar look directions, eq.(5) reduces to

$$V_D = \overline{v} + u_S - \frac{\epsilon^2 C}{2 \tan \theta} \frac{\partial \sigma_0}{\partial \theta} + \frac{\epsilon^2 C}{2} |M^p_H|$$

This equation corresponds to the formulation suggested by [2], notably eq. (B16).

### 2.2 Combining RIM and Doppler method

Following [4] and [6] the NRCS of the sea surface ($\sigma^p_0$) is represented as a sum of radar scattering from the “regular” wavy surface and wave breaking zones:

$$\sigma^p_0 = \sigma^p_{BR} (1 - q) + \sigma_{wb} q$$

where $\sigma^p_{BR}$ and $\sigma_{wb}$ are the NRCS of the regular surface and the wave breaking zone, where $q$ is the fraction of the sea surface covered by these breaking zones. $\sigma^p_{BR}$ is described within the frame of the composite model combining 2-scale Bragg and specular reflections: $\sigma^p_{BR} = \sigma^p_{BR} + \sigma^p_{sp}$. The role of each of the scattering mechanisms in eq.(7) depends on the incidence angle $\theta$, the polarization, and the wind and wave conditions. Examples of model estimates of the relative contribution of scattering mechanisms to the total NRCS are given in [4] and [6]. Eq.(7) can, in turn, be used for calculations of the mean Doppler velocity.

The mean velocity of the scattering facets (first term in eq.(2)) reads

$$\overline{v}^p = P^p_{br} c_{br} + P^p_{sp} c_{sp} + P^p_{wb} c_{wb}$$

where $P^p_{br}, P^p_{sp}, P^p_{wb}$ are the relative contributions of Bragg scattering, specular reflection and wave breaking to the total NRCS, respectively. These depend on the incidence angle $\theta$, the polarization and the wind speed (see e.g.
Figure 1 in [5] and Figure 3 in [6]; \( c_{br} \), \( \bar{c}_{sl} \) and \( \bar{c}_{wb} \) are the respective phase velocities of the Bragg waves, of the mean (weighted over slope spectrum) waves supporting the specular reflections, and of the mean breaking waves (weighted over the "spectrum" of breaking zones \( \bar{q} \)). The last two quantities are defined as:

\[
\bar{c}_{sl} = \frac{\int_{k<k_d} \cos(q_R - \varphi)cB(k)d\ln kd\varphi}{\int_{k<k_d} \cos(q_R - \varphi)B(k)d\ln kd\varphi} \\
\bar{c}_{wb} = \frac{\int_{k<k_d} \cos(q_R - \varphi)c\beta(k)B(k)d\ln kd\varphi}{\int_{k<k_d} \cos(q_R - \varphi)\beta(k)B(k)d\ln kd\varphi}
\]  

(9)

where \( k_d = k_g / 4 \) is the dividing wavenumber in the composite scattering model, and \( k_{wb} = k_g / 10 \) is the wavenumber of the shortest breaking waves providing radar returns.

The effect of vertical motions of scattering facets (described by the third term in eq.(2) and eq.(5)) is also dependent on the scattering mechanisms. At moderate incidence angles (from 25 to 50 degree) this term is dominated by the Bragg scattering mechanism. At smaller incident angles \( \theta < 25^\circ \) specular reflections from the large scale waves (with \( k < k_g \)) remarkably contribute to the NRCS, and e.g. at \( \theta = 20^\circ \) their relative contribution reaches 50% (see Fig.3 from [6]).

Direct application of the third term in eq.(5) for the specular reflection mechanism is not so trivial as for the Bragg scattering. However we may anticipate that the main contribution to the integral in the third term (i.e. contribution to the mean phase velocity) comes from the energy containing waves (for a example, if the wave spectrum has a shape \( k^{-4} \), Phillips spectrum [8], then B is constant, and the integral converges on the lower limit, i.e. on the spectral peak), while the mean square slope of the surface providing specular reflections to a large extent is determined by the shortest waves (by the tail of the spectrum of large scale waves). Therefore, tolerating some inaccuracy, it is suggested that the third term in eq.(5) can be used to estimate the contribution of the wave induced vertical motions to \( U_D \) at all incidence angles of interest (\( \theta > 15^\circ \), in the case of Envisat ASAR) and independently of which scattering mechanism is dominant.

Finally, the impact of the hydrodynamic modulation of scattering facets is described by the last term in eq.(5). This term plays a role (i.e. comparable with other terms) at incidence angles larger than 30^\circ, whereas it is negligible at smaller incidence. At moderate incidence Bragg scattering is a dominating scattering mechanism. Thus M in the last term of eq.(5), can be substituted for MTF of the Bragg waves. More detailed analysis of Bragg waves modulation is given in [5]. In the present calculations, it is simply assumed that M is 4.5 (amplitude of adiabatic modulations).

Calculations of the mean Doppler velocity and its variations on the surface current can now be done within the frame of the RIM proposed in [6]. This is the new DopRim model. The approach of the forward calculations is as follows:

- First, the RIM is executed for a given wind speed, current field and geometry of radar observations.
- The outcome of these calculations are the NRCS (and its components), the corresponding wave spectrum and its modulations by the surface current.
- These quantities are then used to estimate the mean velocity of the scattering facets in eq. (8) and subsequently invoked to calculate the Doppler velocity in eq.(5).

Following this approach, a few 1D sensitivity experiments are presented below for simplified cases with varying polarisations, incidence angles, and wind speed. Figure 1 shows dependences of \( U_D \) for VV and HH polarisation versus incidence angles at a wind speed of 10 m/s. The Doppler velocity (left) attains largest values at low incidence angles, and decreases with increasing \( \theta \). For HH polarization, this decrease is not monotonic, and one may observe an increase in velocity at grazing angles. This results from the increasing role of wave breaking and their modulations in both NRCS and Doppler velocity at HH polarisations. At low \( \theta (\approx 20^\circ) \), the Doppler velocity is relatively large attaining values reaching up to 30-40% of the wind speed. This is much larger than the expected Doppler velocity due to the motion of the Bragg waves (about 0.3 m/s) and the wind induced drift of the surface (about 3% of wind speed). The middle and right plots illustrate the relative contribution of the different mechanism to \( U_D \). At low incidence
angles the main contribution to $U_D$ comes from the tilt of the larger scale waves. At moderate incidence angles the contribution of all the three mechanisms (velocity of facets, tilt and modulations) are comparable in magnitude. At large $\theta$, the effect of tilt becomes negligible, and the Doppler velocity is dominated by the movement of scattering facets and their modulations by longer waves. Note also that at large $\theta$, $U_D$ for VV polarisation is not far from the Bragg predictions, while for HH polarisation the impact of wave breaking is significant, and $U_D$ is reaching 20% of the wind speed.

In Figure 2, the wind dependence of the Doppler velocity for VV and HH polarisations at $\theta = 20^\circ$ are shown. Up to 10 m/s, $U_D$ increases with the wind speed again attaining values reaching up to 30-40% of the wind speed. At wind speeds exceeding 10 m/s, on the other hand, $U_D$ is leveling off and then decreasing. Such behavior results from the dependence of the gradient of the NRCS $\partial^2 \sigma / \partial \theta$ on the wind speed at low incidence angles. The leveling off (saturation) of $U_D$ at higher winds is in agreement with the SAR image derived Doppler velocities estimated reported by [2].

**Figure 1.** Up-wind Doppler velocity for C-band VV (solid line) and HH (dashed line) versus incidence angle at a wind speed of 10 m/s (left). Relative contributions to the Doppler velocity from the motion of the scattering facets (dashed line), the tilt of the longer waves (solid line), and the hydrodynamic modulations (dotted line) for VV polarizations versus incidence angles at a wind speed of 10 m/s (middle). The same presentation as in the middle plot, but for HH polarization (right).

**Figure 2.** Dependence of the C-band Doppler velocity on the wind speed at an incidence angle of $\theta = 20^\circ$ for VV (solid line) and HH (dashed line) polarizations.

### 3 DopRim simulation

The combination of the RIM and the Doppler method (DopRim) is now extended to 2D simulations and compared with ASAR images obtained from the Iroise Sea (Brest coast) and off the coast of Normandy.
The input to the DopRim simulation was obtained from a finite element and finite difference 2-D numerical model applied to obtain maps of currents at 5 m depth. The tide is generated using well known harmonic constituents measured in reference harbors and with the bottom friction adjusted to fit observed current ellipses [7]. The tidal current at the time of the SAR image acquisition is then computed by interpolation from the hourly resolution output of the model (Figure 3, left). In addition, the mean wind speed was set to 5 m/s with a direction towards southwest, while the atmospheric stratification was assumed neutral.

Figure 3. Modeled tidal current from the Iroise sea (left), simulated NRCS (middle), and ASAR image (right). The image sizes are equal about 38 km by 38 km.

It is clearly seen how the currents intensifies across the narrow gaps between the islands and the between the island and the main land reaching up to more 3 m/s and 2 m/s respectively. The simulated NRCS (Figure 3, middle) also reveal a pattern that has zones of strong anomalies in backscatter between the islands. Compared with the ASAR image (Figure 3, right) there is a fair amount of consistency in the backscatter pattern. (The ascending ASAR image is a fragment of the full wide swath image, with the look direction of about 10° (with respect to the east), and an incidence angles in the range 36.5-38.5°. This qualitative agreement is encouraging as both the RIM and the DopRim have been using the model current field that in reality is expected to deviate somewhat from the actual surface current field. In addition the constant wind field is also most likely a simplification. All in all this suggests that both the simulated and observed images demonstrate quite distinct radar contrasts caused by the strong tidal current.

With DopRim we can furthermore proceed and simulate the Doppler velocity (Figure 4, upper left). Figure 4 (upper right) reveal the contribution from the pure surface velocity obtained from projecting the modeled current field in the radar look direction, while Figure 4 (lower left) shows the contribution from the surface roughness and its modulation by the current to the Doppler velocity. In the mean this contribution is significant, and modulations results in strong variability of roughness contribution over the observed area.

The comparison of the full simulated Doppler velocity to the one derived from the ASAR image is then shown in Figure 4 (upper left, lower right). Although the range of the simulated Doppler is larger than the measured, the overall pattern is similar with the strongest Doppler velocity encountered between the islands of about 2 m/s (simulated) and 1.6 m/s (measured). Similar results (not shown) are obtained for the Cherbourg case. Keeping in mind the probable deviations between the real and invoked surface current field and wind field the results are encouraging.

4 Summary

The combined use of the Doppler method and RIM into the DopRim has opened up for consistent investigations of the various contributions to the Doppler velocity. These are arising from the relative contributions of the phase velocity of the Bragg waves, of the mean (weighted over slope spectrum) waves supporting the specular reflections, and of the mean (weighted over "spectrum" of breaking zones ) breaking waves in addition to the background surface current.

Initial tests have been carried using tidal currents off Brest and Cherbourg in France to simulate ASAR images and Doppler velocities that are compared to ASAR images and their estimates of Doppler shift. The results are encouraging and should open up new scientific investigations of mesoscale ocean variability based on SAR, including:
Figure 4. Simulated total Doppler velocity (upper left), surface current induced Doppler velocity (upper right), motion of surface roughness induced Doppler velocity (lower left), and measured Doppler velocity (lower right). The insert in the lower right image marks the position of the SAR image and simulated fields derived from DopRim.

- absolute surface current determination;
- surface current deformation including divergence, shear and rotation;
- surface drift estimation of importance for oil dispersion and pollution transport;
- wave-current interaction.

More evaluations are certainly needed to consolidate and validate this DopRIM method. Provided the method is found to be reliable it will open up new applications and make a significant contribution to operational oceanography. As such this will also contribute to and benefit from operating and approved continuity and experimental SAR satellites, such as ALOS PalSAR, Radarsat-2, TerraSAR-X and Cosmo-Skymed, as well as the planned ESA’s Sentinel-1 mission.

5 References
