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## Simulation of radar backscatter and Doppler shifts of wave–current interaction in the presence of strong tidal current

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### Abstract :

A radar imaging model including a Doppler shift module is presented for quantitative studies of radar observations of wave–current interaction in a strong tidal current regime. The model partitions the Doppler shift into the relative contribution arising from the motion of the backscattering facets including Bragg waves, specular points, and breaking waves that are advected by and interact with the underlying surface current. Simulated and observed normalized radar cross sections and Doppler shifts for different environmental conditions and radar parameters are compared and discussed.

**Keywords :** SAR ; Tidal current ; Waves ; Normalized radar cross section ; Doppler velocity

### 1. Introduction

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Airborne and spaceborne radar measurements at slanting incidence angles offer a method to map the ocean surface roughness linked to surface wind, waves and current, as well as to the presence of surface contaminants. Current shears affect the surface roughness leading to radar intensity-detectable patterns. For quantitative analysis of SAR measurements over the ocean, Kudryavtsev et al. (2005) and Johannessen et al. (2005) proposed a practical RIM of surface current features based on the NRCS model by Kudryavtsev et al. (2003a)

9 Statistical properties of the sea surface result from a solution of the energy balance equation  
10 (e.g. Hughes (1978); Thompson (1988); Lyzenga and Bennett (1988)) where wind forcing,  
11 viscous and wave breaking dissipation, wave-wave interactions, and generation of shorter  
12 waves by breaking waves of longer scales are accounted for. The latter mechanism is described  
13 by Kudryavtsev and Johannessen (2004), and although it does not significantly alter the  
14 background spectrum, it plays a crucial role in the context of wave modulations by surface  
15 current (Kudryavtsev et al., 2005). The RIM thus consists of a particular decomposition  
16 of the sea surface into a regular wavy surface and a number of breaking zones. Radar  
17 scattering from the regular surface is described within the frame of the composite model  
18 combining specular reflection and resonant (Bragg) scattering waves with local tilting effects  
19 due to longer underlying waves (e.g. Plant (1986); Donelan and Pierson (1987); Romeiser  
20 et al. (1994); Romeiser and Alpers (1997)). The contribution from breaking waves can  
21 be described as specular reflections from very rough wave breaking patterns and is taken  
22 proportional to the fraction of the sea surface covered by breaking zones based on wave  
23 breaking statistics proposed by Phillips (1985).

24 Using Envisat Advanced SAR (ASAR) observations, Chapron et al. (2005) demonstrated  
25 the capability to use the Doppler centroid information embedded in the radar signal to  
26 map surface velocity, including wind-generated waves and current, from SAR images. The  
27 difference between a predicted Doppler shift based on precise knowledge of the satellite  
28 orbit and attitude, and the Doppler centroid frequency estimate in this case represents the  
29 geophysical Doppler shift experienced from the moving ocean surface. This geophysical  
30 Doppler shift in turn reflects the line-of-sight velocity of the scatterers, weighted by their  
31 contribution to the backscattered power (Romeiser and Thompson, 2000). The retrieval and  
32 subsequent error correction of the geophysical Doppler shift from the ASAR Wide Swath  
33 Medium resolution image (WSM) product is presented in Hansen et al. (2011a) where the  
34 accuracy of the geophysical Doppler shift is found to be about 5 Hz. This corresponds to  
35 a horizontal surface velocity of 20 cm/s at an incidence angle of 40°, and 40 cm/s at an  
36 incidence angle of 20°. As such, the accuracy is still an issue in single scenes, although

37 temporal averaging has been shown to capture the mean circulation in e.g. the Agulhas  
38 region (Rouault et al., 2010) and in the Norwegian Sea (Hansen et al., 2011b). The range  
39 Doppler velocity is not a direct surface current measurement, but the use of Doppler shift  
40 observations can help to provide valuable insights into the mesoscale dynamics to more  
41 quantitatively interpret high resolution radar roughness changes. The RIM model extended  
42 with a Doppler shift module was first presented by Johannessen et al. (2008) and follows the  
43 concept in RIM by treating the Doppler shift as a result of the partial contributions from  
44 the regular surface and breaking waves.

45 The objective of this paper is to further assess and demonstrate the combined approach  
46 to SAR image interpretation based on the use of both Doppler shift and RIM analysis. In  
47 Section 2, the Doppler shift equations and RIM are consistently combined into the Doppler  
48 Radar Imaging Model (DopRIM) as done in Johannessen et al. (2008), however, with a  
49 more detailed description of the contributions from the different scattering mechanisms. We  
50 do not consider SAR imaging artifacts such as e.g. velocity bunching. Model calculations  
51 providing total and partial contributions to the range Doppler velocity from each type of  
52 the scattering mechanisms for varying incidence angle and wind speed are presented in  
53 Section 3.1, including a comparison to the observed range Doppler velocity signal from  
54 ASAR WSM acquisitions over the Norwegian Sea. In Section 3.2, DopRIM calculations for  
55 a situation of strong tidal current in the Iroise Sea outside Brest, France, are compared to the  
56 NRCS and range Doppler velocity from an ASAR Single Look Complex (SLC) acquisition  
57 on 5 October 2005. Section 4 provides the summary and conclusion.

## 58 **2. The DopRIM Approach**

59 The Doppler shift of the radar backscatter from a moving target is given by  $f_D = -k_R v / \pi$ ,  
60 where  $k_R$  is the radar wavenumber, and  $v$  is the line-of-sight velocity of the target (defined  
61 positive if directed away from the radar). Following a two-scale decomposition, it is suggested  
62 that the sea surface consists of an ensemble of small-scale scattering facets (with local NRCS  
63  $\sigma_0$ ) which cover a large scale surface formed by superposition of longer surface waves. These  
64 scattering facets experience vertical and horizontal movements due to the longer surface

65 waves, resulting in a spatially variable  $\sigma_0$  over the large-scale surface. In this case, the  
 66 average Doppler shift reads (Romeiser and Thompson, 2000; Chapron et al., 2005):

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

67 Here,  $u$  and  $w$  are the horizontal and vertical velocities of the scattering facets in the radar  
 68 incidence plane, and  $\Delta \theta$  is the local modification of the incidence angle  $\theta$  due to waves. The  
 69 geometry in (1) is illustrated in Fig. 6 of Chapron et al. (2005). Following Johannessen et al.  
 70 (2008), each parameter on the right side of (1) can be split as  $y = \bar{y} + \tilde{y}$ , where bar and tilde  
 71 denote spatial mean and wave induced modulations. The latter is of order  $\epsilon$ , where  $\epsilon$  is the  
 72 steepness of the modulating longer waves. To the second order of  $\epsilon$ , (1) gives the following  
 73 expression for the mean horizontal (ground) range Doppler velocity,  $V_D$ :

$$V_D = -\frac{\pi f_D}{k_R \sin \theta} = \bar{c}_f + u_s - \frac{1}{\tan \theta} \cdot \frac{\tilde{w} \tilde{\sigma}_0}{\bar{\sigma}_0} + \frac{\tilde{u} \tilde{\sigma}_0}{\bar{\sigma}_0}, \quad (2)$$

74 where  $\bar{c}_f$  is the mean velocity of the scattering facets relative to the surface current,  $u_s$  is the  
 75 surface current including wind drift, and  $\tilde{u}$  and  $\tilde{w}$  are components of the orbital velocities  
 76 of surface waves carrying the facets in the radar incidence plane. The last two terms on  
 77 the right hand side of (2) describe the net contribution from the correlation of local NRCS  
 78 variations with wave orbital motions. Following a general approach, RIM explains the local  
 79 NRCS variations by changes of the local surface tilt and hydrodynamic modulation of the  
 80 scattering facets, expressed as

$$\tilde{\sigma}_0 = \Delta \theta \frac{\partial \sigma_0}{\partial \theta} + \tilde{\sigma}_0^h, \quad (3)$$

81 where  $\Delta \theta = -(\zeta_1 \cos \phi_R + \zeta_2 \sin \phi_R)$ ,  $\phi_R$  is the radar look direction, and  $\zeta_1 = \partial \zeta / \partial x_1$  and  
 82  $\zeta_2 = \partial \zeta / \partial x_2$  are components of the sea surface slope in an arbitrary coordinate system  
 83  $(x_1, x_2)$ . Note that we have ignored the effects of surface tilt out of the incidence plane in  
 84 (3) which is of order  $O(\epsilon^2)$ , i.e. much less than the remaining terms which are of order  $O(\epsilon)$ .  
 85 Invoking  $\zeta = A e^{i\Phi}$  as the vertical displacement of the surface by harmonic modulating waves  
 86 ( $\Phi = K_j x_j - \Omega t$ ,  $K_j$ ,  $\Omega$  and  $A$  are phase function, wavenumber, frequency and amplitude  
 87 correspondingly), the amplitude of the wave quantities in (2) and (3) can be written as:

88  $\hat{w} = -i\epsilon C$ ,  $\hat{u}_j = \kappa_j \epsilon C$ ,  $\hat{\zeta}_j = \kappa_j \epsilon$ , and  $\hat{\sigma}_0^h = \bar{\sigma}_0 \epsilon M_f^h$  for  $j = \{1, 2\}$ , where  $C = \Omega/K$  is  
 89 phase velocity,  $\epsilon = AK$ ,  $\kappa_j = K_j/K$  is the unit wavenumber vector of the modulating  
 90 wave, and  $M_f^h$  is the hydrodynamic Modulation Transfer Function (MTF) for the facets (see  
 91 e.g. Kudryavtsev et al. (2003b)). In general, the hydrodynamic MTF is a complex number,  
 92  $M_f^h = M_{1f}^h + iM_{2f}^h$ , where the real part,  $M_{1f}^h$ , describes correlation of a scattering facet's  
 93 modulations with the surface elevation, and the imaginary part,  $M_{2f}^h$ , describes correlation  
 94 with the surface slope.

95 If the scattering facets travel along a large-scale surface composed of a wide spectrum of  
 96 long waves with  $K < K_L$ , where  $K_L$  is the spectral cutoff linked to the scale of the facets,  
 97 equation (2) can be written as

$$V_D = u_s + \bar{c}_f + c_f^{TH} s_L^2, \quad (4)$$

98 where  $s_L^2 = \int_{K < K_L} K^{-2} B(\mathbf{K}) d\mathbf{K}$  is the Mean Square Slope (MSS) of the large scale surface  
 99 and  $c_f^{TH}$  is the contribution of long waves through tilt and hydrodynamic modulation of the  
 100 facets:

$$c_f^{TH} = \int_{K < K_L} [(-M_f^t \cot \theta + M_{1f}^h) \cos(\phi_R - \phi_K) + M_{2f}^h \cot \theta] CK^{-2} B(\mathbf{K}) d\mathbf{K} / s_L^2, \quad (5)$$

101 where  $M_f^t = \partial(\ln \sigma_0) / \partial \theta$  is the tilt MTF,  $B(\mathbf{K})$  is the 2D saturation spectrum of large-scale  
 102 waves, and  $\phi_K$  is the direction of  $\mathbf{K}$ . As follows from (5), the two first terms (tilt and real  
 103 part of the hydrodynamic MTF) provide changes of sign in  $c_f^{TH}$  when the radar look direction  
 104 varies from down- to upwind. On the other hand, the effect of facet-slope correlation (third  
 105 term in (5)) does not depend on radar look direction, and should provide down- and upwind  
 106 asymmetry in the range Doppler velocity.

107 If Bragg scattering is the dominant scattering mechanism, then (4) with (5) corresponds  
 108 to the model developed by Romeiser and Thompson (2000). For long quasi-monochromatic  
 109 waves that travel along the radar look direction, (4) and (5) combine to

$$V_D = u_s + \bar{c}_f + \frac{\epsilon^2 C}{2} [(-M_f^t + M_{2f}^h) \cot \theta + M_{1f}^h], \quad (6)$$

110 which also corresponds to equation (B16) suggested by Chapron et al. (2005).

111 Yet, to be fully consistent with previous efforts (Kudryavtsev et al., 2003a, 2005) the  
 112 NRCS of the sea surface,  $\sigma_0^p$ , must also incorporate facets corresponding to wave breaking  
 113 zones, such as the proposed decomposition:

$$\sigma_0^p = \sigma_{0r}^p(1 - q) + \sigma_{0b}q, \quad (7)$$

114 where  $\sigma_{0r}^p$  corresponds to the facets formed by the "regular" surface (at  $p =$  Vertical transmit-  
 115 Vertical receive (VV) or Horizontal transmit-Horizontal receive (HH) polarization), and  $\sigma_{0b}$   
 116 corresponds to very rough facets such as wave breaking zones covering the fraction  $q$  of the  
 117 sea surface. Accordingly,  $\sigma_{0r}^p$  is described within the frame of the composite model combining  
 118 2-scale Bragg scattering and specular reflections:  $\sigma_{0r}^p = \sigma_{sp} + \sigma_{br}^p$ . In this model, the radar  
 119 returns from breaking waves are not polarized, as a Kirchhoff-like term, and can also be  
 120 simply approximated as specular reflections. In consequence, we are in the following dealing  
 121 with three types of scattering facets (Bragg waves, specular points and breakers), and their  
 122 contribution to the Doppler velocity is considered below.

### 123 *2.1. Some background properties of RIM*

124 Each of the scattering mechanisms in (7) depends on the radar parameters and the  
 125 wind speed, and their partial contributions to  $\sigma_0^p$  defined as:  $P_{br}^p = (1 - q)\sigma_{br}^p/\sigma_0^p$ ,  $P_{sp}^p =$   
 126  $(1 - q)\sigma_{sp}/\sigma_0^p$ , and  $P_{wb}^p = q\sigma_{wb}/\sigma_0^p$  for Bragg, specular and wave breaking, respectively.  
 127 Example calculations of these quantities are shown in Fig. 1 for wind speeds of 5, 10, and  
 128 15 m/s in VV and HH polarization. As expected, pure specular reflection dominates the  
 129 radar return at low incidence angle ( $< 20^\circ$ ) for both polarizations, while the relative role of  
 130 non-Bragg scattering (specular reflection from the regular surface and very rough facets) is  
 131 stronger in HH than in VV at moderate incidence angle ( $> 20^\circ$ ).

132 The polarization ratio is an important parameter indicating the role of non-Bragg scat-  
 133 tering in the sea surface NRCS. Fig. 1(c), (f) and (i) shows the model C-band polarization  
 134 ratio for the sea surface at 5, 10 and 15 m/s wind for two types of scattering models: the  
 135 composite model (specular and 2-scale Bragg), as well as the full RIM including wave break-  
 136 ing statistics. The full model predictions are very similar to the experimental data, also as

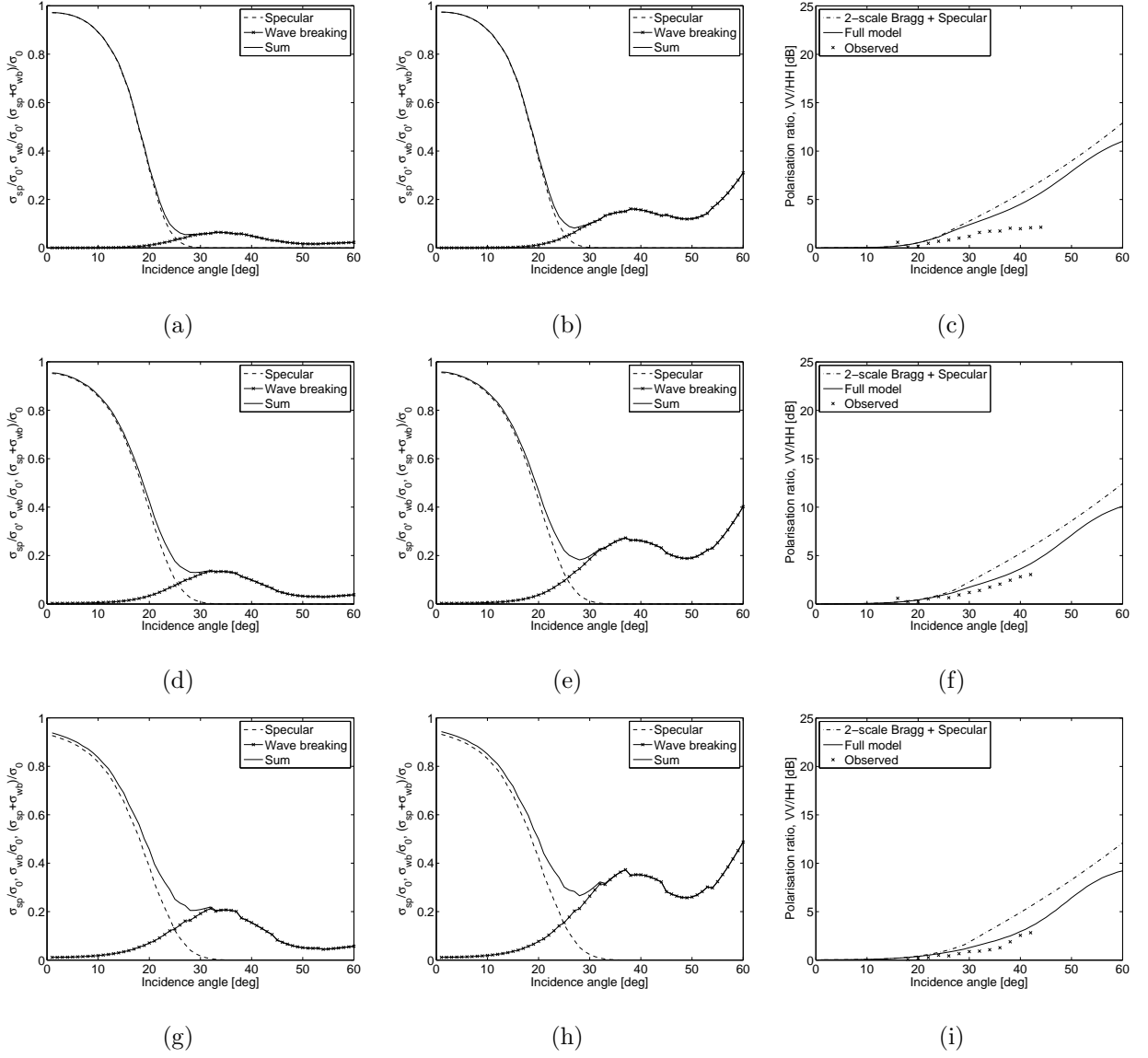


Figure 1: Partial contribution to the total NRCS of specular and wave breaking NRCS, and their sum, at wind speed of 5 m/s (top row) 10 m/s (center row) 15 m/s (bottom row) in upwind configuration for VV (left column) and HH (center column) polarizations. Areas above the solid lines correspond to the partial contribution of Bragg scattering. The C-band polarization ratio for the sum of two-scale Bragg and specular reflection, for the full model, and from ASAR WSM observations over the Norwegian Sea (note that the average signal is here assumed to be wind dominated), is shown in the right column.



137 reported e.g. by Mouche et al. (2006), except for some overestimation at 5 m/s wind speed.  
 138 A significant deviation of the composite scattering model prediction from the observations  
 139 (similar to the full model) shows that the wave-breaking contribution plays an important  
 140 role, and must be accounted for in the Doppler shift model. This correction could, however,  
 141 in principle be more directly included using a more advanced scattering model (e.g. Mouche  
 142 et al. (2007a), Mouche et al. (2007b)).

## 143 2.2. Doppler shift estimate

144 The simplified RIM NRCS as given by (7), will contribute to Doppler shifts associated  
 145 with Bragg waves ( $f \rightarrow br$ ), specular points ( $f \rightarrow sp$ ), and breakers ( $f \rightarrow wb$ ). This  
 146 approach leads to the total range Doppler velocity

$$V_D = u_s + \sum P_j^p(\bar{c}_j + c_j^{TH} s_L^2), \quad (8)$$

147 where  $\bar{c}_j$  and  $c_j^{TH}$  are obtained for each of the scattering mechanisms, and  $s_L^2$  is the MSS of  
 148 the large-scale surface which is also different for each of the scattering mechanisms. Equation  
 149 (8) is the governing equation of DopRIM. The input statistics needed to calculate the range  
 150 Doppler velocity with (8) (e.g. various statistical properties of wind waves and different  
 151 characteristics of the radar backscatter) are essentially taken from the RIM, which was  
 152 described to detail in Kudryavtsev et al. (2005). We suggest that the surface wave field is  
 153 a mixed sea consisting of wind generated waves and swell. We also assume that swell and  
 154 wind waves are well separated in  $k$ -space, i.e. the peak wavenumber of wind waves,  $k_p$ , is  
 155 much larger than the swell wavenumber:  $k_p \gg k_{sw}$ . The phase velocity of the waves is given  
 156 by the dispersion relation, i.e.  $c(k) = \omega/k = \sqrt{g/k + \gamma k}$  where  $\omega$  is the wave frequency,  $g$  is  
 157 the gravitational acceleration and  $\gamma$  is the surface tension. This is used in the calculation of  
 158 the different contributions to  $V_D$ , as further outlined below.

### 159 2.2.1. 2-scale Bragg

160 The velocity of facets corresponding to the Bragg waves is equal to the phase velocity  
 161  $\bar{c}_{br} = \bar{c}(k_{br})$ . The high-frequency cutoff,  $K_L$ , of the large-scale surface in (5) then corresponds

162 to the dividing wavenumber,  $k_d$ , of the 2-scale Bragg model ( $K_L = k_d = dk_R$ , with  $d = 1/4$ ).  
 163 The tilt MTF for Bragg scattering in (5) corresponds to

$$M_{br}^t = \frac{\partial(\ln \sigma_{obr})}{\partial \theta}. \quad (9)$$

164 In the present study, the wave spectrum modulations (prescribing the hydrodynamic MTFs  
 165 for all types of facets in (5)) will be described in a simplified form, making use of the  
 166 relaxation time approximation (see e.g. Alpers and Hasselmann (1978); Phillips (1984)).  
 167 This accounts for the interaction of short waves with the orbital velocities of longer waves  
 168 only (see Kudryavtsev et al. (2003b) for a detailed discussion of the MTF problem). In this  
 169 case, the hydrodynamic MTF reads

$$M^h(\mathbf{k}, \mathbf{K}) = - \left( \frac{1 - i\tau}{1 + \tau^2} \right) \frac{k_1}{N(\mathbf{k})} \frac{\partial N(\mathbf{k})}{\partial k_1}, \quad (10)$$

170 where the “gradient” of the wave action spectrum  $N$  in (10) is

$$\frac{k_1}{N(\mathbf{k})} \frac{\partial N(\mathbf{k})}{\partial k_1} = \cos^2(\phi - \phi_K) \frac{\partial \ln N}{\partial \ln k} - \frac{1}{2} \sin(2(\phi - \phi_K)) \frac{\partial \ln N}{\partial \phi}, \quad (11)$$

171 where  $k_1$  is the wavenumber component of the modulated waves,  $\mathbf{k}$ , along the direction of  
 172 the modulating waves (with wavenumber  $K$ ),  $\phi$  and  $\phi_K$  are, respectively, the directions  
 173 of short modulated and longer modulating waves, and  $\tau$  is the dimensionless relaxation  
 174 parameter. The latter quantity is defined as  $\tau = n\beta\omega/\Omega$ , where  $\beta = c_\beta(u_*/c)^2$  is the growth  
 175 rate of wind-waves,  $c_\beta$  is a constant related to the growth rate,  $\Omega$  and  $\omega$  are the frequencies  
 176 of the modulating and the modulated waves, respectively, and  $n$  is the exponent of the  
 177 spectrum in the parametrization of non-linear energy losses (see Kudryavtsev et al. (2003a)  
 178 for details). For practical applications, the “wavenumber exponent”,  $m_k \equiv \partial \ln N / \partial \ln k$ ,  
 179 can be evaluated approximately as  $m_k \approx -9/2$  (e.g. as for the spectrum suggested by  
 180 Phillips (1980)). Thus for a “typical” angular distribution of the Bragg-wave spectrum (say  
 181  $N \propto \cos \phi$ ), the second term in (11) is, in order of magnitude, less than the first one.  
 182 Moreover, the hydrodynamic MTF appears in (5) under the integral over the modulating  
 183 waves. Since the angular distribution of the large-scale surface (the range of equilibrium  
 184 gravity waves) is approximately isotropic, the integral of the “oscillating” second term over

185 the direction of the modulating waves is assumed to be small relative to the integral of the  
 186 first term. Thus, hereinafter, the second term on the right-hand-side (rhs) of (11) is ignored.

187 For the Bragg-facets, the hydrodynamic MTF (10) is now reduced to

$$M_{br}^h = m_k \cos^2(\phi_R - \phi_K) \left( \frac{1 - i\tau_{br}}{1 + \tau_{br}^2} \right), \quad (12)$$

188 where  $\phi_R$  is the radar look direction, and  $\tau_{br}^2$  is the relaxation parameter taken at the Bragg  
 189 wavenumber. Thus, the effect of tilt and hydrodynamic modulations of Bragg waves on  
 190 the range Doppler velocity,  $V_D$ , is described by a combination of (5), (9), and (12), with  
 191  $k_L = dk_R$  ( $d = 1/4$ ).

### 192 2.2.2. Specular Reflection

193 At low incidence angle ( $15^\circ < \theta < 25^\circ$ ), the specular reflections from slopes of large-  
 194 scale waves with  $k < k_d$  are important. The scattering facet velocity,  $\bar{c}_{sp}$ , in this case  
 195 corresponds to the mean line-of-sight velocity of all facets with slopes providing specular  
 196 reflections (“mirror points”). An expression for the mean velocity of these facets can be  
 197 found in Longuet-Higgins (1957). In an orthogonal coordinate system ( $\mathbf{i}, \mathbf{n}$ ) fixed to a radar  
 198 look direction ( $\mathbf{i}$  and  $\mathbf{n}$  axes along the incidence plane and normal to the incidence plane,  
 199 respectively), the mean velocity of the mirror points in the radar look direction reads

$$\bar{c}_i = (\overline{\zeta_n \zeta_t} \cdot \overline{\zeta_i \zeta_n} - \overline{\zeta_i \zeta_t} \cdot \overline{\zeta_n \zeta_n}) / \Delta_2, \quad (13)$$

200 where  $\zeta_i = d\zeta/di$  and  $\zeta_n = d\zeta/dn$  are the sea surface slopes along and normal to the  
 201 incidence plane,  $\zeta_t = d\zeta/dt$  is the time derivate of the sea surface elevation (i.e. the vertical  
 202 velocity of the sea surface), and  $\Delta_2 = (\overline{\zeta_i \zeta_i} \cdot \overline{\zeta_n \zeta_n} - \overline{\zeta_i \zeta_n}^2)$  is the determinant of the covariance  
 203 matrix of the sea surface slopes. It is more convenient to rewrite (13) in terms of up- and  
 204 cross-wind surface slopes (i.e.  $\zeta_1$  and  $\zeta_2$ , respectively). Given that  $\zeta_i = \zeta_1 \cos \phi_R + \zeta_2 \sin \phi_R$ ,  
 205  $\zeta_n = \zeta_2 \cos \phi_R - \zeta_1 \sin \phi_R$ , and that  $\overline{\zeta_1 \zeta_2} = 0$  (the latter for wind waves only), (13) is reduced  
 206 to

$$\bar{c}_i = -\frac{\overline{\zeta_1 \zeta_t}}{\overline{\zeta_1 \zeta_1}} \cos \phi_R - \frac{\overline{\zeta_2 \zeta_t}}{\overline{\zeta_2 \zeta_2}} \sin \phi_R, \quad (14)$$

207 or finally, in terms of the wind wave saturation spectrum,

$$\bar{c}_{sp} = \frac{\cos \phi_R}{s_{Lup}^2} \int_{K < k_d} \cos(\phi_K) C K^{-2} B(\mathbf{K}) d\mathbf{K} + \frac{\sin \phi_R}{s_{Lcr}^2} \int_{K < k_d} \sin(\phi_K) C K^{-2} B(\mathbf{K}) d\mathbf{K}, \quad (15)$$

208 where up- and cross-wind MSS of the "large-scale" waves ( $s_{Lup}^2$  and  $s_{Lcr}^2$ , respectively) are  
 209 defined as

$$[s_{Lup}^2, s_{Lcr}^2] = \int_{K < k_d} [\cos^2 \phi_K, \sin^2 \phi_K] K^{-2} B(\mathbf{K}) d\mathbf{K}. \quad (16)$$

210 Contrary to the 2-scale Bragg scattering model, the specular reflections model does not  
 211 possess a spectral gap between short waves providing radar reflections, and longer wind  
 212 waves which would tilt and modulate these waves. As follows from (16),  $s_L^2 = \int B(K) d \ln K$ .  
 213 Thus, if the omni-directional spectrum  $B(K)$  is approximately constant (this corresponds to  
 214 wind seas), all the waves almost equivalently contribute to the MSS, and there is no reason  
 215 to introduce the effect of facet modulations by the dominant wind waves.

216 On the other hand, the existence of a mixed sea (swell plus wind waves) is very plausible  
 217 in the open ocean. In this case, the spectral gap between specular facets and modulating long  
 218 waves (swell) is obvious. We should therefore include the effect of swell on the range Doppler  
 219 velocities through tilt and hydrodynamic modulation of the specular facets – the term  $c_{sp}^{TH}$   
 220 in (8). Thus, the large-scale waves in (5) now correspond to swell. The tilt MTF in (5) is  
 221 then  $M_{sp}^t = \partial(\ln \sigma_{sp}) / \partial \theta$ , while  $M_{sp}^h$  in (5) corresponds to the hydrodynamic modulation of  
 222 the specular point density due to modulation of the MSS,  $s_L^2 = \int_{k_p}^{k_d} K^{-2} B(\mathbf{K}) d\mathbf{K}$ , of the wind  
 223 waves (reminding that  $k_p$  is the spectral peak wavenumber of the wind-generated waves).  
 224 With the use of the well-known expression for  $\sigma_{sp}$  (see e.g. equation (10) in Kudryavtsev  
 225 et al. (2005)), the linear hydrodynamic MTF for  $\sigma_{sp}$ , due to modulations of the MSS, is  
 226 expressed as

$$M_{sp}^h = \left( \frac{\tan^2 \theta}{s_L^2} - 1 \right) \int_{k_p}^{k_d} M^h(\phi - \phi_{sw}) B(k, \phi) d(\ln k) d\phi / s_L^2, \quad (17)$$

227 where  $\phi_{sw}$  is the swell direction,  $M^h$  is given by (10) with (11) where (we remind) the second  
 228 term on the rhs is omitted.

229 The swell spectrum is normally very narrow, so its impact on  $V_D$  through tilt and hydro-  
 230 dynamic modulation of specular points can be expressed as

$$c_{sp}^{TH} = C_{sw} [\cos(\phi_R - \phi_{sw})(-M_{1sp}^t \cot \theta + M_{1sp}^h) + M_{2sp}^h \cot \theta], \quad (18)$$

231 where  $C_{sw}$  and  $\phi_{sw}$  are the phase velocity and direction of the swell. The “long-wave”  
 232 MSS (i.e. the swell MSS) is here defined as  $s_L^2 = A_{sw}^2 K_{sw}^2 / 2$ , where  $A_{sw}$  and  $K_{sw}$  are swell  
 233 amplitude and wavenumber.

### 234 2.2.3. Wave Breaking

235 The distribution of breakers over the wave scales can be described in terms of  $\Lambda(\mathbf{c})d\mathbf{c}$ ,  
 236 which defines the length of wave breaking fronts per unit area with velocities ranging from  
 237  $\mathbf{c}$  to  $\mathbf{c} + d\mathbf{c}$  (Phillips, 1985). Assuming that the quantity  $k^{-1}\Lambda(\mathbf{c})d\mathbf{c}$  is proportional to the  
 238 fraction of the sea surface covered by these breakers, the mean breaker velocity weighted  
 239 over all breakers (term  $\bar{c}_{wb}$  in (8)) reads

$$\bar{c}_{wb} = \int_{k < k_{wb}} \cos(\phi - \phi_R) c k^{-1} \Lambda(\mathbf{c}) d\mathbf{c} / \int_{k < k_{wb}} k^{-1} \Lambda(\mathbf{c}) d\mathbf{c}, \quad (19)$$

240 where  $k_{wb} = k_R/10$  is the wavenumber of the shortest breaking waves providing radar returns  
 241 (Kudryavtsev et al., 2003a).

242 Longer waves also tilt the breakers and modulate their surface density. It is thus assumed  
 243 that the wave breaking at wavenumber  $k$  is tilted and modulated by longer waves with  
 244  $K < dk$  (where  $d = 1/4$  as specified before). Following Phillips (1985), Kudryavtsev et al.  
 245 (2003a) suggested that  $\Lambda(\mathbf{c})$  is proportional to the saturation spectrum to the power  $(n_g + 1)$ ,  
 246 with  $n_g = 5$  in RIM. Therefore, the MTF for the breaking front surface density modulations  
 247 caused by longer waves with wavenumber  $K$ , reads

$$\begin{aligned} M_{wb}^h(\mathbf{K}) &= (n_g + 1) \int_{K/d}^{k_{wb}} M^h(\mathbf{K}, \mathbf{k}) k^{-1} \Lambda(\mathbf{c}) d\mathbf{c} \\ &= (n_g + 1) \int_{K/d}^{k_{wb}} M^h(\mathbf{K}, \mathbf{k}) \beta B(\mathbf{k}) d(\ln k) d\phi, \end{aligned} \quad (20)$$

248 with  $M^h$  defined by (10) with 11) where (we remind) the second term on the rhs is omitted.  
 249 In the second equality of (20), we have assumed that the velocity of the breaking crest of  
 250 a wave at given wavenumber approximately obeys the linear dispersion relation, and that  
 251 wave breaking provides most of the energy losses in wind waves. This is compensated by  
 252 the energy input from the wind (Phillips, 1985; Kudryavtsev et al., 2003a). The integral,  
 253  $\int \beta B(\mathbf{k}) d(\ln k) d\phi \propto k^{1+1/n_g}$ , converges rapidly at the upper limit of the integration. This  
 254 means that the main contribution to any wave breaking quantity is coming from the shortest  
 255 breaking waves, and there should be a spectral gap between the dominant breaking facets and  
 256 modulating longer waves. Recognizing that  $M_{wb}^h(\mathbf{K}) \propto 1 - (K/dk_{wb})^{1+1/n_g}$ , the MTF in (20)  
 257 does not depend on the wavenumber of the modulating waves as long as  $K$  is sufficiently  
 258 small. A 2-scale model with an upper wavenumber limit,  $k_L = k_{wb}/10$ , for longer waves  
 259 which modulate the breaking facets, may therefore be introduced. This provides 70% of the  
 260 “available” hydrodynamic modulations of the breaking facets.

261 In order to further simplify the problem we mention that, in the range of short breaking  
 262 waves, the angular distribution of the wave spectrum is  $\cos^{2/n_g}$ , which is significantly broader  
 263 than the angular distribution in  $\beta$  ( $\propto \cos^2 \phi$ ). This allows us to analytically evaluate integrals  
 264 over  $\phi$ . Finally, the hydrodynamic MTF for breaking facets needed for (5) and (8) can, with  
 265 the use of (20), be written approximately as

$$\begin{aligned}
 M_{wb}^h(\mathbf{K}) &= (n_g + 1) \int_{K/d}^{k_{wb}} M^h(\mathbf{k}, \mathbf{K}) k^{-1} \beta B(\mathbf{k}) d\mathbf{k} \\
 &= -\frac{1}{4} m_k (n_g + 1) (1 + 2 \cos^2 \phi_K) \frac{1 - i\tau_{wb}}{1 + \tau_{wb}^2},
 \end{aligned} \tag{21}$$

266 where  $\phi$  is the direction of the modulating waves with wavenumber  $K < k_{wb}/10$ , and  $\tau_{wb}$  is  
 267 the relaxation parameter estimated for breaking waves with  $k = k_{wb}$ . This equation predicts  
 268 very strong modulation of the wave breaking with magnitude of  $M_{wb}^h \approx 20$ . This estimate is  
 269 consistent with experimental findings reported by Dulov et al. (2002), as shown in Fig. 4 of  
 270 Kudryavtsev et al. (2003b).

271 Tilt and hydrodynamic modulation,  $c_{wb}^{TH}$ , of the breaking waves to  $V_D$  is, thus, given by  
 272 (5) with the high-frequency cut-off of the modulating waves  $k_L = k_{wb}/10$ , the hydrodynamic

273 MTF described by (21), and the tilt MTF given through the NRCS of wave breaking as  
 274  $M_{wb}^t = \partial(\ln \sigma_{0b})/\partial\theta$ .

### 275 3. DopRIM Capabilities

276 We present the influence of varying incidence angle and wind speed on the range Doppler  
 277 velocity and the contributing scattering mechanisms in section 3.1. In section 3.2, we then  
 278 present a case study to compare model simulations with Envisat ASAR observations for a  
 279 situation of strong tidal current in the Iroise Sea outside Brest, France. In particular, we  
 280 investigate modulations associated to the impact of wave breaking.

#### 281 3.1. Importance of incidence angle and wind speed

282 The model calculations presented in the following are performed for pure developed wind  
 283 seas, without swell, for a C-band radar. The total and partial contributions to the range  
 284 Doppler velocity at 5 m/s, 10 m/s, and 15 m/s wind speed for each type of the scattering  
 285 mechanisms are shown in Fig. 2. The velocity of the breaker-facets appears weakly depen-  
 286 dent on incidence angle, with some excess at  $\theta < 45^\circ$  which results from tilting by larger  
 287 scale waves. This vanishes at larger incidence angles. An “undulating” shape of the curves  
 288 representing the partial contributions,  $\frac{P_j^p(\bar{c}_j + c_j^{TH})}{\sum P_j^p(\bar{c}_j + c_j^{TH})}$ , for each type of facets to the total range  
 289 Doppler velocity at 5 m/s, 10 m/s, and 15 m/s wind speed is a consequence of the partial  
 290 contribution of wave breaking fronts to the NRCS shown in Fig. 1 (which also demonstrates  
 291 a similar undulation, but less pronounced). This is to some degree considered as an artifact  
 292 resulting from slightly imperfect tuning of the wave breaking parameters, which was origi-  
 293 nally proposed by Kudryavtsev et al. (2003a) for a rather different purpose. The velocity of  
 294 the mirror points dominates  $V_D$  at low incidence angle. At moderate incidence angle, the  
 295 effect of slightly rough facets play a dominant role in VV. For large incidence angles in HH  
 296 polarization ( $\theta > 60^\circ$  for 5 m/s and  $\theta > 35^\circ$  for 10 m/s or higher wind speed), the breakers  
 297 dominate  $V_D$ . Their role in VV is less pronounced but approaches the contribution from  
 298 slightly rough facets at larger incidence angle and higher wind speed.

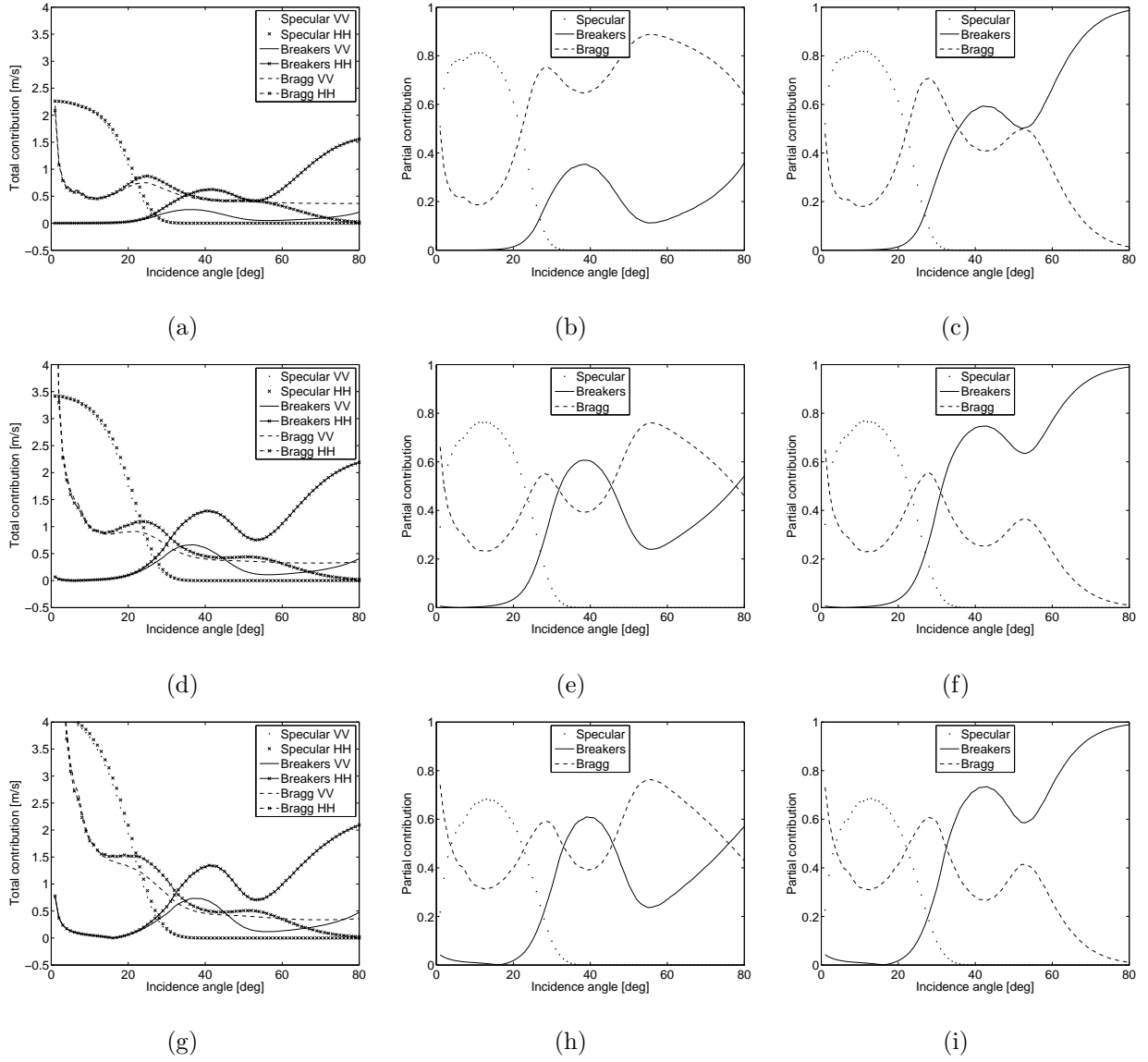


Figure 2: Total (left column) and partial (center and right column) contributions  $P_j^P(\bar{c}_j + c_j^{TH} s_L^2)$  and  $P_j^P(\bar{c}_j + c_j^{TH} s_L^2)/(V_D - u_s)$ , respectively, for each type of facets at 5 m/s (top row), 10 m/s (center row), and 15 m/s (bottom row) wind speed. The center/right column is for VV/HH polarization. All plots are for the downwind configuration.



299 The dependence of the total range Doppler velocity,  $V_D$ , on incidence angle for VV and  
 300 HH polarizations at wind speeds of 5 m/s, 10 m/s, and 15 m/s are shown in Fig. 3 for  
 301 both up- and downwind configurations. At low incidence angles ( $15 < \theta < 25^\circ$ ), the range  
 302 Doppler velocity is relatively large, with mean values reaching 37% (5 m/s), 30% (10 m/s)  
 303 and 26% (15 m/s) of the wind speed. This is much larger than expected from the phase speed  
 304 of the Bragg waves (about 0.3 m/s) and the wind induced surface drift (about 3% of the  
 305 wind speed), and it is thus evident that the contribution from other sources (i.e. the mean  
 306 velocities of specular and breaking facets, and the correlation between the orbital motion of  
 307 waves and the NRCS) must be accounted for. At larger incidence angles, there is a general  
 308 decrease in  $V_D$ , except for HH polarization which reveals an increase in velocity at grazing  
 309 angles. This results from the growing role of very rough patches and their modulation of the  
 310 range Doppler velocity in HH. There is also a clear asymmetry between the range Doppler  
 311 velocity in the up- and downwind configurations. This illustrates the effect of the facet-slope  
 312 correlation (see (5)) which does not depend on the radar look direction.

313 As demonstrated in Johannessen et al. (2008), the present model compares well with  
 314 Doppler shift observations from global Envisat ASAR WSM data in VV and HH polarization  
 315 at incidence angles of  $23^\circ$  and  $33^\circ$ . This is further confirmed by the comparison of observed  
 316 and modeled range Doppler velocities in Fig. 3 for VV polarization. In HH polarization,  
 317 however, there is some overestimation of  $V_D$  for the upwind configuration at 10 m/s and  
 318 15 m/s wind speed. This could probably be improved by a better model fit, but until  
 319 recently the amount of observed data in HH has been too low. Nevertheless, the non-Bragg  
 320 mechanism is seemingly well captured by the proposed approach, and greatly simplifies a  
 321 more advanced approach (e.g. Pedersen et al. (2004); Mouche et al. (2008)). The modeled  
 322 Doppler shift, here, displays a functional relationship with wind speed in good agreement  
 323 with the observations, particularly up to a wind speed of about 15 m/s. In the following  
 324 section, we compare modeled and observed Doppler velocities as well as the corresponding  
 325 NRCS for a specific case of wave-current interaction in the presence of strong tidal current  
 326 in the Iroise Sea outside Brest, France.

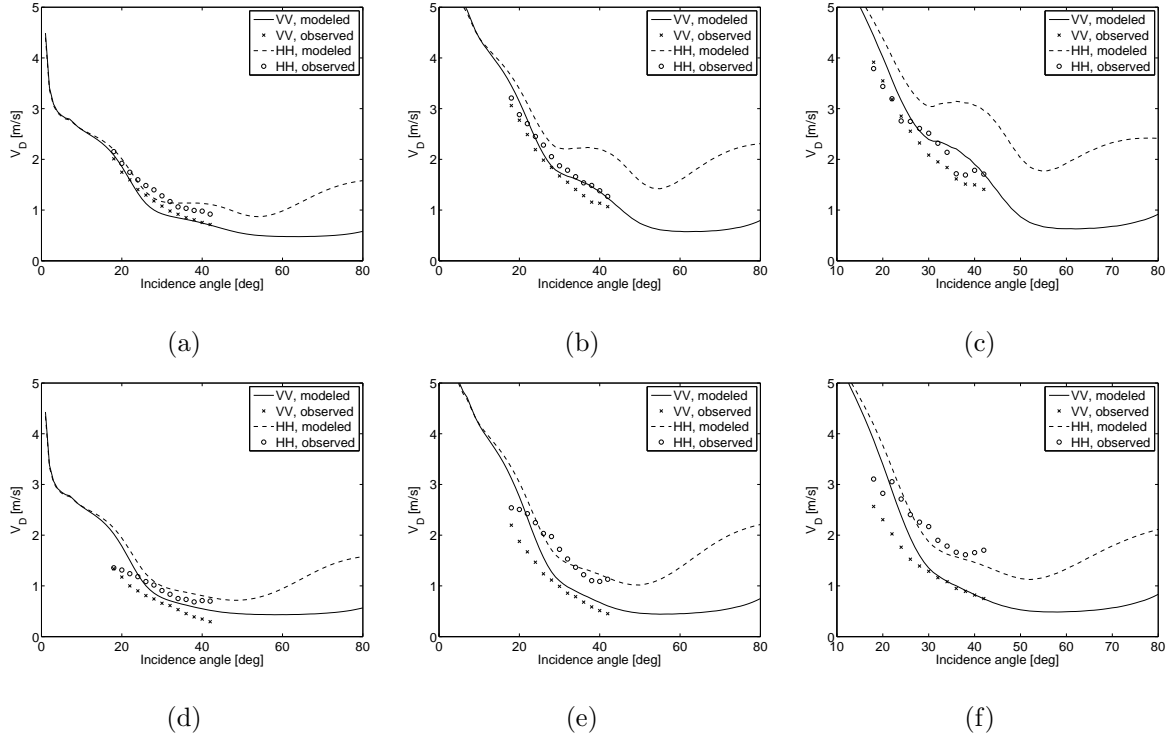


Figure 3: Range Doppler velocities for VV and HH polarization versus incidence angle at wind speed of 5 m/s (left column), 10 m/s (center column), and 15 m/s (right column) in up- (top row) and downwind (bottom row) configuration. 3% wind drift is included in  $V_D$ . The observations represent the median range Doppler velocities at the given wind conditions retrieved from nearly 2200 ASAR WSM acquisitions over the Norwegian Sea from August 2007 to February 2011 (about 1200 in VV and 1000 in HH polarization, respectively).

327 *3.2. NRCS and range Doppler velocity in the presence of strong tidal current*

328 Provided the sea surface state including near surface wind and current is known, Do-  
329 pRIM simulations can be assessed and compared to SAR NRCS and range Doppler velocity  
330 retrievals in order to improve the SAR image interpretation. Thanks to the availability of a  
331 2-D numerical tide model (Le Nestour, 1993), the Iroise Sea (Brest coast, France) was chosen  
332 as a test area for the DopRIM simulations carried out in two steps: (i) Calculation of the  
333 components contributing to the NRCS and their modulations by the surface current with  
334 use of RIM (described to detail in Kudryavtsev et al. (2005)), and (ii) calculations of the  
335 range Doppler velocity field using (8) with the modeled NRCS field and the related statistical  
336 properties of its components (after RIM simulations). Notice that the facet velocities,  $\bar{c}_j$ , as  
337 well as the velocities  $c_j^{TH}$  describing the impact of tilt and hydrodynamic modulations on  $V_D$   
338 via (8) are defined as weighted over the wave spectrum. Therefore they are weakly sensitive  
339 to the wave spectrum modulations due to wave-current interaction. The governing effect  
340 of wave-current interaction on  $V_D$  appears via modulations of the MSS of the large-scale  
341 surface,  $s_L^2$ , and redistribution of the contribution from the different scattering mechanisms  
342 to the total NRCS,  $P_j^p$ . In particular, enhancement (suppression) of wave breaking in the  
343 current convergence (divergence) zones results in  $V_D$  response via the partial contribution of  
344 radar backscatter from breaking waves to the total NRCS.

345 Because of limited coverage of the numerical tide model, the resolution of the range  
346 Doppler velocity from ASAR WSM acquisitions is too low to provide any reasonable com-  
347 parison with the modeled NRCS and range Doppler velocity fields. However, by using the  
348 phase and amplitude information in ASAR SLC data, we have estimated the Doppler cen-  
349 troid frequency using Madsen's method (Madsen, 1989) and chosen a higher spatial resolution  
350 (600 m in range direction and 1600 m in azimuth direction) than given in the range Doppler  
351 velocity from the ASAR WSM products. The case we present here is one rare case where  
352 high resolution current information is available coincident with an ASAR SLC image.

353 The surface current field (input for DopRIM) obtained from the numerical tide model  
354 at the time of ASAR acquisition is shown in Fig. 4(a), and depicts large spatial variations

355 with the current speed reaching up to 1.1 m/s in the gap between the islands in northwest.  
 356 The wind stress governing the short wind waves varies as the atmospheric boundary layer is  
 357 adjusted to the sea surface temperature and current. A modified resistance law, incorporated  
 358 in DopRim, relates surface friction velocity ( $u_*$ ) to the geostrophic wind velocity ( $G$ ) and  
 359 the surface current ( $u_s$ ):

$$u_*^2 = C_{dG} |\mathbf{G} - \mathbf{u}_s|^2, \quad (22)$$

360 where  $C_{dG}$  is the geostrophic drag coefficient depending on the atmospheric stratification  
 361 parameter,  $\mu$  (see Kudryavtsev et al. (2005)). The friction velocity was obtained from (22)  
 362 for a geostrophic wind speed of  $G = 6.0$  m/s from northeast (calculated from a wind speed  
 363 of 4.4 m/s at 10 m height following Kudryavtsev et al. (2000)) under neutral stratification,  
 364 and is shown in Fig. 4(b). As anticipated, the shape of the  $u_*$  field is very similar to the  
 365 pattern of the current field. In particular, the strong southwesterly tidal currents, exceeding  
 366 1.1 m/s between the outer islands and to the north of the island, lead to significant drops in  
 367 the friction velocity.

368 These sea surface current and wind stress fields are input to the DopRIM simulations. The  
 369 simulated contrasts, defined as  $(Y(x, y) - Y_0)/Y_0$  where  $Y_0$  is the background signal induced  
 370 by wind stress, for the Bragg wave spectrum ( $Y = \sigma_{br}$ ) and the MSS of large scale waves with  
 371  $k < dk_R$  ( $Y = s_L^2$ ) are shown in Fig. 4(c) and 4(d). The Bragg waves feel the divergence of the  
 372 current field, and also indirectly the surface current through the wind stress adjustment. The  
 373 spatial variation of the Bragg roughness contrast is quite large near the outer islands (about  
 374 a factor 3 or more, equivalent to 5 dB). Since the wind stress variation in this area is about  
 375 20% ( $(u_{*,\max} - u_{*,\min})/u_{*,\max}$ ), we conclude that the impact of the wind stress adjustment on  
 376 the Bragg waves is much weaker than the impact from the enhancement/suppression of wave  
 377 breaking in the zones of surface current convergence/divergence. Indeed, the direct effect of  
 378 current changes to short waves is negligible owing to the weak relaxation rate and, thus, the  
 379 roughness modulation by intermediate wave breaking appears as the dominant source in the  
 380 presence of a current (Johannessen et al., 2005).

381 The pattern of the MSS contrasts, on the other hand, differs significantly from the Bragg

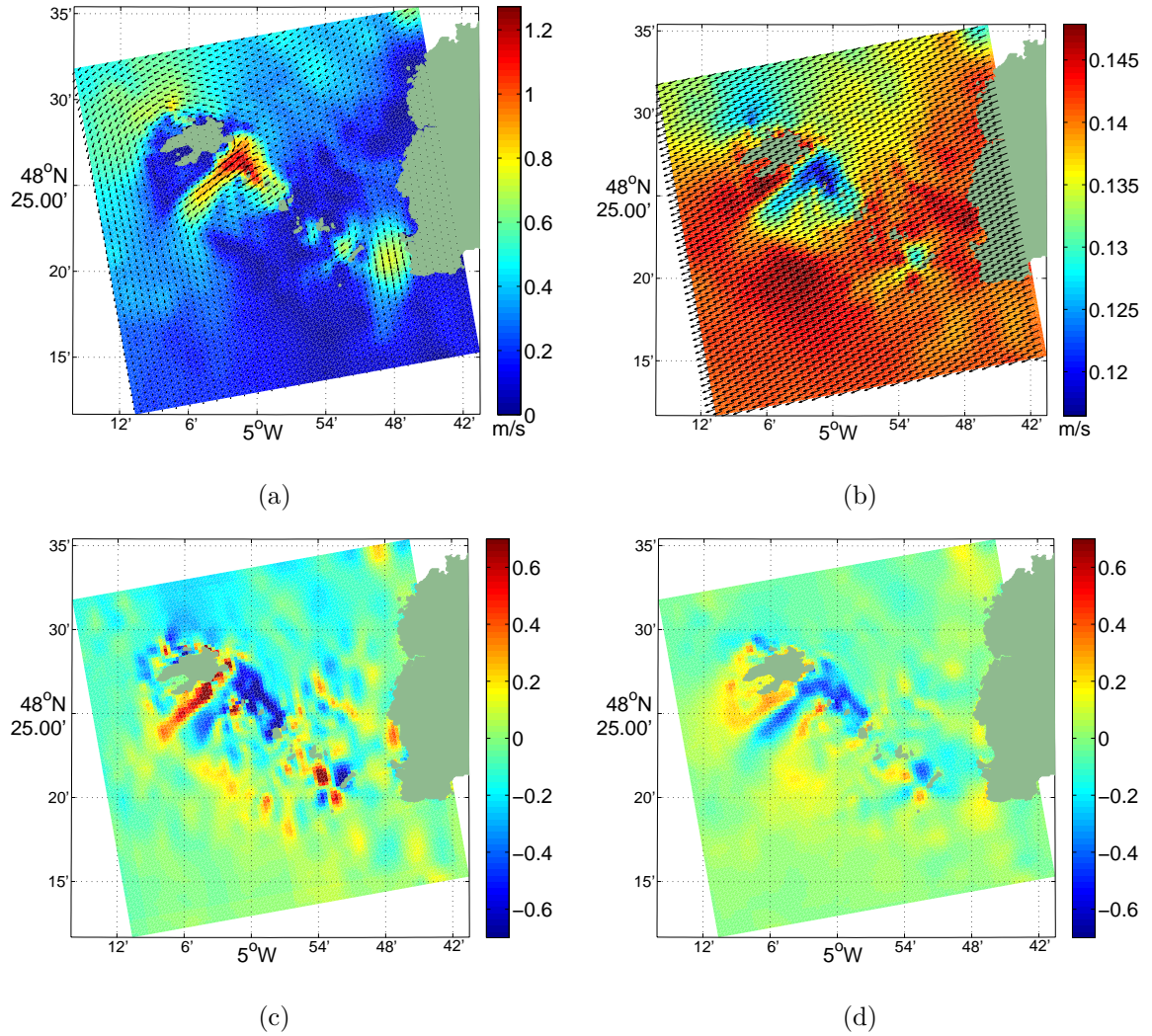


Figure 4: Model tidal current (a) and resulting friction velocity (b), roughness contrast induced by the Bragg wave spectrum (c), and MSS contrast of the large-scale waves (d) at 22:10 UTC on 5 October 2005. The mean wind speed at 10 m height was 4.4 m/s from northeast.

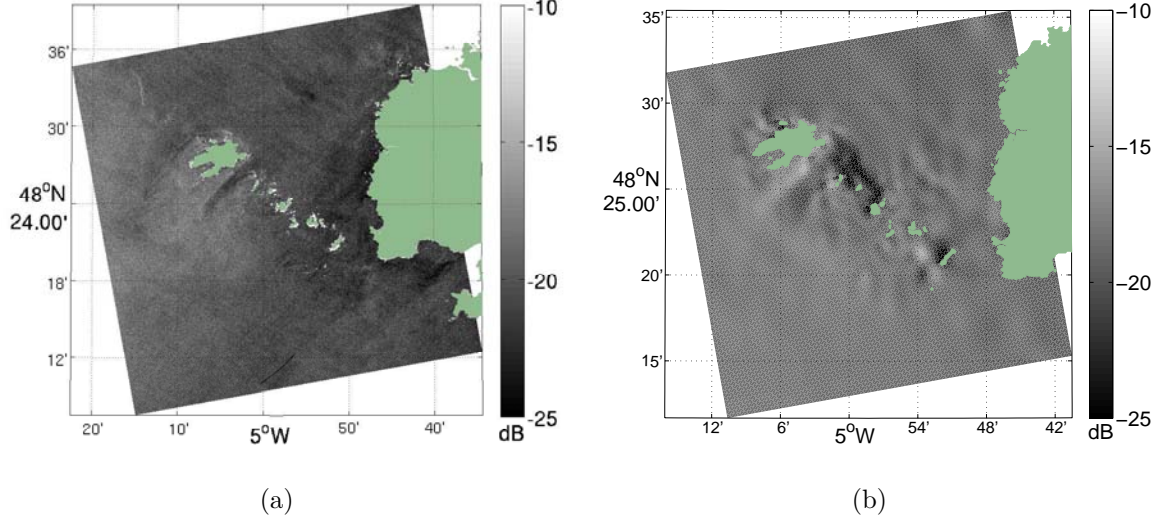


Figure 5: Observed (a) and simulated (b) NRCS on 5 October 2005 at 22:10 UTC. The ASAR data is in VV polarization and was obtained in ascending pass. This is the fifth subswath (IS5), and the image sizes are equal at about  $38 \times 38$  km, which is a fragment of the full subswath image. The look direction is about  $10^\circ$  with respect to the east, with incidence angles (for the subset) ranging from  $36.5^\circ$  to  $38.5^\circ$ .

382 wave contrasts. Since the spatial scales of the relaxation of the long wind waves and the  
 383 current deformation is of similar order, the MSS field predominantly possesses a contrast  
 384 structure imposed by the large-scale patterns of the current field, such as the vorticity leading  
 385 to the focusing of the wave trains downwind of the islands.

386 Finally, the simulated NRCS (Fig. 5(b)) reveals a structure resulting from the combined  
 387 impact of Bragg waves, MSS, and wave breaking. Notice that for an incidence angle of about  
 388  $37^\circ$  in this specific case, the unperturbed background radar scattering is mainly provided by  
 389 Bragg scattering mechanism, while radar returns from breaking waves provide about 6% of  
 390 the total NRCS at the given wind speed (see Fig. 1). In particular, there is evidence of a  
 391 strong suppression between the islands and the enhancement downwind of the main island.  
 392 Compared to the ASAR image (Fig. 5(a)), the mean level of the NRCS is similar ( $-19$  dB),  
 393 and the largest contrasts are depicted in the vicinity of the two outer islands in both images.

394 The range projected (horizontal) model current and the contribution of the surface rough-  
 395 ness and its modulation to  $V_D$  (see (8)) are depicted in Fig. 6(a) and 6(b), respectively. The  
 396 simulated and the observed range Doppler velocity is shown in Fig. 6(c) and 6(d). Distinct

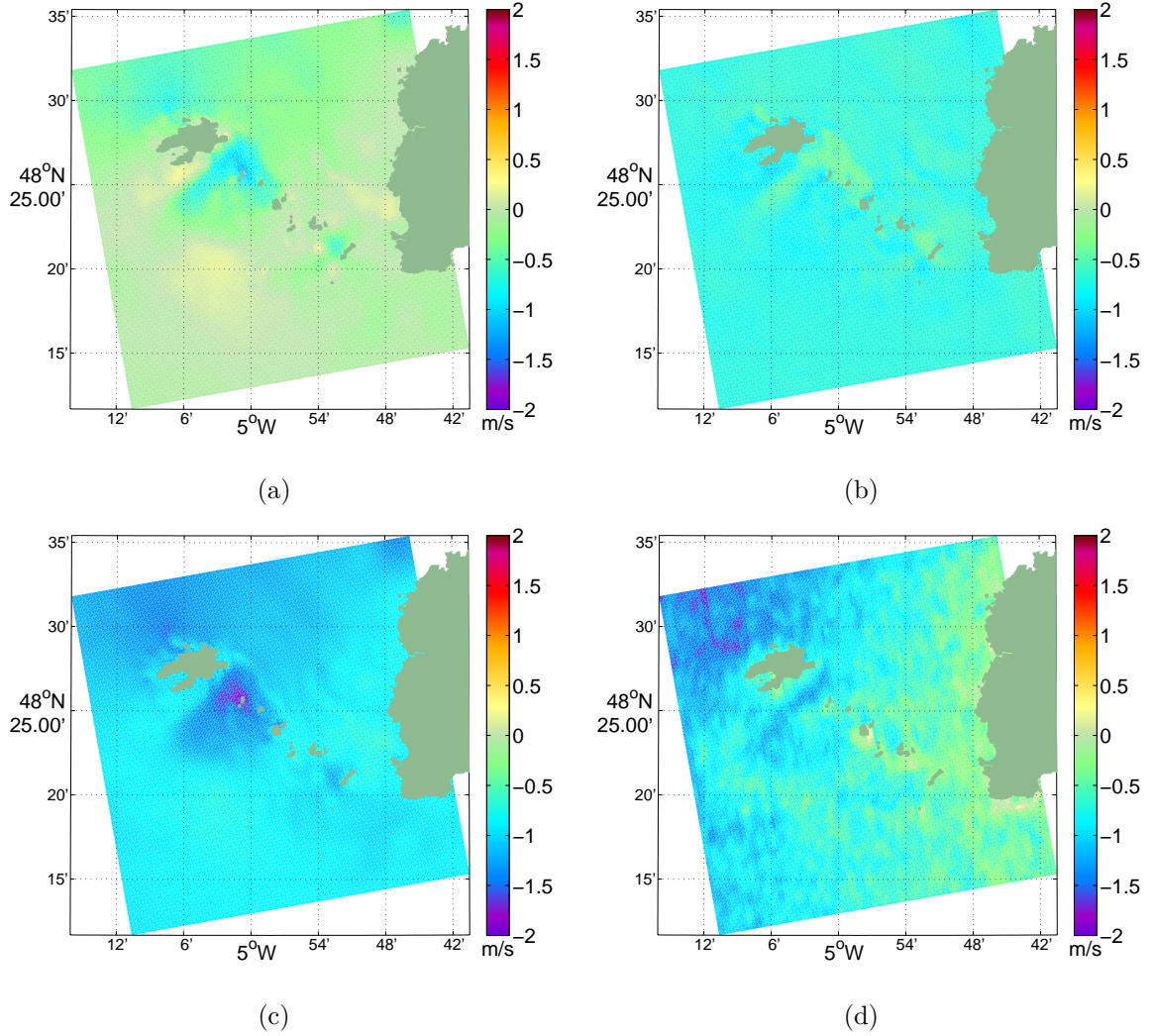


Figure 6: Projection of model current on SAR look direction (a), contribution from the mean facet velocities and the correlation between wave orbital motion and local NRCS variations (last two terms of (2)) to  $V_D$  (b), simulated  $V_D$  (c), and observed  $V_D$  (d) for the same acquisition as in Fig. 5. Note that the model wind speed in the southwest part of the image is higher than that used for the DopRIM simulations (4.4 m/s). This may explain the higher negative signal in the observed range Doppler velocity in the southwest. The accuracy of the observed range Doppler velocity ((d)) is about 5 Hz, which corresponds to 22-24 cm/s at these incidence angles.



397 anomaly patterns are clearly visible in both the simulated and observed range Doppler ve-  
398 locities in the channel between the two islands, with relative speeds ranging from about 1.5  
399 to 2 m/s. Since the contribution from the surface roughness is significant, strong variabil-  
400 ity is encountered across the intense current gradient between the islands. This agreement  
401 is promising and supports further use of DopRIM simulations in combination with ASAR  
402 observations.

#### 403 **4. Summary and Conclusion**

404 A radar imaging model (DopRIM) is described and shown to be useful in order to as-  
405 sist in the quantitative investigations of SAR imagery by consistently combining the RIM  
406 (Kudryavtsev et al., 2005) with a Doppler shift estimation algorithm. The dependence of the  
407 range Doppler velocity on radar parameters and sea state conditions arises via the projected  
408 motions of the slightly rough facets, and the line-of-sight velocities of the specular points  
409 and breaking crests, as well as the surface current. The strength of this approach lies in the  
410 simplified but very efficient separation between the different scattering mechanisms.

411 Simulated NRCS and range Doppler velocities have been compared to corresponding  
412 NRCS and Doppler velocities retrieved from Envisat ASAR WSM data over the Norwegian  
413 Sea, as well as an SLC image. Although some discrepancies are revealed, the overall results  
414 are encouraging as some inaccuracies in the model current field and near surface wind field  
415 are expected. All in all, the results suggest a dominant impact of strong surface currents  
416 and their modulation on both the radar-detected surface roughness and the range Doppler  
417 signals.

418 As regular access to range Doppler velocity information and NRCS from ASAR acquisi-  
419 tions over a few selected sites is now possible, the only missing information mostly relates  
420 to the limited access to independent surface current measurements for validation. Through  
421 such demonstration experiments, DopRIM could be better assessed and explored for transi-  
422 tion from a research tool to an operational application in marine monitoring with SAR. Yet,  
423 as the range Doppler velocity field, with improved accuracy, is becoming a standard feature  
424 of the ground segment on approved and planned SAR missions (such as Sentinel-1), future



425 efforts shall be dedicated to assess the potential to better distinguish the different contri-  
426 butions to both radar signal strength and mean Doppler shift. In particular, the differing  
427 polarization and/or incidence angle sensitivities can be useful to analyze and filter out the  
428 non-Bragg contributions. Also, the combined range Doppler velocity and NRCS with a priori  
429 model fields of surface wind, including wind shadowing by land, and current vectors shall  
430 offer enhanced possibilities to build better constrained methodologies to more consistently  
431 retrieve very high resolution ocean surface information. This will be the topic for future  
432 works.

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### 533 **Abbreviations and Acronyms**

534	<b>ASAR</b>	Advanced SAR
535	<b>DopRIM</b>	Doppler Radar Imaging Model
536	<b>HH</b>	Horizontal transmit-Horizontal receive
537	<b>MSS</b>	Mean Square Slope
538	<b>MTF</b>	Modulation Transfer Function
539	<b>NRCS</b>	Normalized Radar Cross Section
540	<b>rhs</b>	right-hand-side
541	<b>RIM</b>	Radar Imaging Model
542	<b>SAR</b>	Synthetic Aperture Radar
543	<b>SLC</b>	Single Look Complex

544 **VV** Vertical transmit-Vertical receive

545 **WSM** Wide Swath Medium resolution image