Advanced Modeling of Microwave Doppler Spectra and Along-Track Interferometric SAR Signatures of Ocean Surface Currents

Roland Romeiser[1] and Donald R. Thompson

Johns Hopkins University, Applied Physics Laboratory
11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA

[1]) On leave from University of Hamburg, Institute of Oceanography
Troplowitzstraße 7, 22529 Hamburg, Germany
Phone: +49 40 42838 5430 Fax: +49 40 42838 5713 E-Mail: romeiser@ifm.uni-hamburg.de

In contrast to conventional imaging radars, along-track interferometric synthetic aperture radars (ATI) are directly sensitive to scatterer motions, which makes them a promising tool for oceanic surface current measurements. In this paper we present some new model developments and theoretical predictions. We discuss the capabilities and limitations of current measurements by ATI, and we compare advantages and disadvantages of this method with those of techniques based on conventional radar imagery.

INTRODUCTION

Several groups in Europe and North America have recently developed airborne along-track interferometric synthetic aperture radar (along-track INSAR, ATI) systems, i.e. imaging radars with a capability to measure scatterer motions. This capability is achieved by using two antennas separated along flight direction. The expectation value of the phase difference between backscattered signals received by the two antennas with a short time lag τ is proportional to the mean Doppler shift in frequency and thus to the line-of-sight target velocity [1][2]. ATI systems are particularly promising for the assessment of surface current variations over oceanic features like underwater bottom topography in coastal waters. Signatures of such features are visible in conventional radar images (backscattered intensity images) due to a hydrodynamic modulation of the surface roughness, but the imaging mechanism is quite complex and cannot be inverted easily. Direct detection of currents and current gradients by ATI would thus be a great improvement for practical applications such as the operational monitoring of bathymetric changes.

Consistent with theoretical predictions, early ATI experiments have shown that ATI phase images acquired over the ocean do not simply reflect mean line-of-sight velocities of the surface in each resolution cell but mean line-of-sight velocities of the scatterers, weighted by the contribution of each scatterer to the backscattered power [2]. The following effects must be taken into account in the data interpretation:

- The backscattering of microwaves at the ocean surface at moderate incidence angles (say, 20° to 70°) is dominated by resonant Bragg scattering [3]. The negative and positive phase velocities of the two Bragg wave components propagating towards and away from the radar, weighted with the corresponding power spectral densities, enter into the mean Doppler shift and thus the ATI phase.
- Another wave-induced contribution results from the orbital motions of waves that are long compared to the Bragg scattering facets. These motions lead mainly to a broadening of the Doppler spectrum, but the correlation between orbital motions and tilt and hydrodynamic modulation of the backscattered power can also result in an additional Doppler shift.
- Finally, the whole Doppler spectrum and thus the phase difference detected by ATI is shifted due to the presence of a mean current; this is the actual contribution of interest.

These three contributions to ATI phase differences can be of the same order of magnitude. In order to determine actual surface currents from ATI data, contributions of wave motions must be accurately estimated and subtracted. Furthermore, artifacts of the synthetic aperture radar (SAR) imaging mechanism like an azimuthal displacement of targets with nonzero line-of-sight velocity must be taken into account. We have developed a numerical model for a very time-efficient simulation of SAR intensity images and ATI phase images of ocean scenes [4][5]. In the following, we review some basic ideas of the proposed model and present some key expressions in their final form. We discuss capabilities and limitations of current measurements by ATI, and we compare signatures of a known surface current field in simulated intensity and phase images obtained with parameter settings that appear to be favorable.

THEORY

The theory of the proposed composite surface model was first discussed in [5]; a more comprehensive presentation will soon be available in [6]. Key elements can be summarized as follows: Starting with Fourier representations of basic Bragg scattering expressions and of the line-of-sight velocity of wave facets at the ocean surface, and considering terms up to second order in surface slope, we obtain for the mean (ensemble averaged) Doppler spectrum of the backscattered signal

$$S(f_D) = \frac{\langle\sigma_+\rangle}{\sqrt{2\pi\gamma_{D+}^2}} e^{-\frac{(f_D-\langle f_{D+}\rangle_\sigma)^2}{\gamma_{D+}^2}} + \frac{\langle\sigma_-\rangle}{\sqrt{2\pi\gamma_{D-}^2}} e^{-\frac{(f_D-\langle f_{D-}\rangle_\sigma)^2}{\gamma_{D-}^2}} \quad (1)$$

where f_D is the Doppler frequency,

This work was supported by the Alexander von Humboldt Stiftung, Germany, and by the U.S. Office of Naval Research.

$$\langle f_{D\pm}\rangle_\sigma = f_{D\pm}^{(0)} + \mathrm{Re}\left\{\iint D^*(\boldsymbol{k})M_{1\pm}(\boldsymbol{k})k^2\Psi(\boldsymbol{k})d^2k\right\} \quad (2)$$

are the center frequencies of the two Gaussian Doppler spectra that correspond to the backscatter from the two Bragg wave components and that include zeroth-order contributions resulting from the Bragg waves' phase speed and the mean surface current,

$$\gamma_{D\pm}^2 \equiv \langle f_{D\pm}^2\rangle_\sigma - \langle f_{D\pm}\rangle_\sigma^2 = \iint D^*(\boldsymbol{k})D(\boldsymbol{k})k^2\Psi(\boldsymbol{k})d^2k \quad (3)$$

are variances determining the Doppler bandwith, and $\langle\sigma_\pm\rangle$ are normalized radar backscattering cross sections (NRCS) as given in [4]. Furthermore, D is a linear modulation transfer function (MTF) that relates wave slopes to Doppler shifts resulting from orbital motions, $M_{1\pm}$ are MTFs that describe the variation of the local NRCS with wave slope, $\boldsymbol{k}$ is the two-dimensional wavenumber of modulating waves, and Ψ is the spatially varying ocean waveheight spectrum. In our numerical model, $\Psi(\boldsymbol{k},\boldsymbol{x})$ is computed from given current and wind fields according to the approach described in [4] and [7].

An important element of the SAR imaging mechanism is the azimuthal displacement of moving targets by an amount

$$\Delta x = -\frac{R}{U_p}v_r = \frac{R}{U_p}\frac{\pi}{k_e}f_D \quad (4)$$

where R is the distance between radar antenna and target, U_p is the platform velocity, v_r the line-of-sight (radial) target velocity, and k_e the electromagnetic wavenumber of the radar. In the proposed model the azimuthal displacement is simulated by computing the Doppler spectrum at each grid point and mapping small elements of backscattered power to a pixel determined by the actual location of the grid point and the shift given by (4). The power contributions mapped to each individual pixel can then be integrated to obtain a simulated SAR intensity image. If the frequency information is kept during the mapping procedure, the complex autocorrelation function of the signal assigned to a pixel can be computed as

$$R(\tau) = \frac{1}{\langle\sigma\rangle}\int_{-\infty}^{\infty} e^{i2\pi f_D\tau}S_p(f_D)df_D \quad (5)$$

where S_p is the Doppler spectrum of power elements assigned to the pixel (while S in (1) is the Doppler spectrum associated with an actual grid cell at the sea surface). In case of an ATI simulation, τ is the time lag between the two images that are interferometrically combined. The phase of a pixel of the ATI phase image is finally obtained as phase of $R(\tau)$, while the modulus of $R(\tau)$ characterizes the theoretical significance of a phase shift measurement.

MODEL RESULTS

Following our recommendations from [5] and [6], a new ATI system, which is presently being set up by the German company AEROSENSING and which will have been tested in a first experiment in the German Bight by the time of publication of this paper, will operate at X band (10 GHz), vertical (VV) polarization, and a nominal incidence angle of 45°, covering an actual incidence angle range from approx. 25° to 65° across the swath. Nominal flight altitude will be between 2000 and 3000 m and nominal platform speed will be 100 m/s, thus an antenna separation of 0.6 m will result in ATI time lags of 3 ms and 6 ms, depending on the mode of operation (using one or both antennas for transmitting). From a theoretical point of view, these parameters should be well suited for current measurements: Small differences between the intensity variations of the two Bragg wave components at X band as well as high incidence angles ensure reasonable linearity of the imaging mechanism, VV polarization ensures a good signal-to-noise ratio at high incidence angles, and the autocorrelation of the signal at 3 and 6 ms should be good enough to determine ATI phase differences as well as coherence time images (see [8]). A nominal phase resolution of 0.5° corresponds to a velocity resolution of about 0.01 m/s at an incidence angle of 60° (with the short time lag) and a velocity range of 7.20 m/s that can be covered without ambiguities.

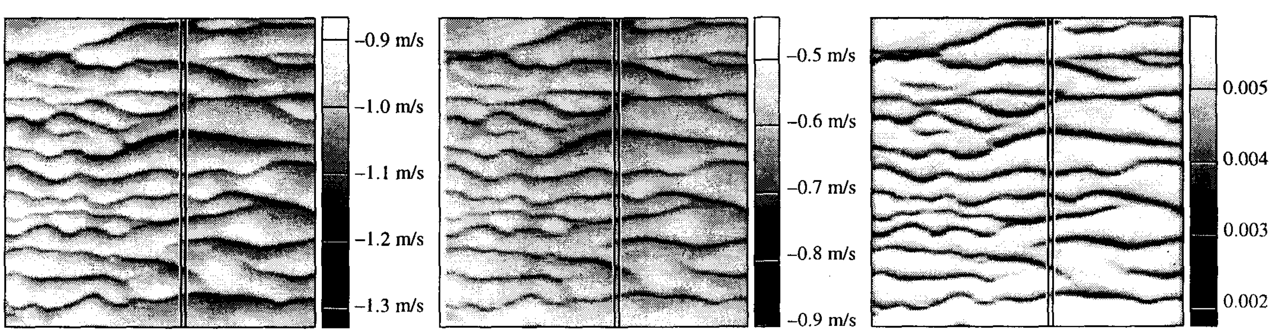

Fig. 1: Current field used as model input (left; positive direction is from bottom to top); simulated ATI-derived current field at X band (10.0 GHz), VV, and an incidence angle of 60° (center); and simulated SAR NRCS image at P band (0.45 GHz), HH, and an incidence angle of 45° (right). Further parameters: Test area size = 5 km × 5 km, wind speed = 7 m/s toward 30° counterclockwise from top of images, flight direction = from left to right, look direction = from bottom to top, flight altitude = 3000 m, platform speed = 100 m/s, ATI time lag = 3 ms. The two lines mark the area for which profiles are shown in Fig. 2.

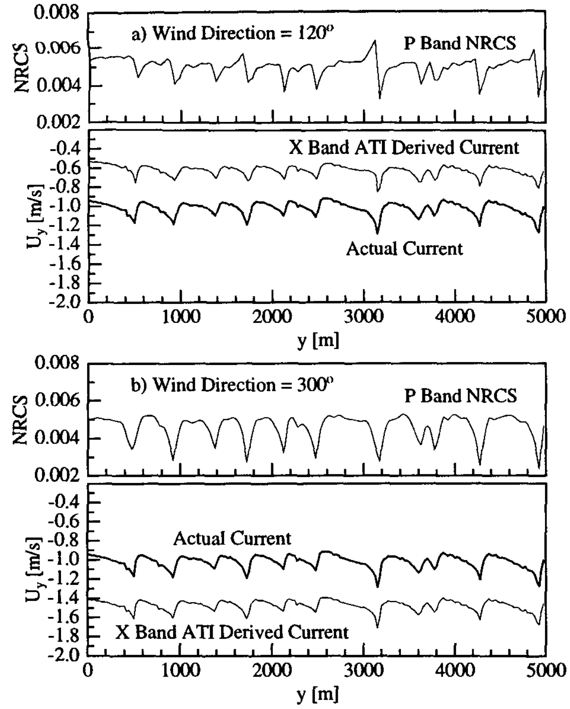

Fig. 2: Profiles of actual current, simulated X band ATI-derived (apparent) current, and simulated P band SAR NRCS along the line marked in Fig. 1; a, for the scenario of Fig. 1; b, for the same scenario with a reversed wind direction.

Fig. 1 shows a typical surface current field over underwater bottom topography in the North Sea, as obtained within the framework of the C-STAR experiment [7], and simulated ATI-derived apparent currents based on the parameters of the AEROSENSING system. For this simulation, the wind speed was assumed to be 7 m/s towards 30° counterclockwise from the top of the image (i.e. 120° from the x axis of the model grid). For comparison, Fig. 1 also shows a simulated SAR intensity image at P band (0.45 GHz). Since the linearity of the relation between surface current and image intensity increases with decreasing radar frequency, P band is usually preferred for the retrieval of surface currents from radar intensity images. Surface current and image intensity profiles along the line marked in Fig. 1 are shown in the plots of Fig. 2a.

Except for a systematic offset of the ATI-derived currents from the actual ones by about 0.4 m/s, which results from the contributions of the surface waves, the two current fields look very similar. A theoretical calculation of the offset for a correction is not difficult. Fig. 2a depicts clearly that the shape of the current field and thus all relative variations and gradients are well preserved in the uncorrected ATI-derived currents. The simulated P band intensity signatures, on the other hand, resemble some features of the current field, but the relationship is obviously more nonlinear, and an inversion would be clearly more complicated.

Fig. 2b shows the same set of signatures as Fig. 2a, but for a reversed wind direction. In this case, the ATI-derived apparent currents are shifted in the opposite direction, since the waves are now propagating towards the radar, but the relationship remains basically linear. As indicated above, actual surface currents can be determined from the ATI-derived apparent currents by subtracting the wave induced contribution on the basis of model results. Only the wind speed and direction must be roughly known for this correction. In contrast to the ATI results, the simulated P band signatures look generally different after the rotation of the wind vector. Without detailed knowledge of environmental parameters, their interpretation can be quite difficult and ambiguous.

CONCLUSION

Based on our model results, we conclude that along-track interferometric SAR systems with the right parameter settings should be clearly better suited for the remote sensing of surface currents than conventional imaging radars. We are looking forward to a first experiment with the proposed system. Preliminary results will probably be available at the time of the conference or shortly thereafter.

REFERENCES

[1] R.M. Goldstein and H.A. Zebker, "Interferometric radar measurement of ocean surface currents", Nature, vol. 328, 1987, pp. 707-709.

[2] D.R. Thompson and J.R. Jensen, "Synthetic aperture radar interferometry applied to ship-generated waves in the 1989 Loch Linnhe experiment", J. Geophys. Res., vol. 98, 1993, pp. 10,259-10,269.

[3] G.R. Valenzuela, "Theories for the interaction of electromagnetic and ocean waves – A review", Boundary Layer Meteorol., vol. 13, 1978, pp. 61-85.

[4] R. Romeiser, W. Alpers, and V. Wismann, "An improved composite surface model for the radar backscattering cross section of the ocean surface", parts 1 and 2, J. Geophys. Res., vol. 102, 1997, pp. 25,237-25,267.

[5] R. Romeiser and D.R. Thompson, "On the detection of spatially varying current fields at the ocean surface by along-track interferometric synthetic aperture radar", Digests IGARSS '96, vol. II, 1996, pp. 981-983.

[6] R. Romeiser and D.R. Thompson, "Numerical study on the along-track interferometric radar imaging mechanism of oceanic surface currents", IEEE Trans. Geosci. and Remote Sens., 1999, in press.

[7] R. Romeiser, S. Ufermann, and S. Stolte, "Energy transfer between hydrodynamically modulated long and short ocean waves by interaction with the wind field", elsewhere in this issue.

[8] R.E. Carande, "Estimating ocean coherence time using dual-baseline interferometric synthetic aperture radar", IEEE Trans. Geosci. Remote Sens., vol. 32(4), 1993, pp. 846-854.