1. Introduction

The growing interest in achieving a better understanding of the physics that govern the cross-polar scattering of microwave radiation from ocean is triggered by recent measurement campaigns over hurricanes performed by NOAA hurricane-Hunter winds and RADARSAT-2 C-band SAR. From this data set, the cross-polarized signals showed no evident loss of sensitivity as the wind speed increased from 20 m/s up to 45 m/s. On the contrary, C-band on-polar backscatter suffered from problems of incidence and azimuth angle dependent signal saturations and damping, which makes it weakly sensitive above 25 m/s. On the basis of these considerations, there are good reasons to think that the cross-polarized data can be a valuable tool for the retrieval of strong-to-severe wind speeds for future scatterometers. In this paper, we present a physical scattering model based on Small-Slope-Approximation theory (Voronovich, 1996), in conjunction with the Vector Radiative Transfer Theory to describe the behavior of cross-polar scattering from ocean as function of the wind speed and direction, and to compare real data from RADARSAT-2 and the brand new empirical Geophysical Model Function, GMF-VH (JadReff et al., 2013).

2. Properties of Ocean Surface

At high wind speeds, generated foam and spume droplets result in the fact that the real surface layer becomes a two-phase “cloud” whose properties (density, dielectric constant etc.) may significantly differ from the air: the sea foam layer modifies the wave behavior, form whitecaps on the surface and baffle plumes under the surface. The sea foam skin depth and penetration depth, at microwave frequencies, narrow our interest to only floating foam layers, excluding deeper bubble plumes. The foam is described as a vertical structure comprising large thin-walled bubbles with high air content (dry foam), close to the air-foam interface, and smaller thick-walled bubbles with lower air content (wet foam) close to the water boundary. The key parameters describing the sea foam are the air void fraction \( f \), the foam layer thickness \( d \), the bubble radius \( r \), and the number of bubbles per unit volume \( N \). Sea foam layer thickness vary from few centimeters up to few meters; in active whitecaps (cross-foam) and from decimeters down to few centimeters when the whitecaps decay (static foam). Our model refers to (Reul & Chapron, 2003) to compute the foam layer dynamics.

3. Sea-Foam Coverage & Thickness

The effect of foam on co-polar and cross-polar signal saturation above 25 m/s has been assessed for different foam coverage models (Mishchenko & Wisniewski, 1999; Mishchenko & Machefchaux, 1998; Bondar & Shumer, 1998) and Melville & Mitrovenko (2002). In this work, the Real & Chanon equation is used to compute the foam layer thickness weighted by the corresponding surface foam coverage and averaged over all breaking wave scales for a given wind speed.

4. Scattering from Rough Ocean

We base the computation of the microwave scattering, from a rough ocean surface, on the Small-Slope Approximation Theory. The SSA replaces the well known two scales description of the scattering process with a unique expression of the scattered fields, with a smooth transition between deep-water and small-portion-of-theta Method to principle, the SSA can be applied to any wavelength, that the tangent of grazing angles of incident/scattered radiation sufficiently exceeds the rms slope of the surface: The Small-Slope Approximation is the result of a Taylor expansion with respect to the powers of surface slopes. In this paper, we refer to the expansion performed at the second order, namely SSA2, which is able to estimate the cross-polarized components of scattering to the plane of incidence.

5. Scattering from Sea-Foam

The geometry of the foam problem is shown in Fig. 4, we identify five major contributing terms for the total scattering from a Rayleigh layer. For a sea surface with static foam coverage \( f_S \) and crest foam coverage \( f_c \), the total scattering coefficient is given by:

\[
\sigma = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left( f_S + f_c \right) \sigma_{\text{bubble}}(\theta) \sin \theta \ d\theta \ d\phi
\]

6. Comparison with Experiments

7. Wind Direction Dependence

8. Conclusions

Although, the small-slope approximation theory (SSA2) alone, can recover some of the scattering features of the ocean, it underestimates the magnitude. The SSA2 model does not account for foam and whitecaps generated by breaking waves; thus it is not adequate for backscattering computations at very strong winds.

In this work, a new analytical model for the full-polarimetric scattering of the smooth ocean surface has been investigated. The model combines the 2nd order Small-Slope Approximation, with the Vector Radiative Transfer Theory to obtain a statistical expression for the ocean full-polarimetric scattering matrix (or presence of foam) as a function of the wind speed and direction.

Cross-polar backscatter signals from RADARSAT-2 C band SAR imagery, are averaged during severe wind events, and collected into time-series. SARIMD wind measurements by NOAA’s hurricane-Hunter aircraft have been used to verify the model. Cross-polar scattering simulations are found in good agreement with the real measurements over a wide range of wind speeds and directions. In particular, both real and simulated cross-polar data show a distinguishable loss of sensitivity with the wind speed and, as such, cross-polar scattering can be a valuable tool for the retrieval of severe wind speeds from future active microwave instruments.

9. Acknowledgments

The authors wish to thank Gijs Gerbr van JadReff, KNMI, for the provision of the RADARSAT-2 data, Bertrand Chapron, PFRECRI, for the interesting discussions on VH-pol modeling and Alexander Voronovich, NOAA, for the useful feedback on the SSA implementation.