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An Analytical Model For The Cross-polar Scattering Of Microwave Radiation From Ocean

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1. Introduction

The growing interest in achieving a better understanding of the physics that governs 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 co-polar backscatter suffered from problems of incidence and azimuth angle-dependent signal saturations and dampening, 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 the 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. Numerical results will be compared with real data from RADARSAT-2 and the brand new empirical Geophysical Model Function, GMF-VH [*Zadelhoff et al.*, 2013]

2. Properties of Ocean Surface

At high wind speeds, generated foam and spume droplets result in the fact that the near surface layer becomes a two-phase "liquid", whose properties (density, dielectric constant etc.) may significantly differ from the air. The sea-foam definition includes, in a broad sense, both whitecaps on the surface and bubble plumes under the surface. The 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 high water content (wet-foam), close to the sea-water boundary. The key parameters describing the sea foam are: the air void fraction f_a, the foam layer thickness δ, the bubble radius r_s, and the number of bubbles per unit volume N. Sea foam layer thicknesses vary from few centimeters up to few meters, in active whitecaps (*crest 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.

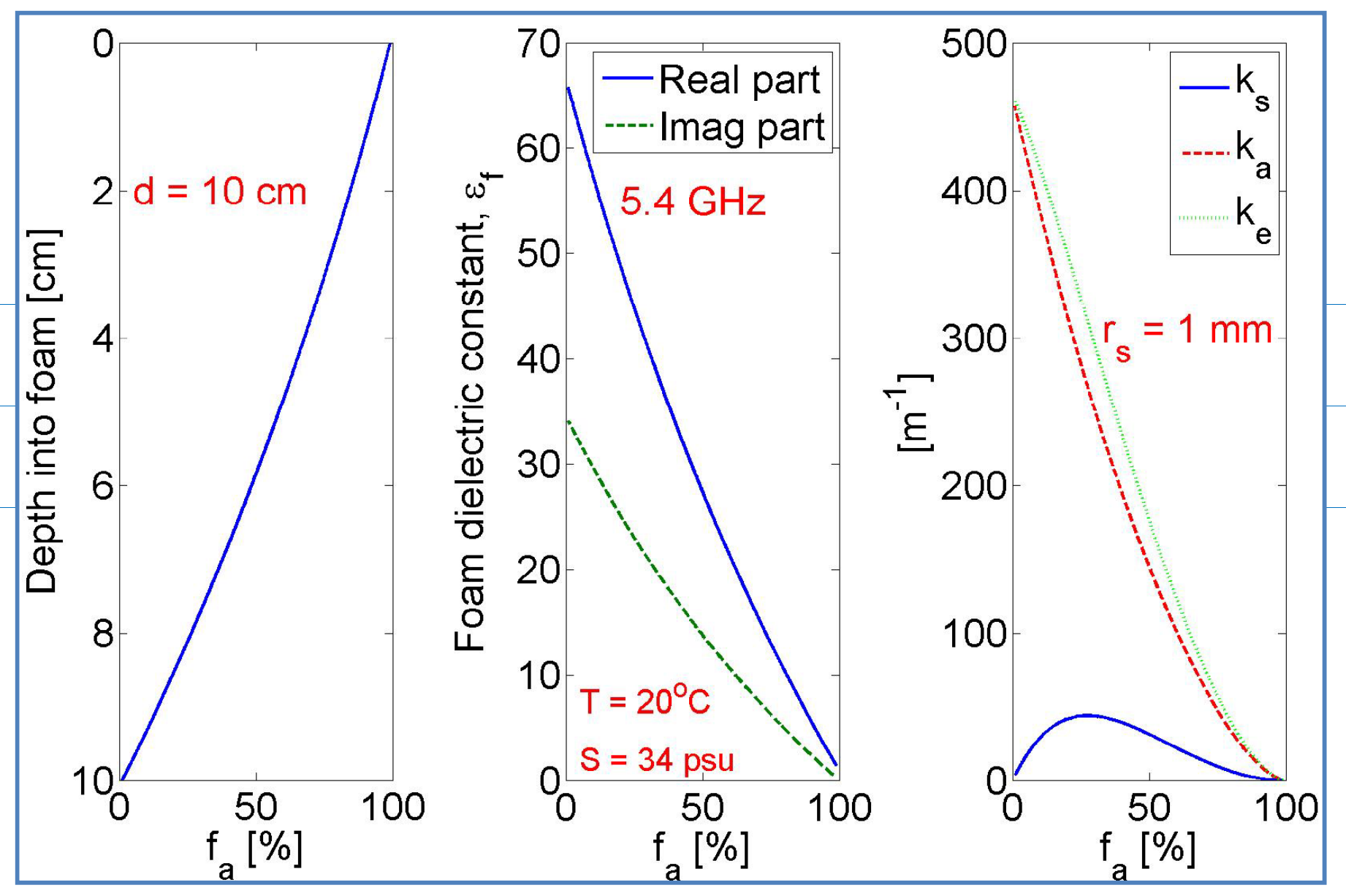


Fig. 1: Exponential void fraction profile $f_a(z)$ in foam layer with 10 cm thickness (left). Real and imaginary parts of the foam dielectric constant at 5.4 GHz (center). Scattering, absorption and extinction coefficients for bubbles with radius r_s = 1mm (right).

3.Sea-Foam Coverage & Thickness

The effect of foam on co-polar and cross-polar signal saturation above 25m/s has been assessed for different foam coverage models (*Monahan & Woolf* [1989], *Monahan & O'Muircheartaigh* [1980], *Bondur & Sharkov* [1982] and *Melville & Matusov* [2002]). In this work, the *Reul & Chapron* 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.

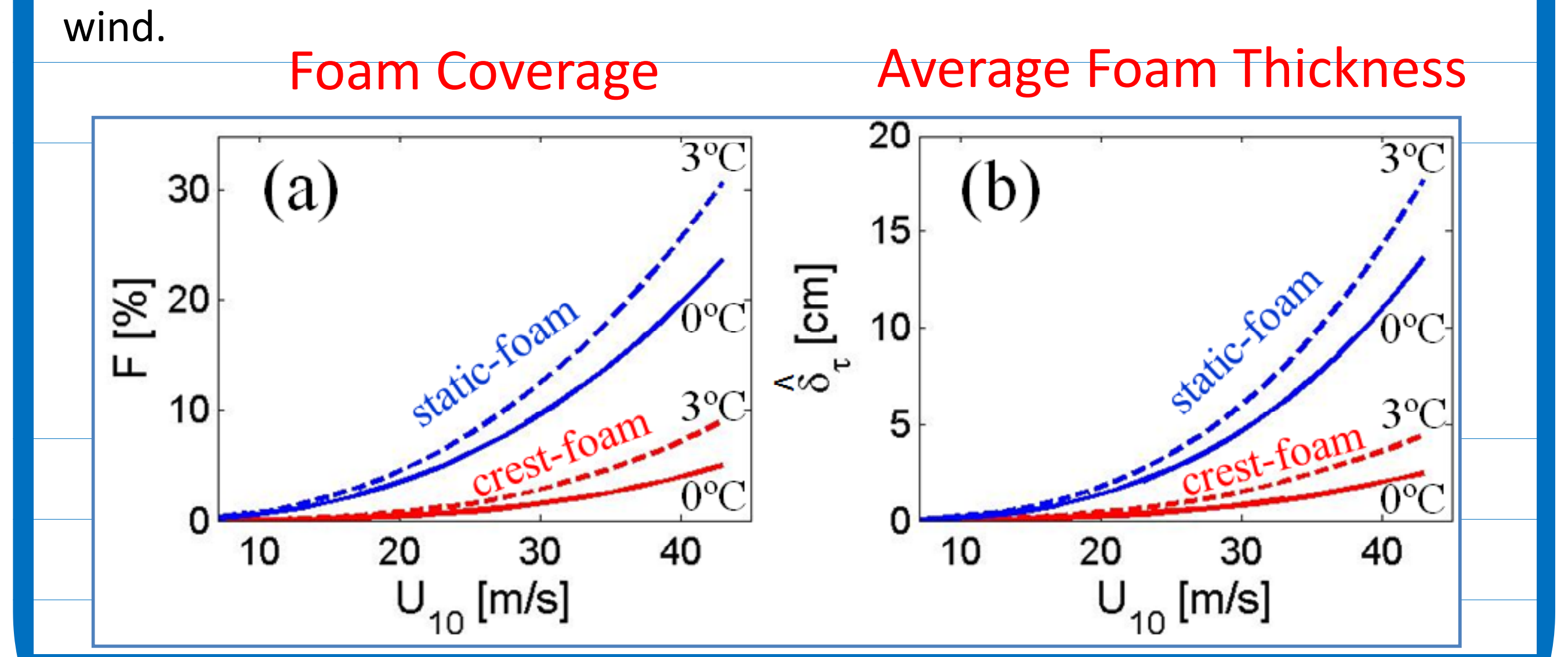


Fig.2. a) Static (blue) and crest (red) foam coverage for ΔT=3°C (dashed lines) and ΔT=0°C (solid lines); b) weighted average thickness of static and crest-foam

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 Geometrical Optics and Small Perturbation Method. In principle, the SSA can be applied to any wavelength, provided 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, named SSA2, which is able to estimate the cross-polarized component of scattering in the plane of incidence.

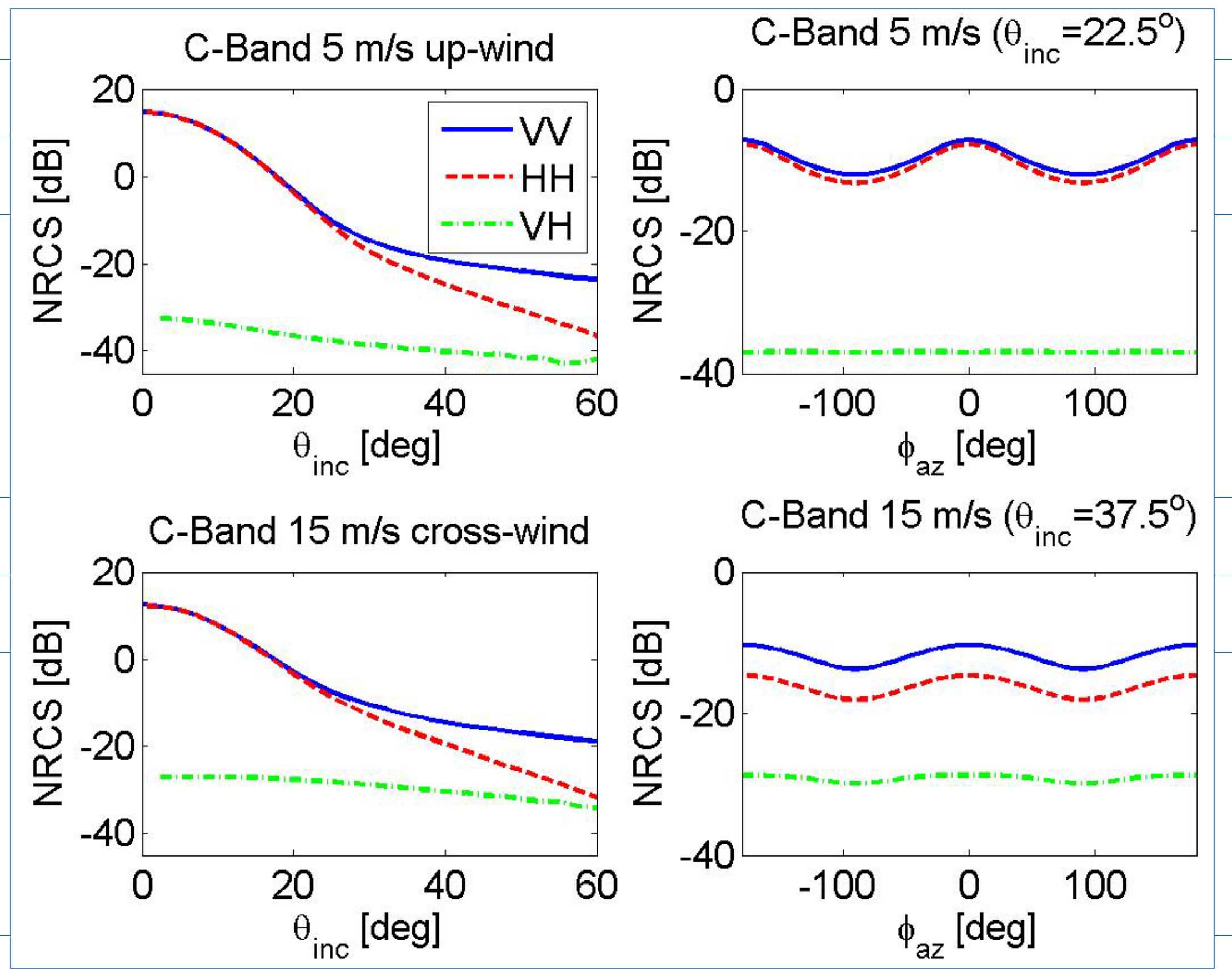
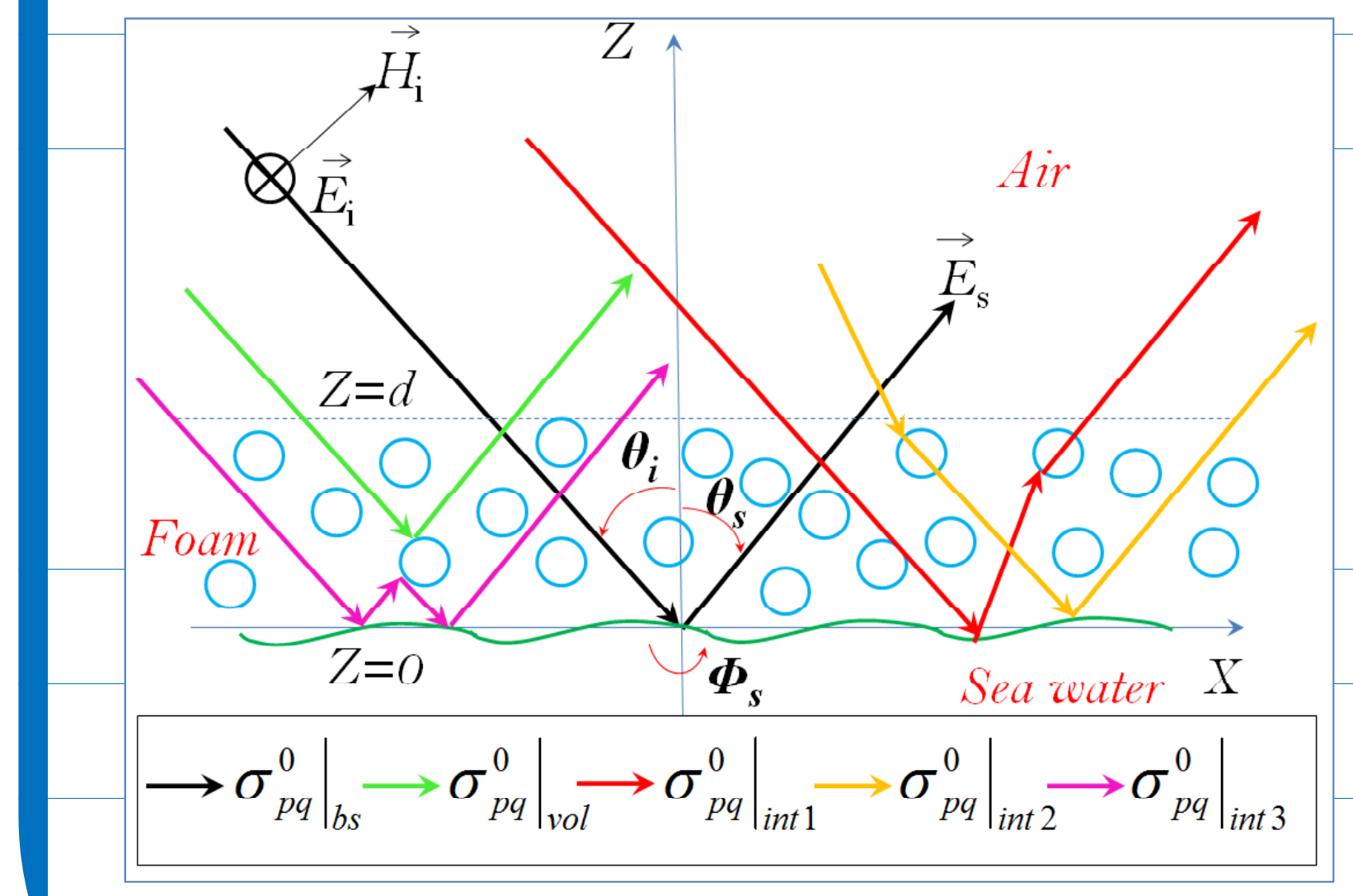


Fig. 3: Normalized radar cross section at 5.4 GHz for two different wind speeds (5 m/s and 15 m/s) and directions. In this simulation, the *Elfouhaily* wave spectrum has been used.

5. Scattering from Sea-Foam

The geometry of the problem is shown in Fig.4, we identify five major contributing terms to 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:

$$\sigma^0_{pq}\Big|_{Total} = (1 - F_s - F_c)\sigma^0_{pq}\Big|_{SSA-2} + F_s\sigma^0_{pq}\Big|_{static-foam} + F_c\sigma^0_{pq}\Big|_{crest-foam}$$



The terms:
$\sigma^0_{pq}\big|_{static-foam}$ $\sigma^0_{pq}\big|_{crest-foam}$
are both sum of 5 different contributions

Fig. 4: Geometry of the foam scattering problem.

6. Comparison with Experiments

The scattering model displays the expected qualitative features of the sea-surface NRCS, namely an enhanced sensitivity to high-wind speeds in VH-pol and an incidence/azimuth angle-dependent signal saturation and dampening in VV-pol, above 25 m/s wind speed.
As depicted in Fig.5b, simulated σ°-VH values are in good agreement with RADARSAT-2 measurements.

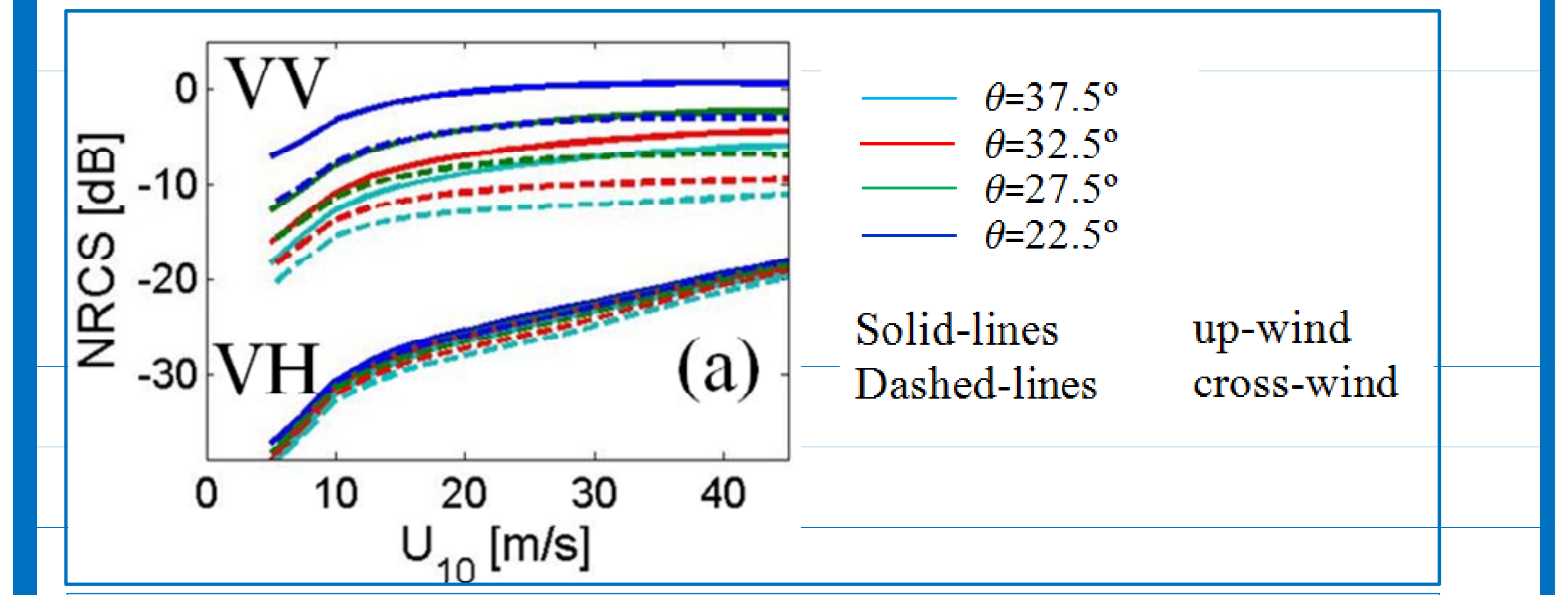
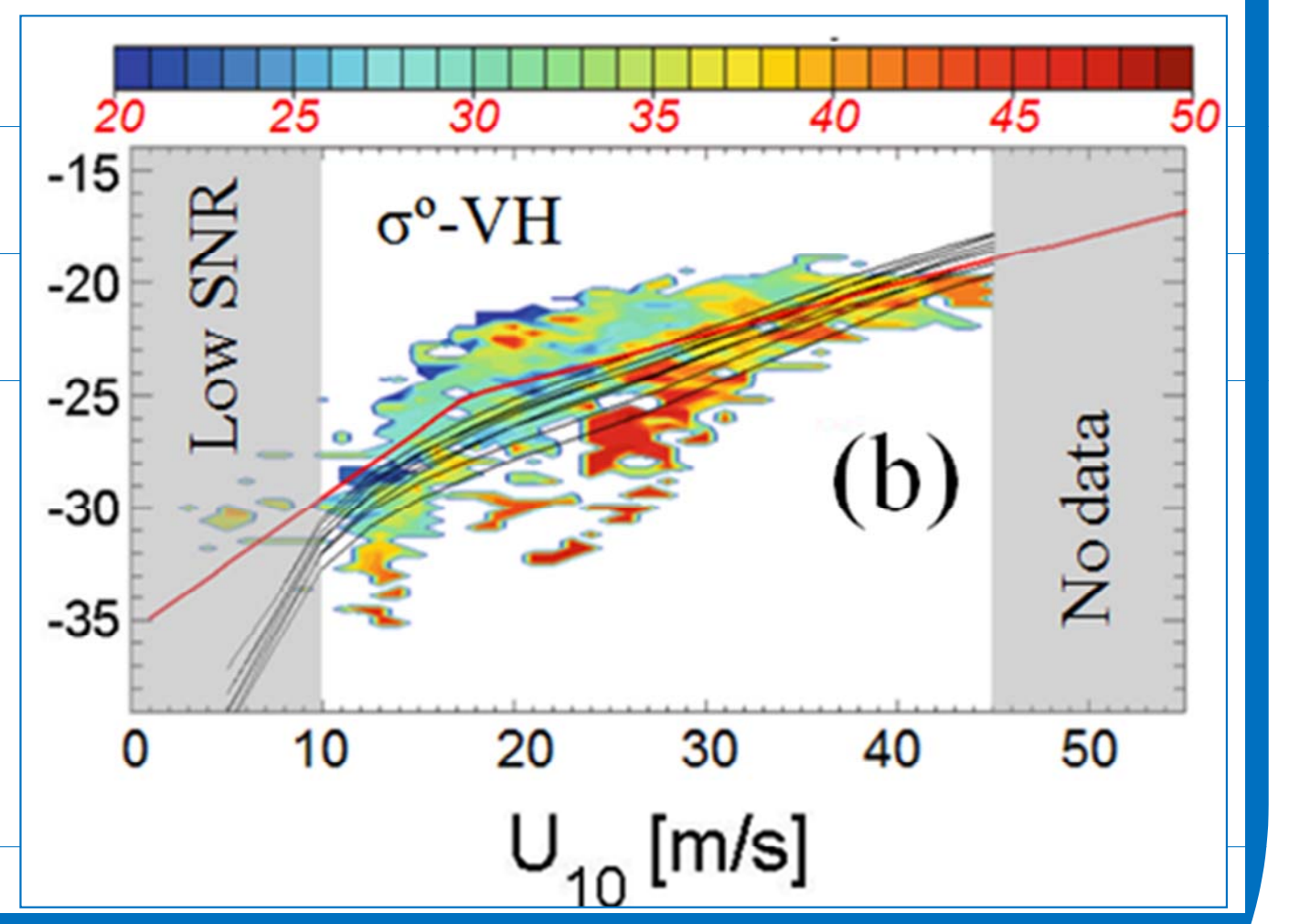


Fig.5a: Simulated NRCS versus wind-speed for 4 different incidence angles and two wind-directions (up-wind/cross-wind).

Fig.5b: Retrieved SFMR wind speeds versus collocated VH RADARSAT-2 measurements from 9 hurricanes. Overlaid are our simulated cross-polar VH-NRCS, obtained (for 4 median incidence angles, 22.5°, 27.5°, 32.5° and 37.5°) in both up-wind and cross-wind configurations, and GMF-VH (in red).



7. Wind Direction Dependence

The wind direction dependence of the simulated NRCS-VH is weaker than the one of NRCS-VV. Simulation results are confirmed by RADARSAT-2 measurements.

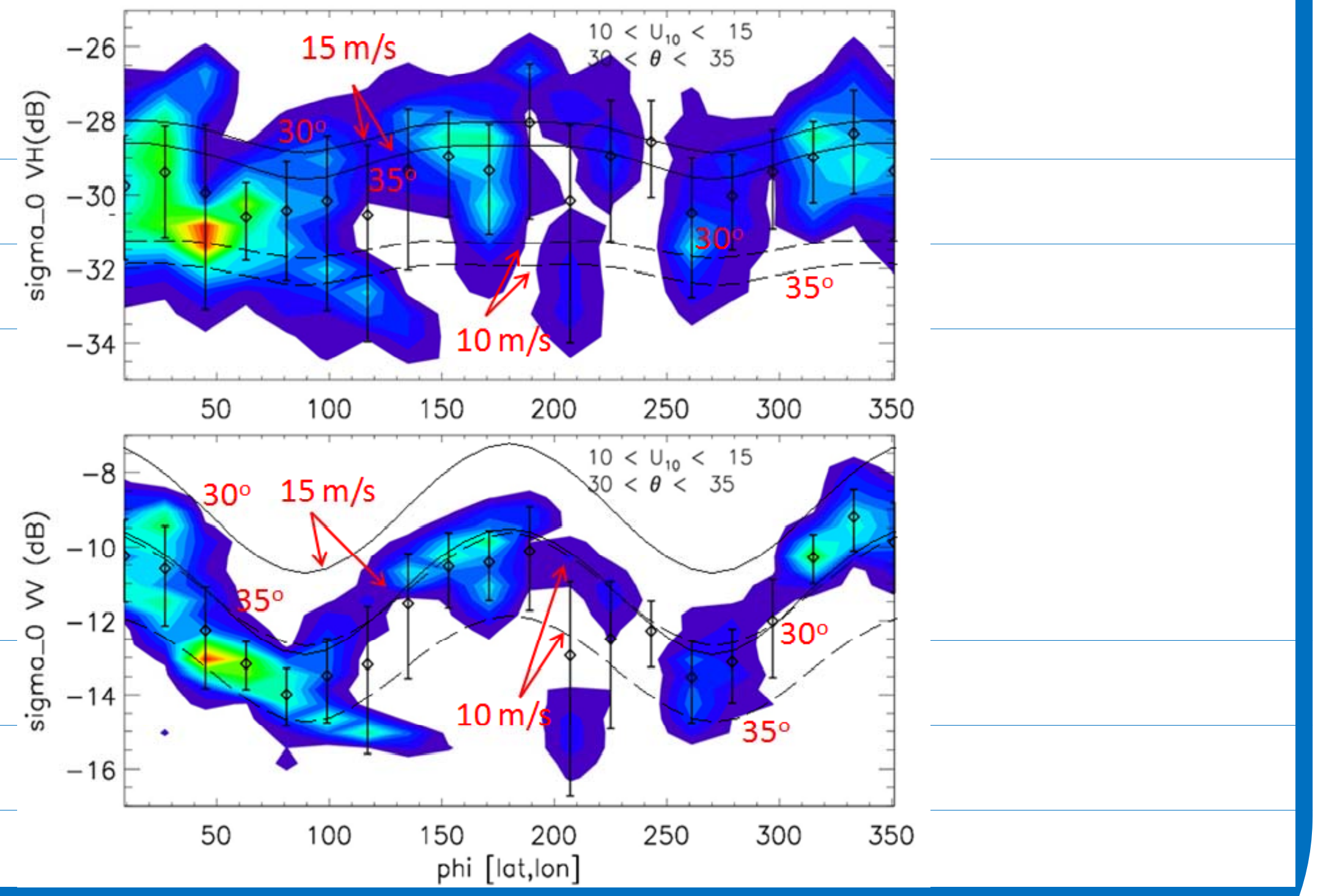


Fig. 6: Comparison of the co-polar & cross-polar simulated NRCS (versus the wind direction) with RADARSAT-2 data.

8. Conclusions

Although, the small-slope-approximation theory (SSA2), alone, can recover some trends of the cross-polarized backscattering, 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 microwave radiation from Ocean has been investigated.
The model combines the 2nd order Small Slope Approximation Theory with the Vector Radiative Transfer Theory to obtain a statistical expression for the ocean full-polarimetric scattering matrix (in presence of foam) as function of the wind-speed and direction.
Cross-polarized backscatter signals from RADARSAT-2 C-band SAR imagery, acquired during severe wind speed events, and collocated/time-coincident SFMR 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-polarized data show no distinguishable loss of sensitivity with the wind speed and, as such, cross-polarized scattering can be a valuable tool for the retrieval of severe wind speeds from future active microwave instruments.

9. Acknowledgements

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