Modeling Rain Effects on Microwave Backscatter from the Ocean

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Abstract- During the Kwajalein Experiment (KWAJEX) in 1999 the effect of rain on Ku band normalized radar cross sections of the sea, σ_0, was measured for a wide range rainfall rates and incidence angles. The primary result was that rain significantly increases the cross section at moderate to high incidence angles, obscuring, if not eliminating backscatter from wind-generated waves. To verify our understanding of the effect of rain on sea surface roughness and to extend it to smaller incidence angles and other microwave frequencies we modeled microwave backscatter from a rain-disturbed ocean surface. To do this, we developed a realistic representation of the ocean surface perturbed by wind and rain which accounts for the damping of surface waves by rain-induced subsurface turbulence and for the enhancement of gravity-capillary and short gravity waves by rain-generated ring-waves. The spectral representation of the ocean surface is used as input to a scattering model. The multiscale scattering model used here separates surface waves into three distinct scales (short, intermediate, and long) and evaluates σ_0 for each scale. Since rain significantly alters short gravity waves (i.e. the intermediate scale), the explicit calculation in the model of backscatter from these waves makes it ideal for diagnosing the effects of rain. We will show that values of σ_0 computed by the model are in quantitative agreement with KWAJEX data. We will also show modeled rain effects on the cross section at low incidence angles for a variety of microwave frequencies.

I. INTRODUCTION

The effect of rain on microwave backscatter from the ocean surface has important implications for the interpretation of remotely sensed data. Rain falling on the ocean surface has a multitude of effects that can alter the water surface and its scattering. The most noted is the droplet splash with its associated ring-waves. Laboratory studies of the effect of splashes on backscatter: [1], [2], [3], [4], and [5] show rain increases σ_0 at moderate and large incidence angles. References [4] and [5] also show that in wave tank studies at wind speeds below about 8 m s^{-1}, rain-created roughness is the source of backscatter not wind-waves. The increase in VV backscatter at incidence angles less than about 60^{o} is attributed to ring-waves, whereas the increase in HH backscatter at incidence angles less than about 30^{o} is attributed to ring-waves and at larger incidence angles stationary splash products, such as the crater, crown, and stalk are the scatterers.

Another, often overlooked effect of rain on the ocean surface is the damping of short gravity waves. Studies analyzing synthetic aperture radar (SAR) images [6] and [7] attribute some of the rain-altered backscatter to rain-induced damping. The damping of gravity waves and its effect on microwave backscatter was investigated and confirmed in wave-tank studies described in [5]. Reference [8] discusses possible mechanisms for the damping and concludes that the damping can be represented by an eddy viscosity of about 3×10^{-5} m^2 s^{-1}.

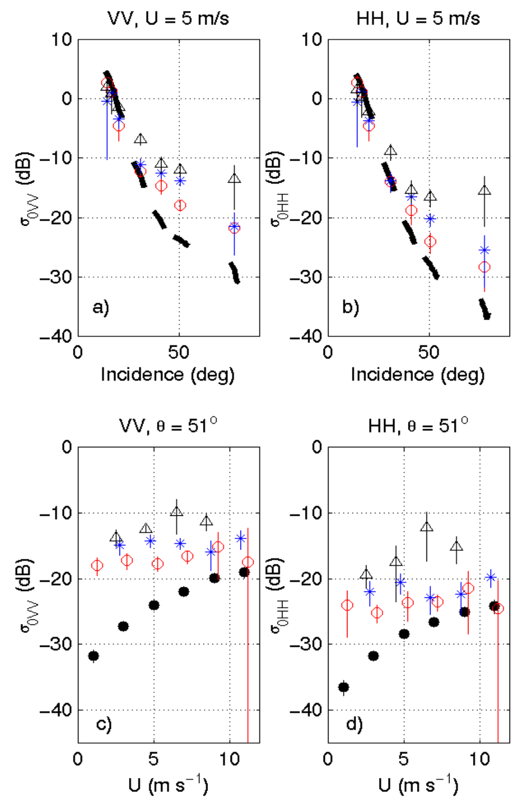

Fig. 1 Normalized radar cross section σ_0 versus incidence angle for a) VV and b) HH polarization for the rain rates: 0.63 to 5 (circle), 5 to 20 (asterisk), and greater than 20 mm hr^{-1} (triangle). Error bars represent the 95% confidence interval. σ_0 versus wind speed at 51^{o} incidence angle for c) VV and d) HH polarization.

The small numbers of studies that have been conducted in the field, [2] and [9] provide further insight into the effect of rain on microwave backscatter from the ocean at low grazing angles. In both studies, rain increased σ_0. However, the measurements were made for a narrow set of conditions and it is difficult and probably inappropriate, to extrapolate the results to different microwave frequencies and lower incidence angles. Our results from KWAJEX [10] which cover a broader range of natural conditions, show that rain enhances Ku band backscatter and makes the signal independent of wind speed at wind speeds below ~10 m s^{-1} and at moderate and high incidence angles. The results also suggest that rain impinging upon the ocean surface can decrease backscatter at low incidence angles.

In this paper, we first describe the field data which is being used to guide our modeling efforts. Then we explain the modeling technique being used. Finally, modeling results are presented and discussed.

II. DATA

The Kwajalein Experiment (KWAJEX) in 1999 was field campaign based at the Kwajalein Atoll Missile Range in the Marshall Islands. During the experiment, measurements of Ku band surface backscatter were made from the NOAA ship *Ronald H. Brown* over a large range of incidence angles for both raining and non-raining conditions with the purpose of quantifying the dependence of backscatter on rainfall rate. Fig. 1 summarizes much of what we learned. Fig. 1a and 1b show the effect of rain as a function of incidence angle for a wind speed of 5 m s^{-1}. The backscatter measured in the absence of rain is the solid line and the symbols are measurements at the rain rates: 0.63 to 5 mm hr^{-1} (circle), 5 to 20 mm hr^{-1} (asterisk) and greater than 20 mm hr^{-1} (triangle).

III. MODELING

To model the effect of rain on microwave backscatter, we first model the ocean surface disturbed by rain, expressing it as the power spectrum of surface height. Then we use this spectral representation as input to a microwave scattering model. The ocean surface model consists of the long-wave spectra developed in [11] in the form introduced in [12] patched to the short-wave spectra developed in [13] and [14]. To add the damping effect of rain, a two layer ocean wave model [15] is incorporated into the wind-wave model and an eddy viscosity consistent with the measurements of [8] is used. To add the effect of ring-waves created by droplet impacts the ring-wave model of [16] is used with a natural rain drop size distribution and added to the rain-damped surface wave spectral model. An alteration that has been made to the ring-wave model is that the high wavenumber tail is increased consistent with surface height measurements being made 3 cm from the rain footprint. Fig. 2a and 2b is an example of the rain modified surface spectra.

It should be kept in mind that scattering from the stationary splash products (i.e. the crater, crown and stalk) is not considered here. Therefore, modeled backscatter during rain is expected to be less than KWAJEX measurements at high incidence angles. Furthermore, at these angles the multiscale model is unlikely to be correct for HH polarization because bound wave effects are not included.

The microwave scattering model developed by [12] is used to compute scattering from the rain-disturbed surface spectrum. This model solves the Kirchhoff integral (Eq. 1 in [12]) for three ranges of wave sizes: small, intermediate, and large. The partitioning of the surface into these three scales allows simplifications of the Kirchhoff integral which makes it feasible to evaluate using the larger scale slopes to set the local incidence angles for smaller waves. It also allows the inclusion of modulation of the smaller waves by the larger ones. The scattering model transitions from moderate to low incidence angles without the use of an ``effective reflection coefficient'' which has been used in composite surface models to match observations. This suggests that the multiscale model correctly incorporates intermediate scale surface waves, which are likely to be significantly damped by rain.

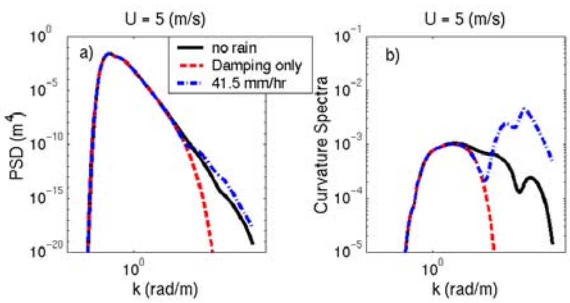

Fig. 2 a) Modeled surface height spectrum Ψ for no rain (solid). Spectrum considering turbulent damping (dashed) and turbulent damping and ring-waves (dash-dot) at a rain rate of 41.5 mm hr^{-1}. b) Modeled curvature spectrum Ψk^4; lines same as a).

IV. RESULTS AND DISCUSION

Fig. 3 compares modeled backscatter at Ku band with the results from KWAJEX for a rainfall rate of 41.5 mm hr^{-1}. VV polarized backscatter is shown in Fig. 3a and HH backscatter in Fig. 3b. Shown are modeled backscatter without rain (solid), with rain but without the rain induced wave damping (dashed-dot), with both rain damping and ring-wave enhancement (dashed), and measurements from KWAJEX (triangles). The model which includes both damping and enhancement quantitatively agrees with the data except at the highest incidence angles.

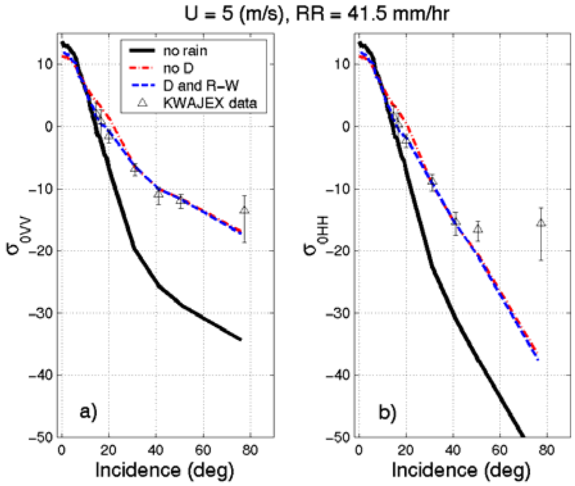

Fig. 3 Modeled Ku band cross sections (lines) and KWAJEX data (triangles) a) VV and b) HH polarization.

Fig. 4a and 4b are the same as Fig. 3a and 3b with the lower incidence angles being emphasized. Two interesting features are shown in this figure. The first is the difference between the non-damped model run and the data in both polarizations between 10 and 30 degrees. This underlines the importance of rain induced turbulent damping to our understanding of the effects of rain on microwave backscatter. Also interesting in Fig. 4a and 4b is the decrease in backscatter at the lowest angles. This effect has significant implications for the interpretation of space-borne Ku band precipitation radars like the TRMM PR, since the surface backscatter is used to estimate atmospheric attenuation.

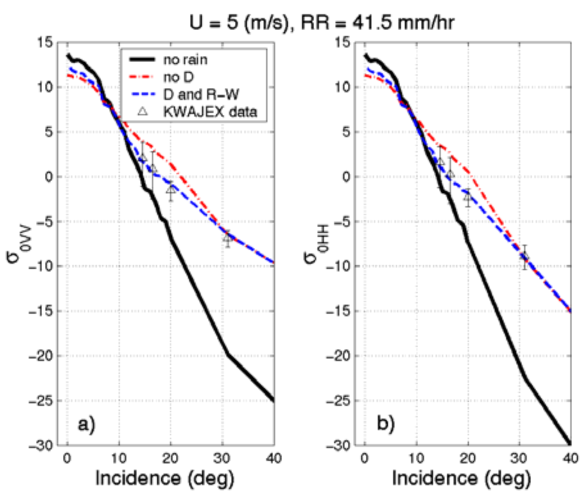

Fig. 4 Modeled Ku band cross sections (lines) and KWAJEX (triangles) a) VV and b) HH polarization.

Fig. 5 is a series of model runs with a wind speed of 5 m s^{-1} and a rain rate of 41.5 mm hr^{-1} at the microwave frequencies: 1.25 (L band), 5.3 (C band), and 9.6 GHz (X band), which are common frequencies used for microwave remote sensing. Backscatter at L band is decreased at moderate incidence angles while it is increased for X band and C band. This is in qualitative agreement with observations [6] and [7].

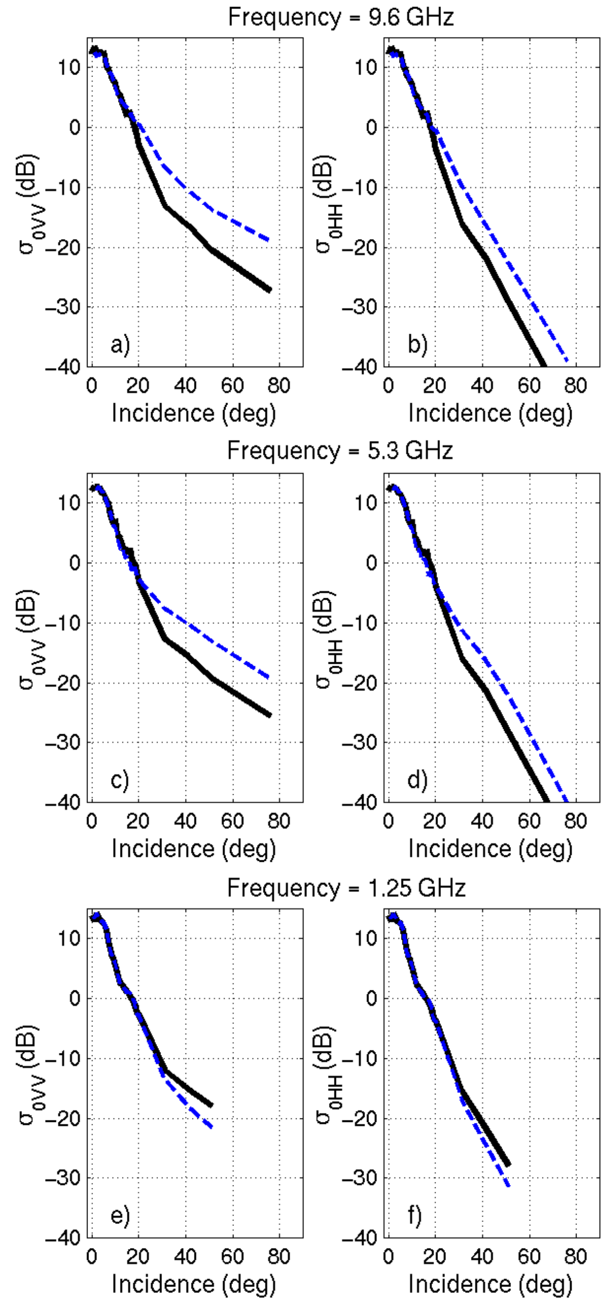

Fig. 5 Modeled cross sections for no rain (solid) a rain rate of 41.5 mm hr^{-1} (dashed) and a wind speed of 5 m s^{-1}: X band a) VV and b) HH polarization; C band c) VV and d) HH polarization; and L band e) VV and f) HH polarization.

Finally it is important to touch upon some of the areas where improvement is needed in this modeling. Although the ring-wave model gives agreement at 41.5 mm hr^{-1}, which is a heavy rain, it under-predicts the spectral density of ring-waves at lower rainfall rates. This may be due to the fact that the ring-wave model was developed in the laboratory and that the artificial rains used were incapable of producing the ring-waves associated with small drops present in natural rain. Further field work and modeling are being performed to develop ring-wave spectra during light natural rains.

Another area requiring improvement is the wind-wave model. The current model under-predicts backscatter at low to moderate wind speeds. Even though σ_0 is independent of wind at these wind speeds, this needs to be corrected if we are to have confidence in the model during light rains.

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