Rain Effects on SeaWinds Data

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Abstract-The effects of rain on SeaWinds data are investigated using one year of SeaWinds σ_0 data, SSM/I and TMI rain rates collocated within 5 minutes of the SeaWinds observation, and tri-linearly interpolated ECMWF 10-m wind analyses. Attenuation and volumetric backscattering are parameterized in terms of rain rate, and the modification of the surface radar cross-section by rain roughening is found. The effects of different rain drop size distributions and non-uniform beamfilling are investigated.

I. Introduction

Rain affects scatterometer measurements in three ways. First, rain attenuates the transmitted signal and the signal backscattered from the sea surface. Second, rain strongly backscatters the transmitted signal. Third, raindrop impacts physically alter the sea surface and normalized radar cross section (NRCS). These effects can be modeled by

$$\sigma_{0,meas} = \tau_r^2 \left(\sigma_{0,wind} + \Delta\sigma_{0,rain}\right) + \sigma_{0,bscat} \tag{1}$$

where $\sigma_{0,meas}$ is the measured NRCS, $\sigma_{0,wind}$ is the NRCS of the sea surface from wind roughening alone, $\sigma_{0,bscat}$ is the radar cross section contribution from volumetric raindrop backscattering, τ_r^2 is the two-way transmission through rain, and $\Delta\sigma_{0,rain}$ is the change in NRCS due to the physical modification of the sea surface by raindrop impacts. Note that $\Delta\sigma_{0,rain}$ may be positive or negative, and $\Delta\sigma_{0,rain}$ may include nonlinear interactions between wind and rain roughening as well as sea-spray.

Stiles and Yueh [1] studied the impact of rain on scatterometer data by assuming the effects of rain could be modeled by a linear relationship between $\sigma_{0,meas}$ and $\sigma_{0,wind}$. The coefficients of the linear relationship depended upon the beam and columnar rain rate (vertically integrated rain rate). They did not investigate the appropriateness of this model.

Tournadre and Quilfen [2] studied the effects of rain on scatterometer data using a theoretical model. The model accounted for rain attenuation and volumetric backscattering, but did not account for surface roughening due to rain. They found beamfilling to be a significant issue.

Stiles and Yueh [1] used empirical fits to data and Tournadre and Quilfen [2] used a theoretical model to study the effects of rain on scatterometer data. This study will use both data and theory to study the effects of rain on SeaWinds scatterometer data by asking the question "*how does rain physically alter the NRCS of the sea surface?*"

II. Data

Since SeaWinds scatterometer data from the ADEOS II satellite are not yet available, we used approximately one year (5000 orbits) of SeaWinds data from the QuikSCAT satellite along with SSM/I and TMI rain rates collocated within 5 minutes of the SeaWinds observation. ECMWF 10-m winds were tri-linearly interpolated in time and space to the SeaWinds observation, and the Ku-2001 model function was used to calculate $\sigma_{0,wind}$. Rain column heights were calculated using climatological SSTs according to the Wentz and Spencer [3] method.

III. Methodology

Before using eq. (1), systematic differences between the scatterometer dataset and the analysis dataset (ECMWF) needed to be removed. The linear correction

$$\sigma_{0,meas}^{no-rain} = \beta\left(b, \left|\mathbf{V}_{wind}\right|\right)\sigma_{0,wind}^{no-rain} + \alpha\left(b, \left|\mathbf{V}_{wind}\right|\right) \tag{2}$$

was used where *b* is the beam, $|\mathbf{V}_{wind}|$ is the analysis wind speed, and β and α were found using linear least squares regression on no-rain situations. Analytical forms of the transmission and volumetric backscattering for uniform beamfilling and Rayleigh backscattering are given by

$$\tau_r^2 = e^{-2H\sec\theta k} \tag{3}$$

$$\sigma_{0,bscat} = \left(\frac{1-\tau_r^2}{2k}\right)\left(\frac{\pi^5}{\lambda^4}\right)\left|\frac{m^2-1}{m^2+2}\right|^2 z \tag{4}$$

where *H* is the rain column height, θ is the incidence angle, λ is the wavelength of SeaWinds, *m* is the complex index of refraction, *k* is the (linear) attenuation coefficient, and *z* is the radar reflectivity factor.

k and *z* are typically related to the rain rate through a power law relationship (Table 1). The International Telecommunication Union (ITU) relationship is the most standard *k-R* relationship available [4]. Meneghini and Kozu [5] derived *k-R* relationships for a number of frequencies, and these are identical to the Atlas and Ulbrich [6] relationships commonly used in meteorology. Meneghini and Kozu assumed spherical drops, so the same relationship is used for both polarizations. Differences in the *k-R* relationship seem to have little effect on the two-way transmission (Fig. 1). The *k-R* relationships are very similar at low rain rates where *k* is small and differ the most a high rain rates where *k* is large. Thus the fractional differences are small for all rain rates and since τ_r^2 is proportional to e^{-k}, the differences in τ_r^2 are small. Interestingly, the ITU *k* values produce almost the same τ_r^2 for both beams because the polarization differences are offset by slant range differences. The National Weather Service (NWS) *z-R* relationships are the most standard *z-R* relationships available [7]. The NWS tropical *z-R* relationship was chosen because the collocated data set consisted mostly of observations within 40° of the equator. Rather than using the NWS standard mid-latitude *z-R* relationship, the Law and Parsons [8] relationship was used. The Law and Parsons *z-R* relationship is the NWS mid-latitude relationship scaled by

Table. 1. *K-R* and *z-R* relationships. The *K-R* relationships are valid for 13.4 GHz. Units: *K* (dB/km), *z* (mm^6/m^3), and *R* (mm/hr).

	Horizontal Polarization	Vertical Polarization
ITU [4]	$K_H = 0.0262\ R^{1.186}$	$K_V = 0.0236\ R^{1.164}$
Meneghini and Kozu [5]	$K_H = 0.0272\ R^{1.152}$	$K_V = 0.0272\ R^{1.152}$
NWS Tropical [7]	$z_H = 250\ R^{1.2}$	$z_V = 224\ R^{1.16}$
Law and Parsons [8]	$z_H = 400\ R^{1.4}$	$z_V = 325\ R^{1.32}$

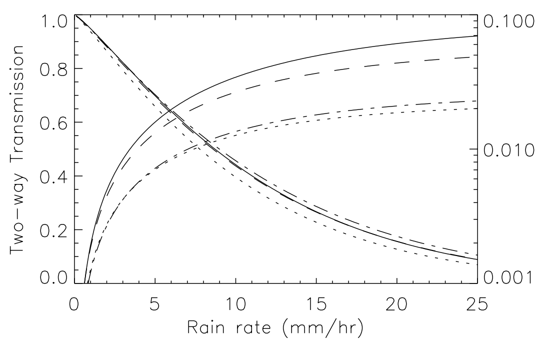

Fig. 1. Two-way transmission curves (originating from top left corner) and $\sigma_{0,bscat}$ curves (originating from lower left corner). A rain column height *H*=3km is assumed. Horizontal polarization: ITU (solid), Meneghini and Kozu (dot-dash), Law and Parsons (solid), and NWS (dot-dash). Vertical polarization: ITU (dash), Meneghini and Kozu (dot), Law and Parsons (dash), and NWS (dot).

1.33, and the ITU *k-R* relationships are similar to those derived using the Law and Parsons drop size distribution [9]. The Sachidananda and Zrnić [10] relationship was used to convert between horizontal and vertical polarization. Fig. 1 shows that differences in the *z-R* relationships result in clear differences in the $\sigma_{0,bscat}$ term, as physically expected. At centimeter wavelengths, the absorption loss dominates attenuation for all rain rates [8]. The absorption loss is proportional to the third moment of the drop size distribution, while backscattering is proportional to the sixth moment of the drop size distribution. Thus, it is natural to expect more variability in the *z-R* relationships than the *k-R* relationships because *z* is more sensitive to the large raindrops whose concentration is small and variable.

IV. Results

The dependence of $\Delta\sigma_{0,rain}$ on rain rate depends strongly on the choice of *z-R* relationship (Fig. 2). The results using the ITU *k-R* relationships are imperceptibly different from the results using the Meneghini and Kozu *k-R* relationship. Positive values of $\Delta\sigma_{0,rain}$ indicate NRCS enhancement while negative values represent NRCS calming. Work by Contreras et al. [11] suggests that at the frequency and incidence angles of SeaWinds, rain should enhance the NRCS. Laboratory tank studies have also found enhancement [12]. Thus, the Law and Parsons *z-R* relationship seems to be providing too much backscatter, and the NWS Tropical relationship seems preferable. Power law relationships of the form

$$\Delta\sigma_{0,rain} = aR^b \tag{5}$$

were fit to the results using the NWS Tropical *z-R* relationship and are presented in Table 2.

Fig. 3 shows the azimuth angle dependence of $\Delta\sigma_{0,rain}$. The choice of *z-R* relationship shifts the $\Delta\sigma_{0,rain}$ curve vertically, but has little effect on the shape or amplitude of the azimuthally dependent signal. The NRCS of rain alone (with no wind) would be expected to be isotropic. Fig. 3 shows that for light wind (left column) or for heavy rain (bottom row), $\Delta\sigma_{0,rain}$ is isotropic. For certain situations with moderate wind and moderate rain, the $\Delta\sigma_{0,rain}$ term exhibits an azimuthal dependence that opposes the wind signal. The horizontal polarization results are similar, but have smaller amplitude (not shown).

Tournadre and Quilfen [2] demonstrated the importance of beamfilling, and how even simple rain cell geometry can yield complicated scatterometer responses. So far this work has assumed uniform beamfilling. To understand the effects of beamfilling, consider eq. (3) rewritten as

$$\tau_r^2 = e^{-2A} \tag{6}$$

where *A* (=$H\sec\theta\, k$) is the attenuation. Noting that the transmission is a convex function of *A* (Fig. 1) Jensen's Inequality gives

$$E\left(e^{-2A}\right) \geq e^{-2E(A)} \tag{7}$$

where *E( )* is the expectation operator. Defining

$$\hat{A} = \frac{\ln\left[E\left(e^{-2A}\right)\right]}{-2} \tag{8}$$

gives

$$\hat{A} \leq E(A) \tag{9}$$

Thus, if the attenuation is not homogeneous over the SeaWinds footprint, the footprint average attenuation will be larger than the attenuation implied by the footprint average transmission. Next, consider calculating the volumetric backscattering from the rain rate. Fig. 1 shows that eq. (4) is a concave function of rain rate. This is primarily because the exponents of the *z-R* relationships are greater than unity. Jensen's Inequality gives

$$E\left(cR^d\right) \leq cE(R)^d \tag{10}$$

for $d \geq 1$. Thus the reflectivity calculated from the average rain rate will be larger than the true average reflectivity. Also note that the attenuation calculated from a *k-R* relationship using the average rain rate will be larger than the true average attenuation. Properly treating beamfilling should increase the transmission (decrease the attenuation) and decrease the backscattering compared to values computed from footprint average rain rates. Examining eq. (1), a decrease in backscatter should increase $\Delta\sigma_{0,rain}$ while an increase in transmission should decrease $\Delta\sigma_{0,rain}$.

The results presented in Figs. 2 and 3 were found using eq. (1) with the same transmission and backscattering values for all of the σ_0 values in a particular wind vector cell. That is, the rain rate was assumed to be constant over the wind vector cell. Even though this is an erroneous assumption, averages

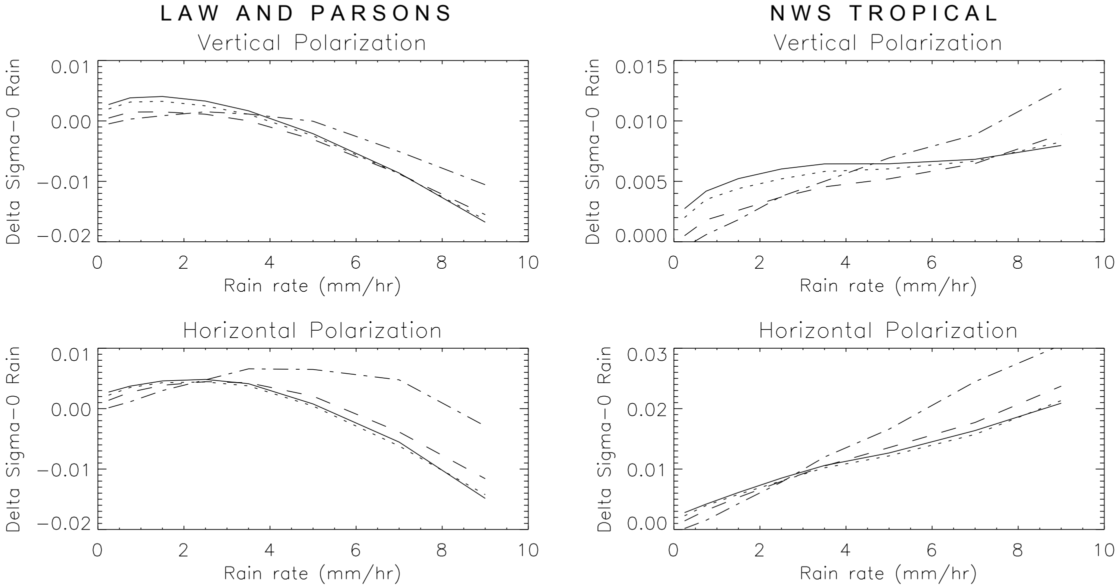

Fig. 2. $\Delta\sigma_{0,rain}$ as a function of rain rate and wind speed 1-4 m/s (solid), 4-7 m/s (dot), 7-10 m/s (dash), 10-15 m/s (dot-dash). The ITU *k-R* relationship has been used for both figures with the Law and Parsons *z-R* relationship (left) and the NWS Tropical *z-R* relationship (right).

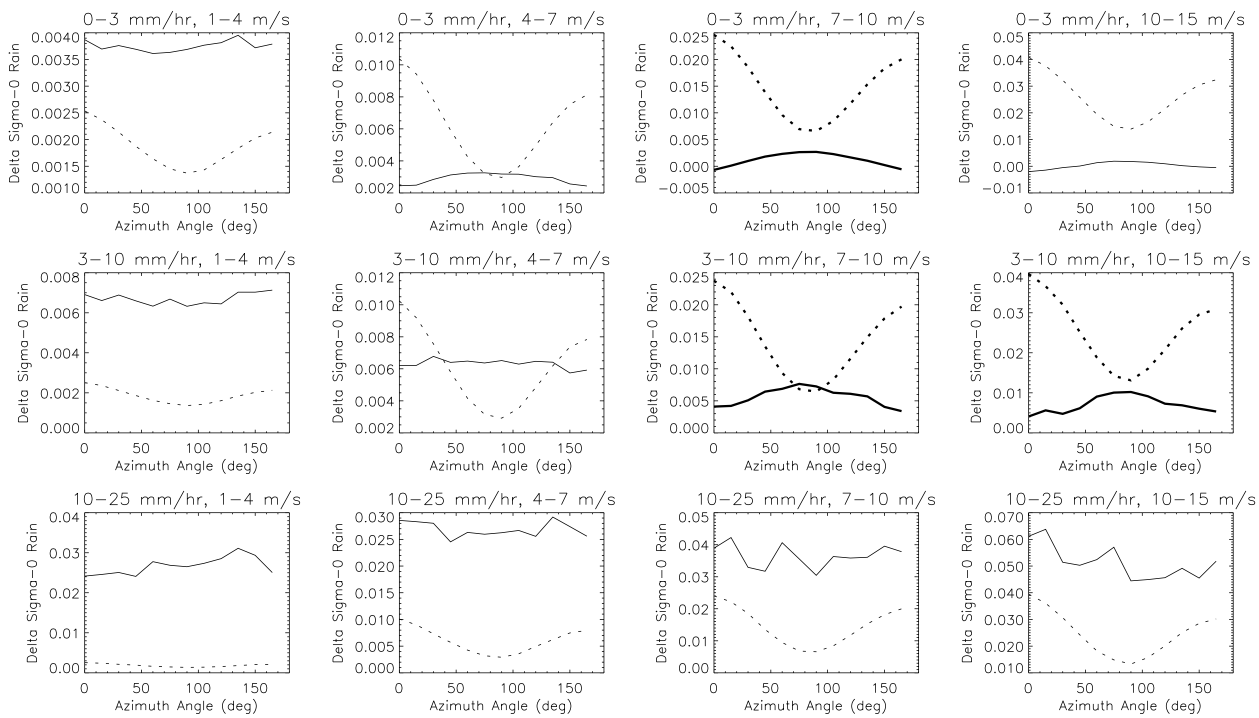

Fig. 3. Azimuth angle dependence of the $\Delta\sigma_{0,rain}$ term (solid) with $\sigma_{0,wind}$ (dot) provided for reference. These are for vertical polarization and have used the NWS Tropical *z-R* relationship and ITU *k-R* relationship.

over a year of data provide meaningful estimates. However, to obtain meaningful retrieved winds, the structure of the rain field must be known so that the transmission and backscattering terms can vary as eq. (1) is applied to each of the σ_0 values in a wind vector cell.

The form of eq. (1) can be used to find cases where the beamfilling is uniform. Cases of uniform beamfilling were found by first fitting

$$\sigma_{0,meas} = m\sigma_{0,wind} + p \tag{11}$$

to the σ_0 values in a wind vector cell using linear least squares regression. In all of the cases there were at least four σ_0 values in the wind vector cell. Uniform beamfilling then required:

$$p \geq 0 \tag{12a}$$

$$0 < m \leq 1 \tag{12b}$$

$$r^2 \geq 0.8 \tag{12c}$$

where r is the correlation coefficient. Eq. (12c) requires at least 80% of the variance between the measured and wind-implied σ_0 values to be explained by a linear relationship.

Only 9% of the data meet the requirements of (12a-c). In fact, only 32% of the data meet (12a) and (12b). This is not a criticism of the model given by eq. (1), but a demonstration of the importance of beamfilling and that SeaWinds and ECMWF winds each contain unique information. Figure 4 and the corresponding power law fits (Table 3) show the significant effect that beamfilling has on $\Delta\sigma_{0,rain}$. The increase in $\Delta\sigma_{0,rain}$ resulting from the decrease in backscatter dominates at low rain rates. The decrease in $\Delta\sigma_{0,rain}$ resulting from an increase in transmission dominates at higher rain rates by a flattening of the slopes of the curves. There are too few data to justify showing results above 5 mm/hr. Removing the cases of non-uniform beamfilling changes the horizontal polarization results more than the vertical polarization results because horizontal polarization is more affected by rain than vertical polarization. Removing the cases of non-uniform beamfilling changes the higher wind cases more than the lower wind cases. It is not clear whether this is an indication that the amount of rain field variation is positively correlated with the wind speed, or if this is an indication that SeaWinds and ECMWF disagree more in high wind situations. The results presented in Table 3 are in agreement with Contreras et al. [11] at low rain rates, but increase much more slowly than in [11].

V. Conclusions

SeaWinds data have been found to predict NRCS enhancement by rain roughening of the sea surface. The choice of *z-R* relationship is a major source of uncertainty, but the NWS Tropical relationship produces favorable results. Rain field variability (the beamfilling effect) is significant and will likely need to be addressed for the corrected NRCS values to produce meaningful retrieved wind vectors.

Table 2. Power law coefficients for $\Delta\sigma_{0,rain} = a R^b$ using all data and ITU *k-R* relationship and NWS Tropical *z-R* relationship (i.e., fit to right panels of Fig. 2). *r* is the correlation coefficient.

ALL DATA

Wind Speed (m/s)	Vertical Polarization (55° incidence)			Horizontal Polarization (47° incidence)		
	a	*b*	r^2	*a*	*b*	r^2
1-4	0.0044	0.28	0.963	0.0053	0.56	0.984
4-7	0.0036	0.36	0.978	0.0048	0.61	0.990
7-10	0.0017	0.74	0.973	0.0040	0.78	0.999
10-15	0.0010	1.18	0.979	0.0018	1.42	0.978

Table 3. Power law coefficients for $\Delta\sigma_{0,rain} = a R^b$ using only uniformly filled data and ITU *k-R* relationship and NWS Tropical *z-R* relationship (i.e., fit to Fig. 4). *r* is the correlation coefficient.

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Wind Speed (m/s)	Vertical Polarization (55° incidence)			Horizontal Polarization (47° incidence)		
	a	*b*	r^2	*a*	*b*	r^2
1-4	0.0075	0.29	0.991	0.0068	0.24	0.844
4-7	0.0074	0.17	0.869	0.0067	0.17	0.946
7-10	0.0072	0.17	0.988	0.0065	0.17	0.993
10-15	0.0089	0.24	0.964	0.0078	0.21	0.957

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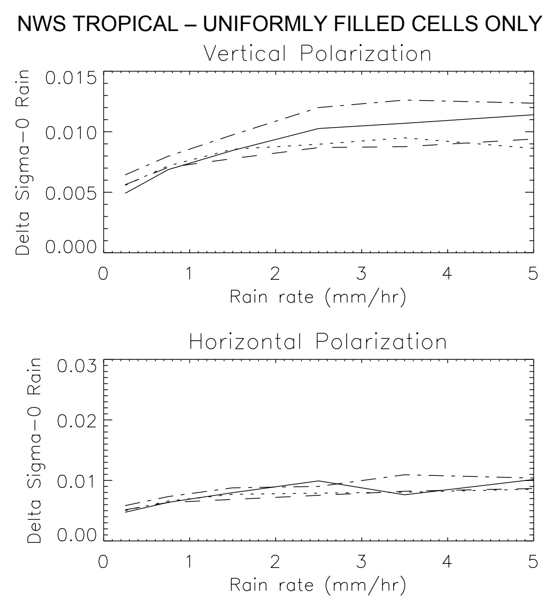

Fig. 4. $\Delta\sigma_{0,rain}$ as a function of rain rate and wind speed 1-4 m/s (solid), 4-7 m/s (dot), 7-10 m/s (dash), 10-15 m/s (dot-dash). The ITU *k-R* relationship and NWS Tropical *z-R* relationship have been used. Only data for which the beamfilling is uniform have been used. Compare to the right panels of Fig. 2.