Simulation of SeaWinds Measurements in the Presence of Rain Using Collocated TRMM PR Data

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***Abstract*-The scatterometer SeaWinds on QuikSCAT measures ocean winds via the relationship between the wind and the normalized radar backscatter cross-section (σ°) from the ocean surface. Scattering and attenuation from falling rain droplets along with ocean surface perturbations due to rain change the backscatter signature of the waves induced by near-surface winds. A simple model incorporates the effects of rain on ocean σ°. Colocated data from the precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite is used to simulate the effects of rain as seen by SeaWinds. PR-derived backscatter, atmospheric rain attenuation, and rain rates are averaged over the SeaWinds footprint. The enhancement in backscatter from rain striking the ocean surface is estimated as a function of rain rate using a least-squares technique. QuikSCAT σ° values are simulated from the PR-derived parameters and numerical weather prediction wind data using the simple backscatter model. The simple model estimates 90% of the observed rain-contaminated QuikSCAT σ° values to within 3 dB.**

I. INTRODUCTION

SeaWinds on QuikSCAT, a spaceborne scatterometer launched in 1999 by NASA, provides daily coverage of instantaneous ocean vector winds. Scatterometer wind retrieval is possible due to the relationship between σ° of the ocean surface and the wind speed and direction. The value of σ° can be influenced, however, by other geophysical parameters. Rain is one of the main environmental factors that significantly modifies σ°. In the presence of rain, the radar backscatter is affected by volume scattering and attenuation from falling hydrometeors. Rain striking the surface alters the wind-induced capillary wave field and causes rings, stalks, and waves from which the signal additionally scatters [1].

In this paper, a simple model is given for the backscatter from the ocean during rain. Data from the precipitation radar (PR) on board the Tropical Rainfall Measuring Mission (TRMM) satellite is collocated with SeaWinds on QuikSCAT data. The TRMM PR data, along with numerical weather prediction model winds, are used to simulate QuikSCAT σ° values. Eleven collocation sets, spanning approximately one month, are used in the analysis. Using a least-squares technique, the effect on backscatter of the rain striking the ocean is estimated. The simple model accurately estimates (within 3 dB) the measured QuikSCAT σ° values. The use of a rain model in the wind estimation process can potentially significantly enhance wind retrieval in the presence of rain.

II. DATA

SeaWinds on QuikSCAT is a dual-beam scanning pencil-beam scatterometer. The outer (v-pol) beam has a 3dB footprint of 37 x 52 km and the inner (h-pol) beam has a 3dB footprint of 34 x 44 km. The 1800 km wide swath is segmented into a grid of (approximately) 25 x 25 km wind vector cells (wvcs). All valid measurements centered at a wvc are used to create a wind vector estimate. The wind speed and direction is related to σ° through the empirically determined geophysical model function (GMF). The wind is inferred by inverting the GMF using a maximum likelihood technique.

The PR on board TRMM is a Ku-band nadir-looking scatterometer which provides tropical rainfall profiles in three spatial dimensions. The PR has a spatial resolution of $\sim$ 5 x 5 km and a swath width of approximately 200 km. Standard PR data products used in this report include unadjusted reflectivities in 3 spatial dimensions (Z_m), integrated rain rates (R), and path integrated attenuation or PIA from the 2A25 data product.

III. SIMPLE MODEL FOR σ°

Combining the mechanisms explained in Section I for backscatter during rain, we give a simple phenomenological rain/wind backscatter model. The scatterometer-observed backscatter can be represented by

$$\sigma_m = (\sigma_w + \sigma_{sr})\alpha + \sigma_r \tag{1}$$

where σ_m is the measured σ° from space, σ_w is the wind-induced surface radar backscatter, σ_{sr} is the surface backscatter due to rain striking the water, α is the two-way atmospheric attenuation, and σ_r is volume scattering due to falling rain droplets.

In the model, we assume that σ_w and σ_{sr} linearly combine to form a net backscatter surface return. Although this relationship does not fully represent the complicated nature surface scattering from wind and rain produced ocean waves, it has been shown that surface rain generally augments σ° due to wind [1]. Thus, for this first order analysis, we assume a linear relationship.

A. Determining Model Parameters

Data from the TRMM PR and numerical weather prediction (NWP) model fields allow us to calculate values for σ_w, α, and σ_r. In order to make the notation tractable, where a quantity is calculated for both PR and QuikSCAT resolutions, the symbol is primed ($'$) if it has the resolution of the PR, and is unprimed if it has the resolution of QuikSCAT. Also, parentheses in the subscripts of symbols are used to indicate the source of the data used to estimate that parameter.

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The Level 2B QuikSCAT wind data includes collocated estimates of the wind from the National Centers for Environmental Prediction (NCEP). These wind fields are interpolated to the same grid as the SeaWinds 25 x 25 km wind product. For each QuikSCAT σ° value, the nearest-neighbor NCEP wind vector is projected through the GMF to produce an estimated value for the wind-induced backscatter ($\sigma_{w(NCEP)}$) at each measurement point.

Although NCEP provides an estimate of the non-rain wind σ°, NCEP σ° has some error (ϵ) due to prediction errors, etc. The σ° error is location-dependent. Because NCEP is very low resolution, we assume that ϵ is spatially correlated. Further, since each collocation region covers only a few hundred wind vector cells, we assume that ϵ is constant over the collocation region. For each collocation region (n), we represent the error by the symbol ϵ_n. Thus, the effective wind σ° for each rain-contaminated region is: $\sigma_w = \sigma_{w(NCEP)} + \epsilon_n$. The bias error parameter ϵ_n is estimated in Section III-B.

The two-way atmospheric attenuation factor (α) is calculated from the PIA estimates in the TRMM 2A25 data sets: $\alpha'_{(PR)} = 10^{-\frac{\text{PIA}}{10}}$. The PIA estimate is formed from an maximum likelihood technique given TRMM 2A21 PIA estimate from a surface reference method and a Hitschfeld-Bordan method [2]. For each QuikSCAT observation, the SeaWinds-observed attenuation ($\alpha_{(PR)}$) is calculated by averaging the collocated values of $\alpha'_{(PR)}$ over the SeaWinds 6dB footprint weighted by the SeaWinds gain pattern.

Estimates for the volume-scattering rain cross-section (σ_r) are calculated from unadjusted reflectivities (Z_m) obtained from the TRMM 1C21 data set. The actual reflectivity of the atmospheric rain (Z_e) at range r is related to the unadjusted reflectivity via $Z_m(r) = Z_e(r)\alpha(r)$ where r is the range, and $\alpha(r)$ is the path integrated two-way attenuation at range r. The volume backscattering coefficient at range r can be found from [4],

$$\sigma_{vr}(r) = 10^{-10}\frac{\pi^5}{\lambda_0^4}|K_w|^2 Z_e(r) \quad \text{m}^2/\text{m}^3 \tag{2}$$

where λ (cm) is the electromagnetic wavelength, and $|K_w|^2$ is a coefficient related to the absorption properties of water (assumed to be 0.9). The volume backscattering cross-section observed by the satellite (σ_{vro}) is attenuated by the two-way attenuation factor, $\alpha(r)$ and is equal to,

$$\sigma_{vro}(r) = \sigma_{vr}(r)\alpha(r) = 10^{-10}\frac{\pi^5}{\lambda_0^4}|K_w|^2 Z_m(r). \tag{3}$$

The total atmospheric rain backscatter as seen by the PR ($\sigma'_{r(PR)}$) is σ_{vro} integrated through the PR antenna beam to the lowest no-surface-clutter range,

$$\sigma'_{r(PR)} = \Delta r \sum_{s=1}^{N_{nc}} \sigma_{vro}(s) \quad \text{m}^2/\text{m}^2 \tag{4}$$

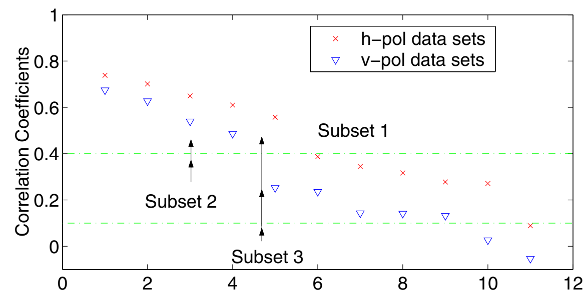

Fig. 1. The correlation coefficients (sorted) between $R_{(PR)}$ and $\sigma_{m(QSCAT)}$ for each collocation set. Each analysis subset is shown.

where Δr is the vertical range resolution of the PR (250 m) and N_{nc} is the lowest no-surface-clutter range bin. The SeaWinds-observed backscatter due to atmospheric rain ($\sigma_{r(PR)}$) is formed by averaging ($\sigma'_{r(PR)}$) over the SeaWinds footprint. Values for $\sigma'_{ri(PR)}$ where there is no rain detected are set to zero.

Since the PR is nadir-looking and SeaWinds operates at relatively high incidence angles, the values of $\alpha_{(PR)}$ and $\sigma_{r(PR)}$ may be slightly underestimated for SeaWinds geometry because the SeaWinds beam has a longer path to the surface from the rain top. In addition, TRMM PR and SeaWinds measurements are only collocated at the ocean surface. Thus, for decreasing range, the TRMM and SeaWinds beams become increasingly misaligned. This effect may alter our estimate of SeaWinds σ^0. Also, temporal changes in rain profiles between the TRMM observation and SeaWinds observation times introduces additional errors.

To ameliorate the effects of misalignment, we perform the remaining analysis on 3 subsets of the data which involve differing levels of correlation between the QuikSCAT σ° values ($\sigma_{m(QSCAT)}$) and the PR rain rate averaged over the SeaWinds footprint ($R_{(PR)}$). Examining the correlation coefficients between $R_{(PR)}$ and $\sigma_{m(QSCAT)}$ for each collocation set, we find natural breaks in the values around 0.4 and 0.1 (see Fig. 1). Subset 1 is all data within the collocation sets with correlation coefficients greater than 0.4. Subset 2 is all data within collocation sets with correlation coefficients greater than 0.1. Subset 3 is all the collocation data.

B. Modeling σ_r, α and σ_{sr}

Both σ_r and α are inherently related to the rain rate by power-law models in the TRMM processing [2]. They can be expressed as: $-\alpha_{(PR)}(\text{dB}) = cR^d_{(PR)}$ and $\sigma_{r(PR)} = eR^f_{(PR)}$ The parameters c, d, e, and f are calculated by taking the logarithm of both sides of these equations and using linear least squares estimation on the PR data. Table I gives the values obtained by this method. Both σ_r and $\alpha(\text{dB})$ are linear functions of rain rate.

Unfortunately, a relationship for the surface enhancement

TABLE I

VALUES OF THE PARAMETERS c, d, e, f IN THE EQUATIONS $-\alpha = cR^d$ AND $\sigma_r = eR^f$.

Parameter	c	d	e	f
Value	0.05	1.0	0.0003	1.0

due to rain (σ_{sr}) cannot be extracted from either TRMM or SeaWinds data alone. However, an estimate of this parameter can be obtained by solving Eq. (1) for σ_{sr}. After adding appropriate subscripts, we obtain

$$\begin{aligned}\sigma_{sr(CALC)} = \; & \alpha^{-1}_{(PR)}(\sigma_{m(QSCAT)} - \sigma_{r(PR)}) \\ & - (\sigma_{w(NCEP)} + \epsilon_n). \qquad (5)\end{aligned}$$

Supposing that σ_{sr} has a power-law dependence on the rain rate [1], we conclude that $aR^b_{(PR)} = \sigma_{sr(CALC)}$.

The only unknown on the right hand side of Eq. 5 is the error parameter ϵ_n. We estimate parameter to be the mean difference between $\sigma_{m(QSCAT)}$ and $\sigma_{w(NCEP)}$ for all observations where $R_{(PR)}$ is between 0 and 0.7 mm/hr in a given collocation region. The threshold of 0.7 mm/hr is the lower bound for the sensitivity of the TRMM PR rain measurements [3]. The observations below the threshold are practically unaffected by the rain, but are located near the heavier rain-contaminated regions, allowing for a fairly good approximation of the average error over the area containing rain.

Since $\sigma_{sr(CALC)}$ can take on negative values, a non-parametric estimation technique with an Epanechnikov kernel is used to give averaged values of $\sigma_{sr(CALC)}$ at discrete bins of $R_{(PR)}$. Next, using non-linear least-squares estimation, values for a and b are estimated as the best least-squares fit to the averaged values. In order to ensure robustness, all values of $\sigma_{sr(CALC)}$ that are further than 2 standard deviations from the model estimate are discarded and the estimation process is performed again.

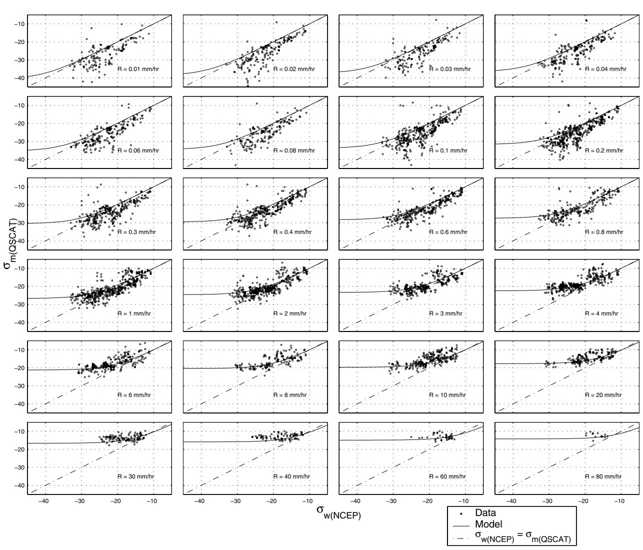

Fig. 2. Wind/Rain model versus $\sigma_{w(NCEP)}$ plotted with the actual QuikSCAT σ° data.

TABLE II

VALUES OF a AND b WHERE $\sigma_{sr} = aR^b$ FOR EACH COLLOCATION SUBSET AND POLARIZATION.

subset	a_{hpol}	b_{hpol}	a_{vpol}	b_{vpol}
1	1.86×10^{-3}	0.67	0.50×10^{-3}	0.75
2	2.20×10^{-3}	0.75	1.74×10^{-3}	0.45
3	2.18×10^{-3}	0.76	1.46×10^{-3}	0.49

Estimates of a and b are given in Table II for each collocation subset. The h-pol data is not very sensitive to the subset used. The v-pol data is more sensitive to the subset. We use the results from subset 1 in Section IV.

IV. VISUALIZATION OF THE MODEL/CONCLUSIONS

The full wind/rain σ° model is now parameterized by the wind σ° and the rain rate as

$$\sigma_m = (\sigma_w + aR^b)10^{-\frac{cR^d}{10}} + eR^f. \qquad (6)$$

This model is calculated for a range of rain rates and plotted against $\sigma_{w(NCEP)}$ in Fig. 2 for all h-pol observations. The data follows the model closely, helping validate the simple approach taken in this paper. The standard deviation of the error between the calculated and measured $\sigma_{(QSCAT)}$ values is less than 2 dB for both h-pol and v-pol data sets. Also, over 90% of all calculated measurements are within 3 dB of the measured QuikSCAT values.

Examining the shape of the curves in Fig. 2, we notice three regimes. Below a threshold in σ_w, the signal from the rain dominates, making the σ_m not very sensitive to the wind. In this regime, the rain almost completely corrupts the wind information. Above a higher threshold in σ_w, the measured backscatter follows σ_w very closely, indicating that the wind signal dominates. In between these two thresholds, the contributions from wind and rain are on the same order of magnitude. By incorporating a rain rate parameter into the wind retrieval process, wind estimates may potentially be improved in this "middle" regime. In addition, rain rate may be inferred from the scatterometer signal in both the middle regime and the regime where the rain signal dominates.

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