PROGRESS TOWARD VALIDATION OF QUIKSCAT ULTRA-HIGH-RESOLUTION RAIN RATES USING TRMM PR

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ABSTRACT

Although originally designed solely for wind retrieval, the QuikSCAT scatterometer has also proved to be a useful tool for rain retrieval. Resolution enhancement algorithms designed for QuikSCAT allow for ultra-high-resolution (UHR) (2.5 km) simultaneous wind and rain (SWR) retrieval. To enable SWR retrieval, we adjust the geophysical model function (GMF) to account for rain effects such as attenuation or increased backscatter due to increased surface roughness. Comparisons of a co-located data set show that QuikSCAT UHR SWR rain rates are comparable to those from Tropical Rainfall Measuring Mission Precipitation Radar (TRMM PR) but have higher variance. The noise level of the QuikSCAT rain estimates can be reduced by forming the reduced resolution rain rate estimates. As expected, rain estimates are significantly worse in regions where wind dominates the backscatter.

1. INTRODUCTION

The QuikSCAT scatterometer, launched by NASA in 1999, was designed to measure wind vectors over the ocean. An orbiting scatterometer is ideally suited for remote sensing of ocean winds due to the large coverage area and regular sampling pattern made possible in low earth orbits. Although QuikSCAT measurements are unaffected by cloud cover or time of day, accurate wind estimation requires that measurements are uncontaminated by other radar observable phenomena such as rain.

Rain contamination of QuikSCAT measurements is a significant problem if unaccounted for. Rain contamination typically results in overestimated wind speeds and strong directional bias during wind retrieval. Rain contamination can be mitigated by simultaneously estimating the rain rate and the wind vector using a model which compensates for rain effects. Such a model and a method for simultaneous wind and rain retrieval was proposed in [1] for QuikSCAT 25km conventional-resolution products.

Here we discuss the application of the rain model proposed in [1] to 2.5km UHR products produced using QuikSCAT data and the AVE resolution enhancement algorithm [2]. The application to 2.5km resolution requires several trade-offs which include: UHR rain model parameters, an improved UHR rain flag, computational efficiency, and optimal resolution for rain retrieval. To demonstrate the viability of SWR retrieval at UHR we address each of these issues and then briefly evaluate algorithm performance.

2. QUIKSCAT AND TRMM PR BACKGROUND

The QuikSCAT scatterometer measures the radar backscatter of the Earth's surface using a 13.4GHz dual-polarization rotating pencil-beam antenna. The nominal incidence angle for each polarization is 46° for horizontal polarization (H-pol) and 54° for vertical (V-pol). The swath region where there are both V-pol and H-pol measurements is termed the inner swath; this is the only part of the swath where rain retrieval is possible. Measurements of radar backscatter, termed σ^o, are used to estimate wind vectors via a maximum likelihood estimation technique whereby backscatter measurements are mapped to wind vectors through a GMF [3].

Simultaneous wind and rain retrieval is possible for the inner swath using QuikSCAT [1]. To properly calibrate the QuikSCAT rain model for SWR retrieval requires independent data sets. The development of the rain model uses measured rain data provided by the TRMM PR as the comparison rain data set and wind products from the National Centers for Environmental Prediction (NCEP) as the comparison wind data set.

TRMM PR provides rain data at a 4 km resolution with a narrower swath than QuikSCAT, but is limited to tropical latitudes. The validation data set we use is composed of QuikSCAT and TRMM PR measurements co-located to within 10 minutes. We compare the co-located QuikSCAT 2.5 km resolution rain data to a spatially interpolated TRMM PR data set. To obtain co-located wind data, NCEP winds were interpolated spatially and temporally to match QuikSCAT resolution and measurement times.

Validation of conventional resolution (25 km) QuikSCAT rain data has been studied previously [4]. However at UHR, several additional issues arise in SWR retrieval. Due to the signal processing implementation, QuikSCAT has essentially no range resolution, and because rain occurs up to an altitude of 6 km, the incidence angles used by QuikSCAT can cause up to 6 km of apparent horizontal spreading of the rain signal. The antenna spatial response and the resolution enhancement algorithm result in additional horizontal spreading of the rain signal, causing rain contamination of measurements in wind vector cells (WVCs) near rain events.

3. UHR RAIN MODEL

Scatterometer wind retrieval can be adapted for wind and rain estimation by modifying the geophysical model and likelihood function. Falling hydrometeors introduce several changes in the observed radar backscatter that must be accounted for in the model. Rain striking the ocean surface increases the surface roughness and observed backscatter. Atmospheric hydrometeors also cause attenuation of the surface backscatter signal in addition to volume scattering from the raindrops themselves. To sufficiently account for these effects, we adopt a widely used combined rain effect model

$$\sigma_o = \sigma_w \alpha_r + \sigma_e \tag{1}$$

discussed in [5] where σ_o is the observed backscatter, σ_w is the backscatter due to wind, α_r is the attenuation due to rain and σ_e is the effective rain backscatter.

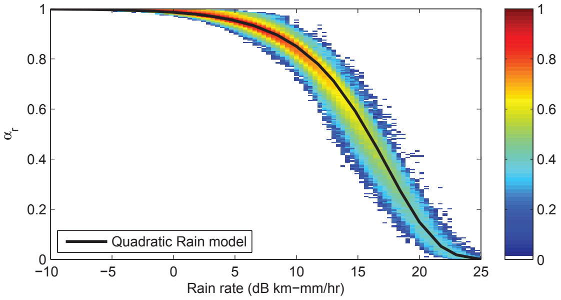

Fig. 1. Model for $\alpha_r(R_{dB})$ as a function of rain rate in dB km-mm/hr. The background shows a scatter density plot of the TRMM PR data used to derive the model.

We estimate the rain model parameters for QuikSCAT using the two independent data sets discussed previously: NCEP winds and TRMM PR rain rates. To ensure that σ^o values observed by QuikSCAT are temporally comparable to TRMM PR rain rates, we use a data set in which all QuikSCAT and TRMM PR measurements are within 10 minutes of one another. NCEP winds are only available at 6 hour intervals and at significantly lower resolution (25km), so we use both spatial and temporal interpolation to interpolate NCEP winds to the time and resolution of QuikSCAT.

The attenuation factor α_r model can be estimated directly using co-located TRMM PR measurements of path-integrated attenuation after compensating for QuikSCAT slant range. Figure 1 shows the attenuation factor and rain rate from TRMM PR and the resulting quadratic attenuation model.

To estimate the effective backscatter model we use the interpolated NCEP winds to estimate σ_w via the GMF, the measured backscatter σ_o, and the attenuation model. To reduce modeling error we attempt to use only rain-dominated measurements. The resulting data set of σ_e estimates as a function of rain rate is shown in Fig. 2 together with the quadratic rain model.

4. SIMULTANEOUS WIND AND RAIN RETRIEVAL

Simultaneous wind and rain retrieval is accomplished using maximum likelihood estimation to estimate the wind vector and rain rate that “explains” the observed backscatter. SWR retrieval differs from the wind-only retrieval method by using the combined rain effect model instead of the conventional wind-only model. The combined rain effect model is obtained by substituting the conventional wind-only GMF, $\mathcal{M}(S,\chi)$, for σ_w in Eq. 1 where S is the wind speed and χ is the relative wind direction. The rain model can then be written

$$\mathcal{M}_R(S,\chi,R) = \mathcal{M}(S,\chi)\alpha_r(R) + \sigma_e(R) \tag{2}$$

where $\alpha_r(R)$ and $\sigma_e(R)$ are the quadratic rain model terms and R is the rain rate in dB km-mm/hr. The log-likelihood equation can be written as

$$l(\mathbf{z}|S,\chi,R) = -\sum_k \ln(\varsigma_k) + \frac{1}{2}\frac{(z_k - \mathcal{M}_r(S,\chi,R))^2}{\varsigma_k^2} \tag{3}$$

where $\mathbf{z}$ is the vector of measured σ_o values, k is the measurement index, and ς_k is the model variance. As in wind-only retrieval, the local maxima of the wind-rain log-likelihood function are the SWR ambiguities.

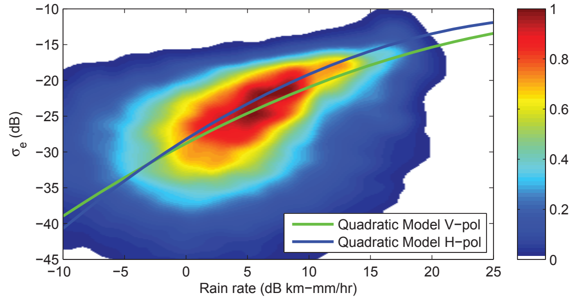

Fig. 2. Model for $\sigma_e(R_{dB})$ as a function of rain rate in dB km-mm/hr. The background shows a scatter density plot of the estimated σ_e for the co-located data set. Note that there is high variability as a function of rain rate.

To classify the wind and rain effects apparent in SWR retrieval, we divide SWR solutions into regimes. Regimes are determined by the ratio of the effective rain backscatter, $\sigma_e(R)$, to the model backscatter, $\mathcal{M}(S,\chi,R)$, for each solution. Regime 0 indicates a wind-dominated solution, regime 1 indicates that wind and rain backscatter are co-dominant, and regime 2 indicates a rain-dominated solution.

5. RAIN FLAG

Searching for maxima of the wind-rain log-likelihood function, Eq. 3, is computationally intense. To ease computation we adopt a simple rain flag to determine if there is rain in the WVC and therefore whether to use SWR or wind-only retrieval. The rain flag we adopt is calculated after performing wind-only retrieval. We use the most likely wind-only solution and the SWR log-likelihood function and rain model to determine if the given wind-only solution is more likely to have a non-zero rain rate.

This computation is performed by searching for a maximum of the SWR log-likelihood function in rain rate while keeping S and χ fixed according to the wind-only solution. If there is a more likely raining solution, i.e., a maxima exists in the rain rate domain, we flag the WVC as rain-contaminated and perform SWR retrieval. This simple rain-flagging method is what we term the rain likelihood flag (RLF). Figure 3 shows TRMM PR rain rates, QuikSCAT rain rates, and the RLF for a single co-location. Note that the RLF flags more WVCs than necessary and has diminished performance around small rain storms with low rain rates. As noted below, unlike conventional rain flags, this over-flagging is acceptable and desirable because the RLF is only used to indicate where SWR retrieval should be performed.

To demonstrate the effectiveness of this simple rain flagging technique, we evaluate the probability of missed detection (P_{md}) and the probability of false alarm (P_{fa}) for the RLF. Figure 4 shows the overall rain flag performance. The rain threshold on the x-axis is the TRMM PR rain rate in km-mm/hr used to define a rain event. A given rain threshold indicates that lower rain rates are considered non-rain events.

The false alarm rate for the RLF is relatively high regardless of the rain threshold. This is acceptable in this application of the RLF since it simply indicates rain is probable, therefore SWR retrieval should be performed. For rain events with high rain rates, the probability of missed detection decreases steadily. This indicates that it is

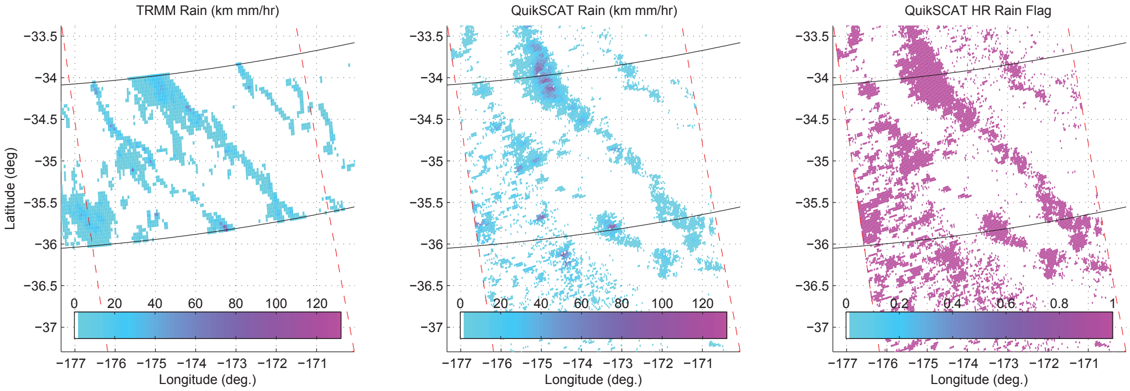

Fig. 3. TRMM PR rain rate (left), QuikSCAT rain rate (middle), and QuikSCAT RLF (right) for one overlapping region. TRMM PR swath edges are indicated by thick black lines; dashed lines indicate the edges of the processed QuikSCAT data. Although QuikSCAT fails to detect the lowest rain rates, the spatial correlation of the three data sets is quite apparent. The rain rate color scale for the left images ranges from 0 to 132 km-mm/hr.

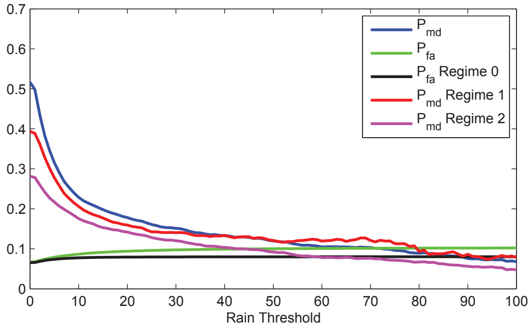

Fig. 4. Probability of false and alarm and probability of missed detection for the RLF as a function of rain threshold and regime. P_{md} is not included for regime 0 since when wind is dominant rain detection is known to be poor. The rain threshold is the rain rate which in each comparison indicates a rain event. The decreasing missed detection rate indicates that the RLF correctly identifies high rain rates in most cases.

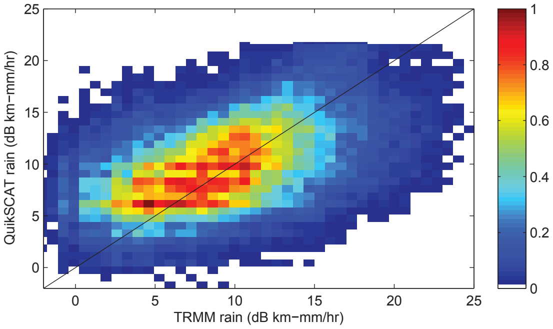

Fig. 5. Scatter density plot of TRMM PR rain rates and QuikSCAT retrieved rain rates. The equality line is shown for comparison. There is significant bias in QuikSCAT rains for both high and low rain rates.

rare for the RLF not to flag moderate to high rain rates. The probability of false alarm also increases with the rain threshold, which is not a concern since the RLF is always sensitive to lower rain rates and so false alarms can be triggered by lower, but significant, rain rates. As might be expected, the false alarm rate is lower for wind-dominated conditions and the missed detection rate is lower for rain-dominated conditions.

Some performance degradation of the RLF can be attributed to uneven beam-filling. Due in part to the resolution enhancement process, beam-filling can have some misleading effects. The QuikSCAT antenna spatial response is much larger than the pixel size at UHR, causing high rain rates to appear as lower rain rates spread across several WVCs. This can be noted in Fig. 3 where QuikSCAT appears to widen the north-south rain bands apparent in TRMM PR rain rates. Since the highest rain rates are typically localized to a few WVCs, the RLF missed-detection rate can be higher than expected due to beam-filling effects. It is possible to adjust the sensitivity of the RLF to further reduce the missed detection rate at the cost of the increasing the number of false alarms. This trade-off in the RLF performance is the subject of ongoing research.

6. SWR ACCURACY AND RESOLUTION

It has been demonstrated that SWR retrieval at conventional (25km) resolution can produce unbiased estimates of the measured rain rate but that there is significant variance in the estimates [1],[4]. At UHR the noise level of the QuikSCAT rain rates increases and bias is introduced. The bias is due in part to noise amplification due to resolution enhancement. Figure 5 shows the scatter density plot for QuikSCAT and TRMM PR rain rates at UHR. There is significant bias in both high and low rain rates; however, this bias can be corrected in large part by adjusting the rain model. The variance of the QuikSCAT rain estimates, which can exceed 20 dB (km-mm/hr)^2, may not be tolerable in many applications. To mitigate estimation noise, we consider resolution reduction.

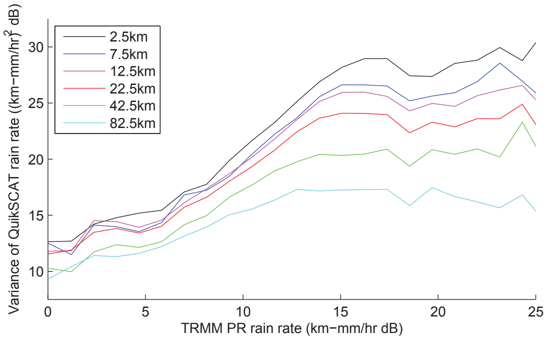

Fig. 6. Variance of QuikSCAT rain rate estimates as a function of TRMM PR rain rates at various resolutions for regimes 1 and 2. Note that resolution reduction is very successful at reducing the estimate noise particularly for moderate to high rain rates.

Reduced resolution measurement fields are produced by spatially averaging the resolution enhanced backscatter fields. The spatial average can be performed using a variety of methods but for this study we use uniform weights with 7.5km, 12.5km, 22.5km, 42.5km and 82.5km windows. Although spatial averaging reduces the effective resolution, SWR retrieval is still performed and reported using 2.5km WVCs.

As illustrated in Fig. 6, which shows QuikSCAT variance for regimes 1 and 2 at each resolution, reducing the resolution also reduces the QuikSCAT rain estimate variance. At higher rain rates resolution reduction becomes more effective.

Resolution reduction has minimal success in reducing the QuikSCAT rain rate bias. Fig. 7 shows the resulting bias in QuikSCAT estimates after reducing the resolution for regimes 1 and 2. Note that for some rain rates the 7.5km and 12.5 km resolutions reduce the variance, but in general the improvement over UHR is insignificant. However, it may be possible to develope a separate rain model for each resolution to more effectively reduce the bias. Resolution-dependent rain models are a subject of ongoing research.

Although QuikSCAT SWR rain estimates are certainly noisy, they do correspond quite well with TRMM PR rain rates and the correspondence is improved by reducing the resolution. By refining the rain model at all resolutions we anticipate a further reduction of the rain estimate bias and variance.

7. CONCLUSIONS

Despite significant bias levels in QuikSCAT rain rates, SWR estimates generally correspond with rain rates measured by TRMM PR. We have also demonstrated that rain estimates from SWR retrieval can be futher improved by reducing the effective resolution. While SWR retrieval is a significant computational increase when compared with wind-only retrieval, some of the increase can be mitigated using the RLF. Although SWR retrieval rain estimates are noisier than those obtained by TRMM PR, our results indicate that QuikSCAT can be used as a reliable instrument to increase daily rain measurements and extend measurement coverage into the polar regions. Research is ongoing to refine the rain model to produce unbiased rain estimates and to further reduce the computational cost of SWR retrieval.

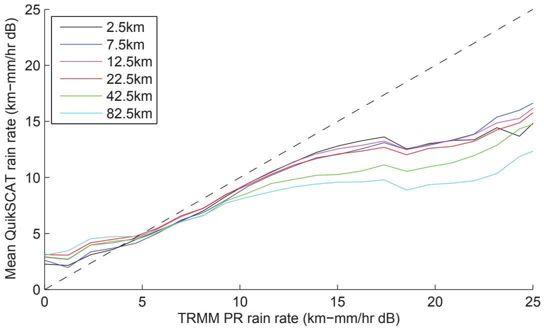

Fig. 7. Mean QuikSCAT rain rate estimates as a function of TRMM PR rain rates at various resolutions for regimes 1 and 2. Note that rather than reducing the bias, resolution reduction increases bias, particularly for low rain rates. The dashed equality line is shown for comparison. Interestingly, reducing resolution has only a small effect on bias.

8. REFERENCES

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