Simultaneous Wind and Rain Retrieval for ERS Scatterometer Measurements

Congling Nie and David G. Long
Electrical and Computer Engineering Department
Brigham Young University Provo Utah 84602
Email: nie@mers.byu.edu

***Abstract*—Using collocated ESCAT, TRMM PR, and ECMWF data, the effects of rain on the ESCAT wind-only retrieval has been evaluated. For high incidence angle measurements, the additional scattering of rain causes estimated wind speeds to appear higher than expected. It is also noted that the selected directions of the rain-corrupted wind vectors generally point along swath in heavy rain, regardless of the true wind. A simultaneous wind/rain retrieval method (SWRR) is developed using a simple wind/rain backscatter model. Validation shows that SWRR method significantly improves the wind vector estimates at high incidence angles in heavy rain cases. It also provides an estimate of the surface rain rate.**

I. Introduction

The wind scatterometer mode (ESCAT) of the active microwave instrument (AMI) on the European Remote Sensing (ERS) satellites was designed to measure the surface wind speed and direction over the ocean, which provides high quality, global coverage of ocean surface winds. In non-raining areas, scatterometer backscattering is principally from gravity-capillary waves (Bragg waves) generated by the instantaneous surface wind stress. In a rainy area, the σ° from ocean surface is altered by rain. Falling raindrops in the atmosphere attenuate and scatter the scatterometer signal. For C-band, these two effects are considered negligibly small except for heavy rain. Raindrops striking the water create various splash products including rings, stalks and crowns. These splash products have different contributions to the backscattering, which varies with incidence angle and polarization. Raindrops impinging on the sea surface also generate turbulence in the upper water layer which attenuates the short gravity wave spectrum. The net effect of the rain on the sea surface depends on the wavelength of the water waves and is still not well understood. For incidence angle higher than 30°, the net effect of rain generally enhances the backscatter [1]. A wind/rain backscatter model has been proposed to model the rain effect on the ESCAT measurements at incidence angle higher than 40° in [1].

It is shown in [1] that the rain has significant impact on the high incidence angle data under medium to heavy rain cases. Since the wind-only GMF does not account for the contribution of rain, the conventional wind-only wind retrieval method introduces errors in the wind estimation. For the Ku-band QuickSCAT/SeaWinds scatterometer, rain contamination causes overestimated wind speeds and the retrieved wind to align with the cross-swath direction [2], [4]. Having different antenna-look geometry and rain sensitivity, the wind-only retrieved wind vectors for ESCAT have different error features. Using collocated data from ESCAT, Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR), and numerical predicted wind fields (ECMWF), rain effect on the traditional wind-only wind retrieved wind direction and wind speed is evaluated and analyzed.

To improve the wind retrieval for rain-corrupted data, we apply the C-band wind/rain backscatter model in [1] in the wind retrieval procedure, developing a simultaneous wind/rain retrieval method for ESCAT. The method retrieves surface rain rates and wind vectors simultaneously using an adjusted MLE. Because only high incidence angles are usable in the model, we implement the simultaneous wind/rain retrieval for data at incidence angles greater than 40°. It is noted that the rain effect on ESCAT low incidence angle data is small, which makes the conventional wind-only retrieval relatively invulnerable to rain.

II. Effect of Rain on Conventional Wind-only Retrieval Method

For ESCAT, the wind retrieval process involves inversion of the GMF given the σ° triplet measurements. Here, the GMF inversion method is based on minimization of a maximum likelihood estimator (MLE) given the surface wind speed s and wind direction d, assuming Gaussian noise and independent samples,

$$MLE(\sigma^\circ|s,d)=\sum_{i=1}^{3}\frac{(\sigma_i^\circ-M_i(s,d,\phi_i,\theta_i))^2}{(\varsigma_i(s,d))^2} \qquad (1)$$

where σ_i° is the measured σ° value, M is the GMF, s is the wind speed, d is the wind direction, ϕ_i is the azimuth angle of the instrument, and θ_i the incidence angle for each measurement. The index i indicates antenna beam position. ς_i^2 is the measurement variance, which is a measure of the noise in σ°. ς_i is caused by the uncertainty in the GMF, signal noise due to fading, thermal noise, and beam-filling effects. It can be expressed as $\varsigma(s,d)=K_pM(s,d,\phi,\theta)$ where K_p is a normalized standard deviation of the data. K_p can be defined as a combination of K_{pm}, the normalized standard deviation of the GMF, and K_{pc}, the normalized standard deviation of the communication or signal noise.

Minimization of the MLE often results 1 to 4 local minima due to the symmetry in the GMF and uncertainty from the noise. Each local minimum represents a possible wind vector solution, which is named an ambiguity. The two primary ambiguities correspond to the two most likely solutions, which differ by about 180° in direction. The occurrence and location of the other minima often depend on the normalization [3]. A method proposed in [3] transforms the measurement to a z space by the form $z = (\sigma^\circ)^{0.625}$, resulting in a circular distribution that is ideal for inversion.

After all the ambiguities are determined at each WVC, an ambiguity removal procedure is implemented to select one unique solution. In general, the ambiguity removal procedure uses median filtering and nudging techniques to choose the best solution. The European Space Agency uses short-range ECMWF forecast fields as the nudging wind field. For ESCAT on ERS 1/2, a selection filter is implemented to iteratively select the ambiguity at each WVC, based on a weighted average of the differences from the surrounding WVCs. At each WVC, the selection filter is nudged by the ECMWF model first guess wind vectors [3].

To show the rain effects on wind-only retrieval wind estimates, the statistics of wind speed and wind direction retrieved from rain-free WVC and rain-corrupted WVC for different WVC groups and rain rate ranges are investigated. It is noted that TRMM PR rains used as a reference in this paper are antenna-weighted average rain rates over the ESCAT footprint [1]. Fig. 1 shows the mean of difference between the selected wind speed ambiguity and collocated ECMWF wind speed ($Spd_{ERS} - Spd_{ECMWF}$) under conditions of rain-free, and over 3 mm/hr rain rate for four WVC bins. For rain-free conditions, no bias appears. Under moderate to heavy rain, the bias of selected wind speed estimates increases from low WVCs to high WVCs. Furthermore, the densities of the selected wind speed and wind direction for rain-free and rain-corrupted ($\geq$3 mm/hr) conditions and ECMWF wind speed for rain-free data are compared in Figs. 2 and 3 for the same WVC groups. It is noted that the densities of selected wind speed and ECMWF wind speed are consistent for rain-free conditions, while the mean of density gradually shifts to right from low to high WVCS for rain-corrupted conditions. It is noted that the density of the rain-free selected wind direction agrees with the density of the collocated ECMWF wind direction. For rain-corrupted data, the along-swath bias become more serious for higher WVCs, while it is not obvious for WVCs 1 to 5.

III. Simultaneous wind/rain retrieval

As analyzed above, the conventional wind-only retrieval method produces errors in estimating the wind velocities from rain-corrupted data. To correct the rain-induced errors, a simultaneous wind/rain retrieval method (SWRR) is developed and analyzed in this section. The SWRR method is based on the simple additive wind/rain backscatter model proposed in [1], which represents the rain-modified measured backscatter σ_m

$$\sigma_m = \sigma_{wind}\alpha_{atm} + \sigma_{eff} \tag{2}$$

where σ_m is the ESCAT-measured σ°, σ_{wind} is the wind-induced surface backscatter, α_{atm} is the two-way rain-induced atmospheric attenuation, and σ_{eff} is the effective rain

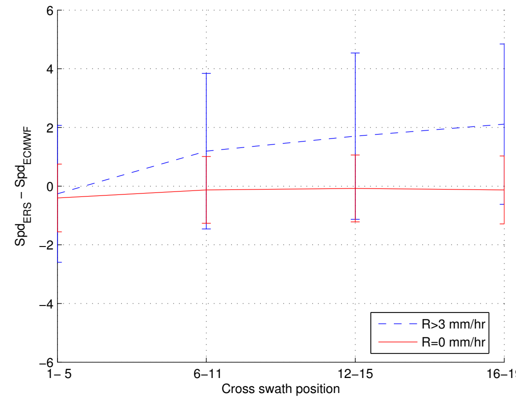

Fig. 1. The mean of difference between the wind-only retrieval method selected wind speed ambiguity and collocated ECMWF wind speed under conditions of rain-free, and over 3 mm/hr rain rate for different WVC bins.

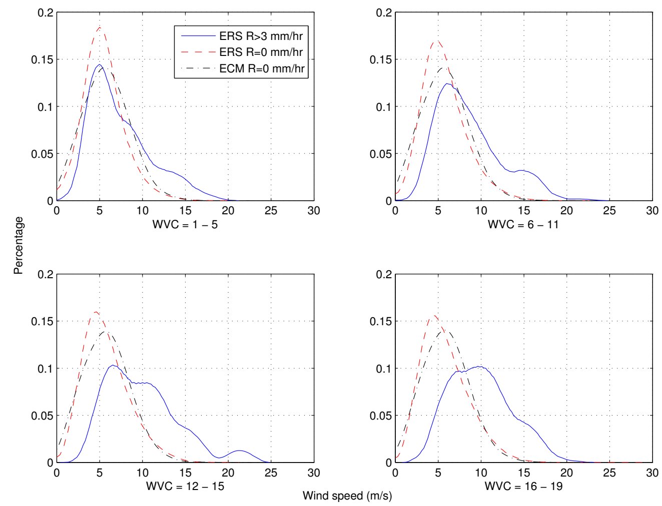

Fig. 2. Densities of the wind-only method selected wind speeds for rain-free and over 3 mm/hr rain rate and collocated ECMWF wind speeds for different WVC bins.

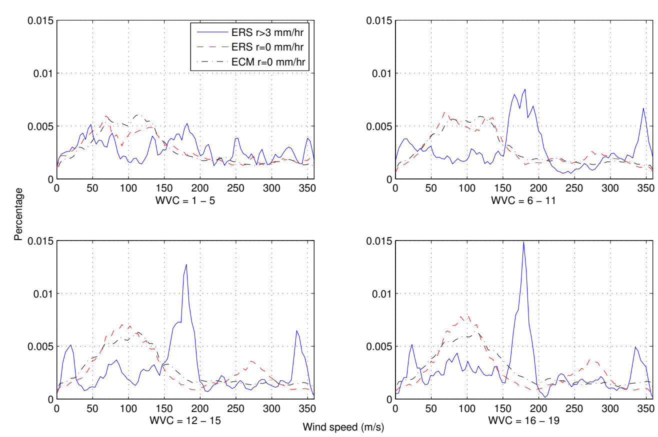

Fig. 3. Densities of the wind-only method selected wind directions for rain-free and over 3 mm/hr rain rate and collocated ECMWF wind directions for different WVC bins.

backscatter due to the attenuated surface perturbation and the rain-induced atmospheric scattering [1], [4]. α_{atm} and σ_{eff} are related with surface rain rate R in mm/hr by empirically derived linear or quadratic log-log models [1]. The MLE likelihood function of equation (1) is written as

$$MLE(\sigma^\circ|s,d) = \sum_{i=1}^{3} \frac{(\sigma_i^\circ - M_i'(s,d,\phi,\theta,R))^2}{(\varsigma_i'(s,d))^2} \quad (3)$$

where M' is GMF for wind and rain. ς'^2 is the variance of the wind/rain measurement, which is approximately expressed as [5]

$$\varsigma'^2 \approx (1+K_{pc}^2)(M^2\alpha_{atm}^2 K_{pm}^2 + \sigma_{eff}^2 K_{pe}^2) + K_{pc}^2(\sigma_{eff} + M\alpha_{atm})^2. \quad (4)$$

The term K_{pc} is computed for each WVC and stored in the ERS product. The value for K_{pm} varies between about 0.14 and 0.22, depending on the incidence angle [6]. The mean value of K_{pm} is about 0.2, 0.14, and 0.17 for measurements of 35 to 45 degree, 45 to 55, and 55-65 degree incidence angles, respectively [6]. K_{pe}, the normalized standard deviation of σ_{eff}, is assumed to be 0.2.

Wind velocity and rain rate estimates can be retrieved simultaneously by minimizing the MLE for s, d, R given the triplet measurements. For simplicity, the normalization method proposed in [3] is not used in this research, though the normalization method may further improve the accuracy of the SWRR. Similar to the wind-only retrieval method, minimization of the MLE results to several ambiguities with a corresponding wind speed, wind direction, and rain rate. To determine a unique solution, an ambiguity removal method is implemented. Following the method proposed in [5], all ambiguities are used for nudging and median filtering is performed using modified vector-median filter. Collocated ECMWF wind data is used for nudging.

IV. Validation and Example

To validate SWRR, SWRR-retrieved wind/rain estimates are compared with collocated TRMM PR surface rain rate and ECMWF wind fields. A scatter density plot displaying the SWRR retrieved rain rate and the TRMM PR rain rate within ± 15 minutes is shown in Fig. 4. Because the plot is in log-log space, zero rain rates in either of the SWRR or TRMM PR datasets are not displayed. Of the rain rates that are zero in one of the two datasets, over 95% have relatively small rain rates ($\leq$ 3 mm/hr) in the other dataset. It is noted that the SWRR rain rate and TRMM PR rain rate have a relatively high correlation, although the SWRR rain rates have considerable scatter compared with the PR rain rates. It is also noted that SWRR rains are biased high for low rain rates ($\leq$ 2 mm/hr), showing that SWRR method is less accurate for estimating low rain rates.

Figs. 5 and 6 present scatter density plots of SWRR and wind-only method selected wind speed versus ECMWF wind speed for different rain fraction (F) bins. The rain fraction (F) is defined as the effective rain backscatter divided by the

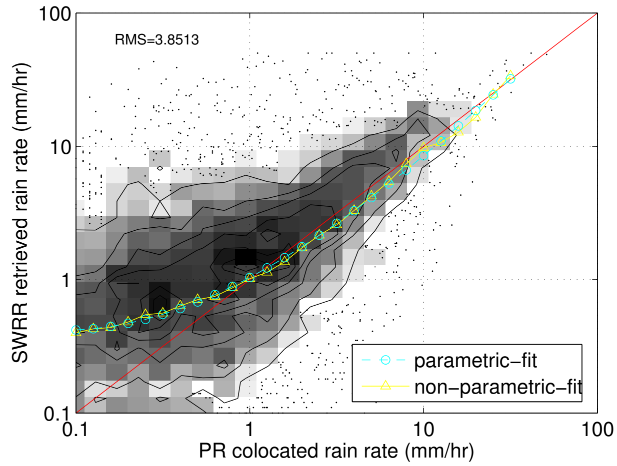

Fig. 4. Scatter density plot of SWRR rain rates versus TRMM PR-derived effective weighted average rain rates. Non-parametric fit and best quadratic fit to TRMM PR rain rate (log space) are also shown.

total model backscatter given the ambiguity selected rain rate and vector wind, averaged over the measurements [5]. It is noted that when F is less than 50%, the performances of the SWRR and wind-only method are close, while the wind speed estimates of SWRR is somewhat noisier. When F is over 50%, wind-only retrieval overestimates the wind speed and the root mean square error (RMS) of wind-only method is much higher than the SWRR method. Figs. 7 and 8 show scatter density plots of SWRR and wind-only selected wind direction versus ECMWF wind direction for different rain fraction (F) bins. It is noted that when F is over 50%, the wind-only retrieval method retrieves wind direction at essentially only the along swath direction, while the SWRR wind direction estimates are much closer to the true directions.

The validation shows that the SWRR method significantly improves the wind vector estimates under the conditions of heavy rain. For low to medium rain cases, the performance of SWRR is close to the wind-only method. In the following, we examine a collocated ESCAT/PR example. Fig. 9 shows the ESCAT-derived wind vectors for both SWRR and wind-only retrieval, along with the ESCAT-derived rain rates and the collocated TRMM PR-derived effective weighted average rain rates. In heavy rain areas, wind-only retrieval exhibits many rain-induced features that are corrected by the SWRR. The most obvious of these features are the wind-only-retrieved wind vectors pointing along swath.

V. Conclusion

Using collocated ESCAT, TRMM PR, and ECMWF data, the effects of rain on the ESCAT wind-only method have been examined. For high incidence angle measurements, the additional scattering of rain causes estimated wind speeds to appear high. It is also noted that the selected directions of the rain-corrupted wind vectors generally point along swath in heavy rain, regardless of the true wind. Since the rain-induced backscatter is small for low incidence angle data, rain has

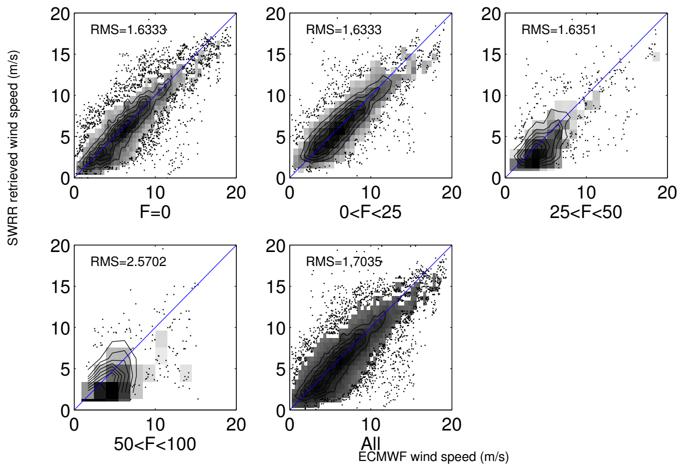

Fig. 5. Scatter density plot of the SWRR-retrieved wind speeds vs. ECMWF wind speeds for various rain fraction bins.

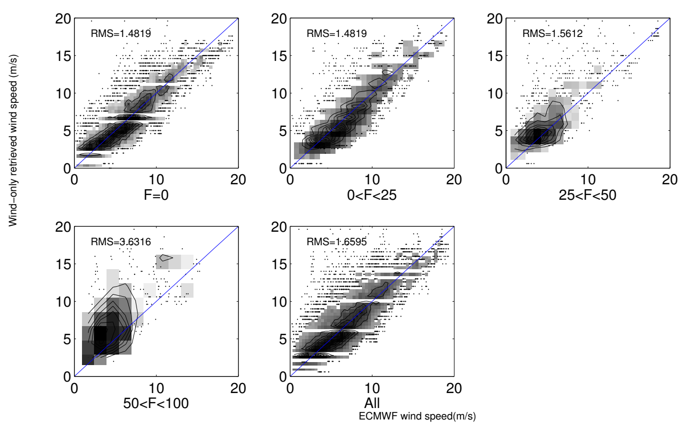

Fig. 6. Scatter density plot of the wind-only-method-retrieved wind speeds vs. ECMWF wind speeds for various rain fraction bins.

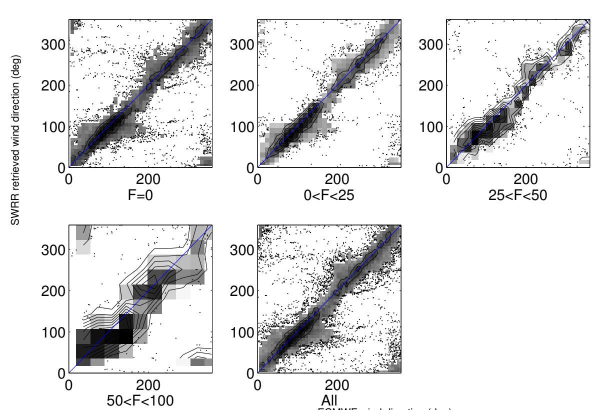

Fig. 7. Scatter density plot of the SWRR-retrieved wind directions vs. ECMWF wind directions for various rain fraction bins.

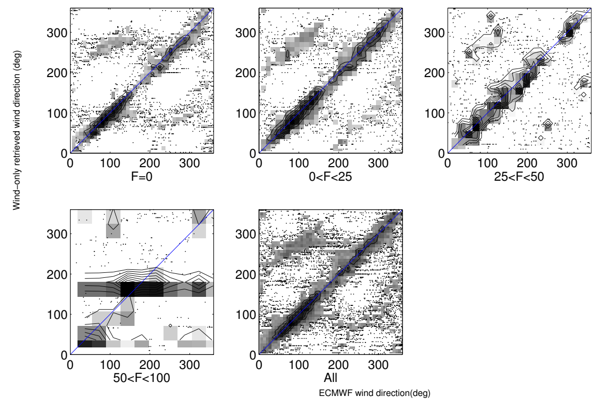

Fig. 8. Scatter density plot of the wind-only-method-retrieved wind directions vs. ECMWF wind directions for various rain fraction bins.

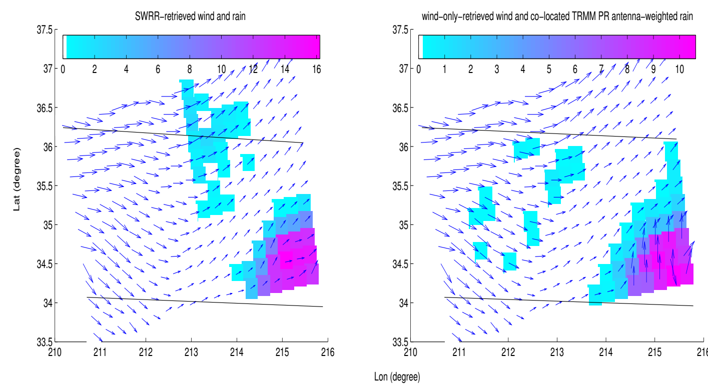

Fig. 9. a) ESCAT SWRR-retrieved wind/rain. b) ESCAT wind-only retrieval with collocated TRMM PR-derived effective weighted average rain rates. The lines show the PR swath.

little effect on the retrieved wind at low incidence angles. A simultaneous wind/rain method is developed using a simple wind/rain backscatter model. Validation shows that SWRR method significantly improves the wind vector estimates at high incidence angles in heavy rain cases. It also provides an estimate of the surface rain rate.

References

[1] Congling Nie and David G. Long, "A C-band Wind/Rain Backscatter Model", *IEEE Trans. Geosci. Remote Sensing*, Vol. 45, No. 3, pp. 621-631, 2007.

[2] J. N. Huddleston and B. W. Stiles, "A multi-dimensional histogram rain flagging technique for Sea Winds on QuickSCAT", in *Proc. IGARSS.*, Vol. 3, pp. 1232-1234, Honolulu, HI, 2000.

[3] A. C. M. stoffelen and D. L. T. Anderson, "Scatterometer data interpretation: measurement space and inversion", *J. Atmos. Oceanic Technol.* Vol. 14, pp. 1298-1313, 1997.

[4] D. W. Draper and D. G. Long, "Evaluating the effect of rain on SeaWinds scatterometer measurements," *J. Geophys. Res.*, vol. 109, no. C12, pp. C02005.1-C02005.12, Feb. 2004.

[5] D.W. Draper and D.G. Long, "Simultaneous Wind and Rain Retrieval Using SeaWinds Data," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 42, No. 7, pp. 1411-1423, 2004.

[6] P. E. Johnson, D. G. Long, T. E. Oliphant, "Geophysical modeling error in wind scatterometry," In *proceeding of the International Geoscience and Remote Sensing Symposium (IGARSS),* vol. 3, pp. 1721-1723, IEEE, 1996.