Non-Uniform Beamfilling Within the Context of QuikSCAT Wind Estimation

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Abstract—SeaWinds on QuikSCAT is a microwave scatterometer designed to measure near surface vector winds over the earth’s oceans. Rain within the field of view of the scatterometer induces errors in the wind estimates. The relatively high spatial variability of rain rate increases the difficulty of compensating for its effects. These complications resultant from the high spatial variability are referred to as the beamfilling problem. A QuikSCAT algorithm for simultaneously retrieving the vector winds and rain rate information was developed by Draper and Long[1]. This paper explores the non-uniform beamfilling effect of rain cells on QuikSCAT wind speed estimates using both the standard (wind only) processing and the simultaneous wind/rain processing.

I. INTRODUCTION

Near-surface ocean wind is a crucial element of sea-air interaction, global energy transport, and ocean circulation. Accurate knowledge of ocean winds has proven useful in understanding weather patterns and global climate. It also aids in researching factors contributing to phenomena such as El Nino and changes in the polar ice caps, and studying the long term effects of deforestation. Large scale measuring of near-surface ocean winds has long been one of NASA’s goals, as traditional methods such as buoys and ships fail to provide accurate global coverage.

A. QuikSCAT

NASA’s SeaWinds on QuikSCAT mission is designed to measure near-surface ocean winds. It covers nearly 90% of the earth’s surface daily with a 1900 km swath and approximately 25 km resolution. The SeaWinds scatterometer was launched aboard the QuikSCAT satellite on June 19, 1999. Scatterometers are specialized radars that infer near-surface ocean vector winds by bouncing electromagnetic signals off the surface and interpreting the return (normalized radar cross-section, $\sigma^\circ$) using an empirical model function. They are accurate in most observation conditions. Scatterometers can peer through cloudy and clear skies both day and night to retrieve measurements typically accurate to within 2 m/s.

The standard wind retrieval algorithm requires multiple ‘looks’ of the same location to invert the geophysical model function. These independent observations are acquired at different azimuth angles, thus yielding direction information as well as speed. Standard processing does not include rain rate as a model parameter.

Draper and Long extended the geophysical model function to include rain rate as well as wind speed and direction[1]. The effect of rain on $\sigma^\circ$ is modeled according to

$$\sigma_m = \sigma_w \alpha_r + \sigma_e$$

where $\sigma_m$ is the measured backscatter, $\sigma_w$ is the backscatter component due to wind, $\alpha_r$ is the two-way atmospheric attenuation from falling rain, and $\sigma_e$ is the effective rain backscatter due to surface perturbation and atmospheric scattering.

B. TRMM

Rain rate information is obtained from the Tropical Rainfall Measuring Mission (TRMM) and co-located temporally and spatially to QuikSCAT wind speed estimates. TRMM provides three-dimensional rain data through the first satellite based precipitation radar (PR). The PR scans the tropical regions of the earth (about $\pm 36^\circ$ latitude) with a resolution of approximately 4.34 km. Measurements are made over land and oceans with a 247 km swath.

C. Non-Uniform Beamfilling

Rain within the QuikSCAT observation is one of the challenges in obtaining universally accurate wind estimates. Rain affects the $\sigma^\circ$, and in turn the wind estimate. The high spatial variability of rain rate relative to the sensor footprint size induces errors referred to as partial or non-uniform beamfilling (NUBF) errors. They arise from irregularly weighted averaging over the $25 \times 25$ km QuikSCAT aperture function. Most rain cells average about $5 \times 5$ km or less[2] and do not fully or uniformly fill the larger QuikSCAT antenna footprint (see Figure 1). Since they are generally of the same order as the 4.3 km TRMM footprint, TRMM will better resolve the smaller scale details of rain events, although it too is known to suffer from NUBF effects[3].

II. ANALYSIS

Through co-location of QuikSCAT wind estimates with TRMM PR data, we can observe the effects of rain on the QuikSCAT wind retrieval algorithm. Although it is difficult to isolate the NUBF effects from other rain induced errors, we observe that rain rate—as estimated by TRMM—does vary spatially at a smaller scale than the QuikSCAT footprint. We also observe higher variability of wind speed estimates within rainy areas.

To further explore the NUBF effect, we simulate several wind vector cells and model the NUBF effect as added variance in the $\sigma^\circ$ value. We observe the resultant wind-only estimates and compare with the simultaneous wind/rain estimates.
Fig. 1. Relative sensor footprint sizes. The QuikSCAT measurement footprint is much larger than that of TRMM. The smaller rain cells do not fully or uniformly fill the QuikSCAT footprint (nor occasionally the TRMM footprint) resulting in non-uniform beamfilling (NUBF) errors.

A. Co-located TRMM / QuikSCAT observations

A near simultaneous observation of the ocean surface around 7°N and 65°E is explored for NUBF conditions. This observation is co-located temporally to within one minute. Figure 2 shows the position of the co-location and the wind field estimated by QuikSCAT. In this figure, arrows indicate wind direction and colors indicate wind speed. Figure 3 overlays the co-located TRMM rain rate data. The band running across the figure indicates the TRMM swath with part of its extent shaded for rain rate. The dots indicate only the centers of the QuikSCAT wind vector cell (WVC) locations, not their observation area. The WVC’s are sized to fill the prescribed area. With this in mind, we observe that many features seen by TRMM in the rain field are clearly smaller than the QuikSCAT footprint size. In comparing Figures 2 and 3, we observe that the rain’s effects on wind speed are faintly evident in the QuikSCAT wind field.

B. Simulation

To visualize the effects of irregularly weighted footprint averaging, we perform a much simplified simulation of rain rate retrieval. A 100 sample Gaussian aperture function is generated. Two identical 10 sample rain cells are placed within the simulated footprint. The first is placed at the edge of the half-power beamwidth of the aperture (Figure 4) and the second is placed at the center of the footprint (Figure 5). The true average rain rate across each footprint is 0.05 (unitless). However, the actual retrieved rain rate is 0.0333 for the first case and 0.0493 in the second case. This is clearly a significant simplification of the retrieval process. We have discounted the model function entirely as rain is not directly measured. Still, it appears reasonable that in absence of a more sophisticated model, we can treat the effects of non-uniform beam filling as an added variance in the directly measured parameter, \( \sigma_o \). Proceeding under this premise, we develop a more sophisticated simulation.

Simulating NUBF effects as additional variance in \( \sigma_o \), we set up several WVC’s for wind retrieval. Parameters including latitude, longitude, WVC number, and observation orientation for each of the QuikSCAT 'looks' are derived from actual wind vector cell measurement conditions. Wind speed, wind direction, and (uniform) rain rate are all set at runtime. We process the parameters in the geophysical model function to obtain an underlying normalized radar cross section, \( \sigma_o \), for each QuikSCAT observation within the WVC. An additional variance is added to the \( \sigma_o \) value for each independent QuikSCAT observation simulating the NUBF effects, and 500 realizations of wind retrieval with different measurement
noise are processed under these conditions. The mean and standard deviation of these 500 realizations are recorded. This procedure is repeated for 60 cases of NUBF error. A selection of wind speeds, wind directions, and rain rates were simulated.

The errors in wind speed and wind direction are observed.

1) Speed Error: The mean and standard deviation of wind speed error are plotted as a function of true wind direction under different conditions. The error bars indicate one standard deviation for the 60 realizations of NUBF error. The first retrieval is carried out for a WVC with true wind speed of 15 m/s and integrated rain rate of 1 km-mm/hr. In this case the backscatter from the wind, $\sigma_w$, dominates that of the rain, $\sigma_r$. We see that both the wind only and the simultaneous wind/rain algorithms perform well. Both exhibit near zero mean speed error across the range of wind directions simulated. The standard deviation of the speed error is higher for simultaneous wind/rain retrieval than for wind only retrieval under these conditions—especially for near-cross-track ($\sim 90^\circ$) winds.

The second retrieval is implemented for a WVC with true wind speed of 7 m/s and an integrated rain rate of 7 km-mm/hr. In this case, the backscatter from the rain, $\sigma_r$, is nearer the magnitude of the wind backscatter, $\sigma_w$. Here, the simultaneous wind/rain retrieval performs much better on average than does wind only retrieval. Simultaneous retrieval once again exhibits nearly zero mean error, while the wind only algorithm exhibits much higher mean error—especially for near-along-track ($\sim 180^\circ$) winds. Once again, the standard deviation of the wind speed error is generally greater for simultaneous retrieval than for wind only—especially for near-cross-track winds.

2) Direction Error: The mean and standard deviation of wind direction error is plotted as a function of true wind direction under the same conditions as above. For case 1, simultaneous retrieval exhibits much lower mean error than wind only retrieval. The standard deviation of direction error for this case is also generally lower for simultaneous retrieval. With the higher relative rain rate in case 2, the mean direction error is once again much better for simultaneous wind/rain retrieval than for the wind only algorithm. The standard deviation of error is once again higher for simultaneous retrieval, however.

III. Conclusion and Future Work

Non uniform beamfilling is an important source of error for QuikSCAT wind and rain retrieval. NUBF errors occur as a
Fig. 8. Wind direction error case 1. The mean (top) and standard deviation (bottom) of the wind direction error is plotted for simultaneous wind/rain (dashed) and wind only (solid) retrieval. Error bars indicate one standard deviation of the 60 NUBF error realizations for each true wind direction simulated. True wind speed: 15 m/s. Integrated rain rate: 1 km-mm/hr.

Fig. 9. Wind direction error case 2. The mean (top) and standard deviation (bottom) of the wind direction error is plotted for simultaneous wind/rain (dashed) and wind only (solid) retrieval. Error bars indicate one standard deviation of the 60 NUBF error realizations for each true wind direction simulated. True wind speed: 7 m/s. Integrated rain rate: 7 km-mm/hr.

result of the relatively high variability of rain rates compared to the QuikSCAT observation resolution. Characterizing the effects of non-uniformly beamfilled rain on QuikSCAT wind and rain estimation is a complicated task. This paper summarizes the preliminary steps taken in this regard. In general, the simultaneous wind/rain retrieval developed by Draper and Long exhibits lower mean wind speed and wind direction error, but higher standard deviation of error than does the wind only algorithm.

There are many avenues for additional improvement. The analysis of a larger set of QuikSCAT/TRMM co-locations would prove useful. Relative orbit geometries severely limit the number of co-locations, however. We would also like to explore the use of the NEXRAD weather radar network for exploring NUBF effects on QuikSCAT. NEXRAD is a high-resolution land-based weather radar that would provide additional storm detail. Its marine coverage only extends a short distance from the coast, however, so co-located data is once again limited.

Additional beamfilling-type effects come into play because of QuikSCAT’s unique observation conditions. Wind retrieval is carried out on a wind vector cell basis. Several independent observations are included in each WVC retrieval, however. These observations, while nearby one another, do not view exactly the same area. This creates the possibility that one ‘look’ may observe rain within it’s field of view, while another ‘look’ within the same WVC may not. This has been termed the WVC-filling[1] problem (Figure 10). We would like to further explore and characterize this potential error source.

REFERENCES