

Applicability of Conventional Scatterometer Model Functions to High-resolution Wind Retrievals: The Effect of Spatial Averaging

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ABSTRACT

The automated retrieval of high-resolution wind speed maps from synthetic aperture radar (SAR) images is reaching a level of maturity that it is nearing operational capability. Under the sponsorship and guidance of the National Oceanic and Atmospheric Administration (NOAA), the Johns Hopkins University Applied Physics Laboratory has been routinely processing SAR images from Radarsat and Envisat into high-resolution ocean wind maps. In this paper, we outline this processing and consider candidate SAR wind speed model functions. The relationship between wind speed and direction to normalized radar cross section (NRCS) has been developed in the context of buoy and model comparisons with NRCS measurements from the ERS-1/2 scatterometers and other measurements. In most of these cases, the NRCS measurements have been averaged over 25-km or larger diameter areas. Given that the relationships are non-linear, the question arises as to whether these model functions are applicable to very high-resolution NRCS measurements. We address this question by comparing wind speed retrievals over different averaging areas with each other and with model wind estimates. We find little or no bias between high-resolution and large-area average wind speed retrievals. We conclude that the conventional model functions are applicable to SAR wind speed retrievals.

Keywords: SAR, wind speed, scatterometer, spatial averaging.

1 INTRODUCTION

Since the late 1990s, the Johns Hopkins University Applied Physics Laboratory (JHU/APL) has been routinely converting high-resolution SAR NRCS measurements into wind speed maps from Radarsat SAR data. More recently, we have been similarly processing Envisat SAR images into wind speed. The processing is performed using the APL/NOAA SAR Wind Retrieval System (ANSWRS) built using IDL (Interactive Data Language). The entire system is automated and regularly produces wind speeds images in near-real-time. Wind speeds images are posted on the web both as images and Google Earth files.

The relationship between wind speed and direction and NRCS takes the general form (with some slight deviations) of

$$\sigma^0 = A(\theta)U^\gamma(\theta)[1 + B(U, \theta)\cos\phi + C(U, \theta)\cos 2\phi] \quad (1)$$

where σ^0 represents NRCS, U is wind speed at 10-m altitude for a neutrally-stratified atmosphere, θ is the radar incident angle with respect to the mean surface, and ϕ is the relative angle between the wind direction and the radar look direction. A , γ , B , and C are parameters that can, in general, be function of wind speed and incident angle. The salient feature of this relationship is that given a wind speed and direction it is possible to compute an associated NRCS. However, the inverse is not true. A particular NRCS is associated with any number of different wind speed and direction pairs. However, if wind direction is known then Equation 1 can be inverted to estimate wind speed. It is also important to note that the maximum NRCS occurs when the radar looks into the wind ($\phi = 0^\circ$). There are NRCS minima when the wind direction and the radar look direc-

tion are perpendicular ($\phi = \pm 90^\circ$). Another smaller maximum in NRCS exists when the radar is looking downwind ($\phi = 180^\circ$).

By default, the ANSWRS software uses wind directions from the Naval Operational Global Atmospheric Prediction System (NOGAPS) or other numerical weather models to perform the inversion to wind speed. Alternatively, wind directions can be derived from linear features in the image. Both approaches have their merits and perhaps the best solution is to integrate the approaches. Wind directions derived from features in the image can also be accommodated in the ANSWRS software. Wind speed retrievals have been validated against buoys to within a standard deviation of 1.76 m/s [1]. When compared against QuikSCAT scatterometer wind retrievals and using QuikSCAT directions to initiate the wind speed retrievals, Radarsat SAR retrievals have been shown to agree to a standard deviation of 1.25 m/s [2].

ANSWRS is now deployed at a number of institutions besides JHU/APL and NOAA, including the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS), the Alaska Satellite Facility (ASF), and Risø National Laboratories in Denmark.

2 MODEL FUNCTION COMPARISONS

There is an entire body of literature on the relative merits of model functions relating wind speed and direction to NRCS at C-band [3-8]. These were developed in the context of the C-band scatterometer on ERS-1 and ERS-2 operating at VV polarization. Until recently, the CMOD4 model function was the mostly commonly used model function [8]. Radarsat-1 operates at C-band HH polarization for which there was no well-understood model function. To process Radarsat HH polarization data, we developed a semi-empirical relationship relating NRCS at VV polarization to NRCS at HH polarization [9].

Recently, Hersbach developed CMOD5 [3], especially tuned for higher wind speeds. For such winds, CMOD4 tends to underestimate the speed. Moreover, we have observed in hurricane imagery that the dependence of NRCS on the relative angle between the radar and the wind decreases and perhaps disappears. Unlike CMOD4, the CMOD5 model function incorporates a decrease in angular dependence at higher wind speeds. Figure 1 shows a comparison of wind speed retrievals from Hurricane Rita captured by Envisat at VV polarization on 2005 Sep 22 13:44:32 UTC using both CMOD4 and CMOD5. Wind directions from the National Ocean Partnership Program (NOPP) model were used for the retrieval. The arrows represent the model winds and their color is related to wind speed on the same scale as the underlying SAR image. Note that the retrieval using the CMOD4 model function (left) underestimates the wind speed, while the CMOD5-based retrieval (right) more closely agrees with the model analysis.

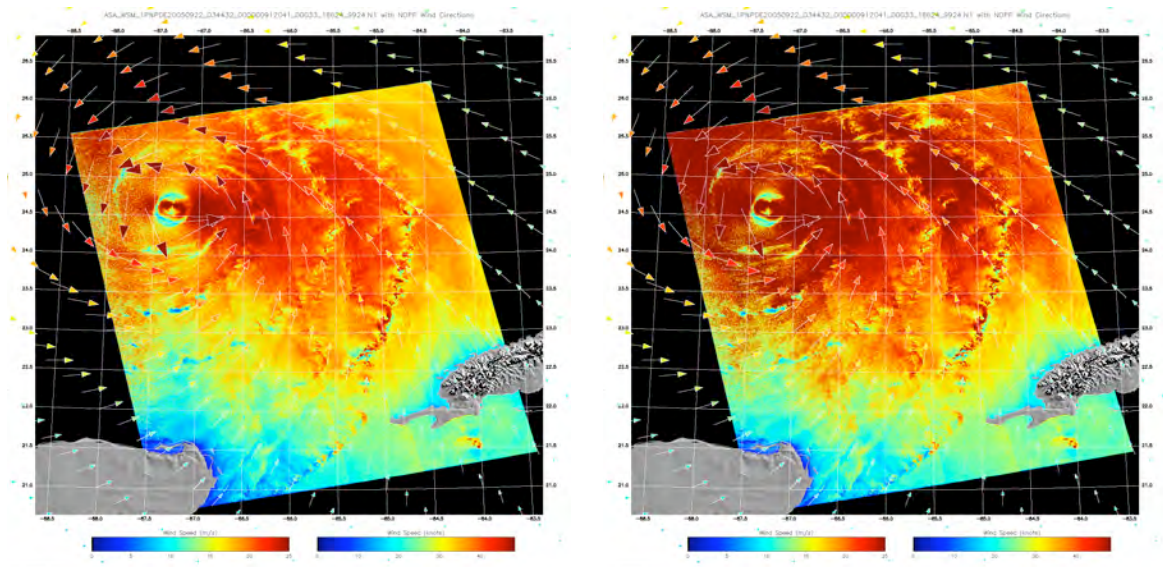


Figure 1. Envisat VV-polarization SAR wind speed retrieval using NOPP wind directions. The retrieval on the left was made using the CMOD4 model function, while the retrieval on the right used the CMOD 5 model function.

To make a more systematic comparison, we compiled over 200 VV polarization images from Envisat. By using VV polarization, we avoided issues in relating VV and HH model functions. We then compared the wind speed retrievals using CMOD4 and CMOD5 at the NOGAPS model $1^\circ \times 1^\circ$ longitude/latitude grid points. The model wind speeds are on a much coarser grid than the sub-kilometer resolution SAR wind retrievals. To make appropriate comparisons, the wind speed retrievals were performed on NRCS measurements averaged over a 25-km diameter area. The results of these comparisons are shown in Figure 2.

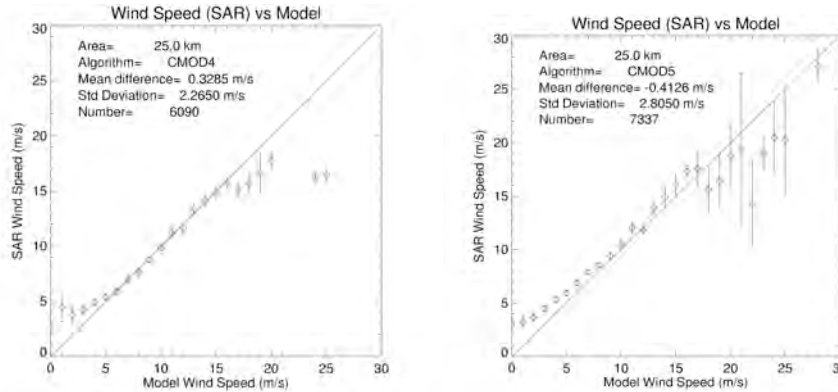


Figure 2. Comparison of Envisat SAR wind speed retrievals and NOGAPS model predictions using the CMOD4 (left) and CMOD5 (right) model functions.

Comparison of SAR wind speed retrievals against model predictions typically show a larger standard deviation than similar SAR comparisons with buoys. However, since there are so many more potential comparisons, using a model permits us to look for systematic errors in the SAR retrievals. Figure 2 makes clear that although CMOD5 experiences a higher standard deviation when compared to model predictions, it does not systematically underestimate winds above 20 m/s as CMOD4 does.

3 AREA AVERAGES

The relationship between the wind vector and NRCS is, in general, non-linear. There is, therefore, no guarantee that the model functions relating the wind vector to NRCS values that were empirically determined by comparing wind vector measurements and NRCS measurements averaged over areas 25 km and larger will be applicable to wind retrievals at the sub 1-km levels. To address this issue, we systematically compared wind speed retrievals over a variety of area averages to determine if we could find any important systematic differences.

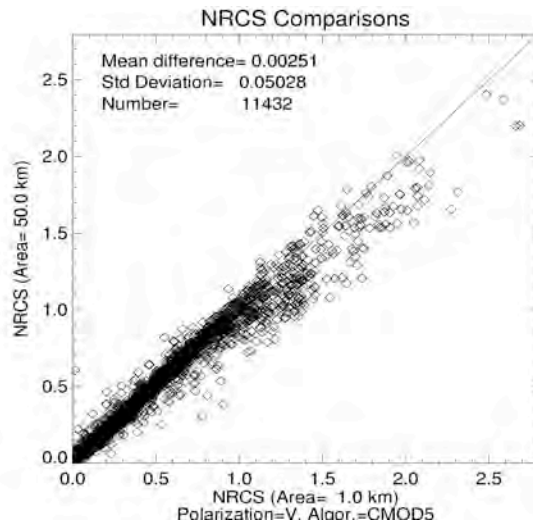


Figure 3. Point-by-point comparison of NRCS averaged over 1-km and 50-km diameter averaging areas.

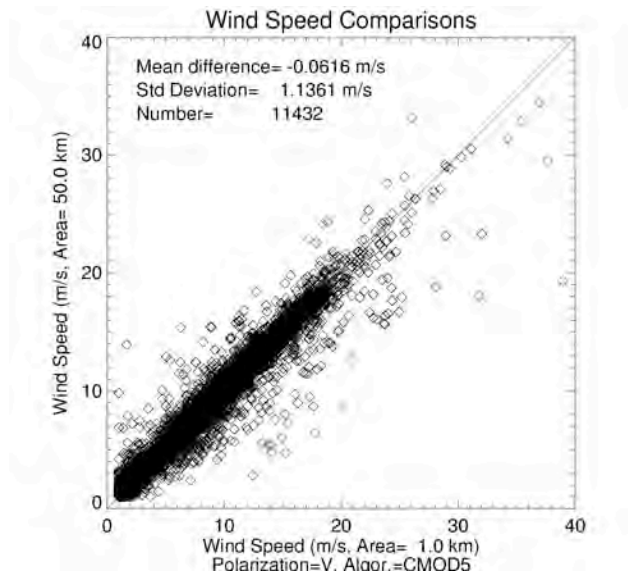


Figure 4. Point-by-point comparison of wind speeds computed from NRCS averaged over 1-km and 50-km diameter averaging areas.

In the previous section, we described how we compared wind speed retrieval with model predictions at every $1^\circ \times 1^\circ$ longitude/latitude grid points. With this same data set, we also computed the wind speeds from circular areas, centered at the same points, retrieved from SAR-measured NRCS averages of 1, 2.5, 5, 10, 25, and 50 km in diameter. Figure 3 shows point-by-point comparisons of the associated NRCS averaged over a 1-km diameter area and a 50-km diameter area. Although the 1-km NRCS averages are slightly higher than 50-km, overall the differences represent the scatter one would expect between high and low resolution measurements. Figure 4 is a similar comparison using wind speed computed from the CMOD5 model function and NRCS averaged over 1 and 50 km. There is a very little bias of -0.06° m/s. The differences simply represent scatter associated with the NRCS scatter.

Finally Figure 5 represents a plot of the mean and standard deviation between the area-averaged wind speed retrievals and those averaged over 1 km. Note that the mean difference between is very small and largely independent of averaging area. As expected, the scatter between wind speeds computed from 1-km diameter area-averaged NRCS and those computed from NRCS averaged over larger areas increases with the area diameter. From Figure 5 we can draw two inferences: (1) Conventional model functions can be used to retrieve un-biased high-resolution wind speed despite the fact that the model functions used were derived

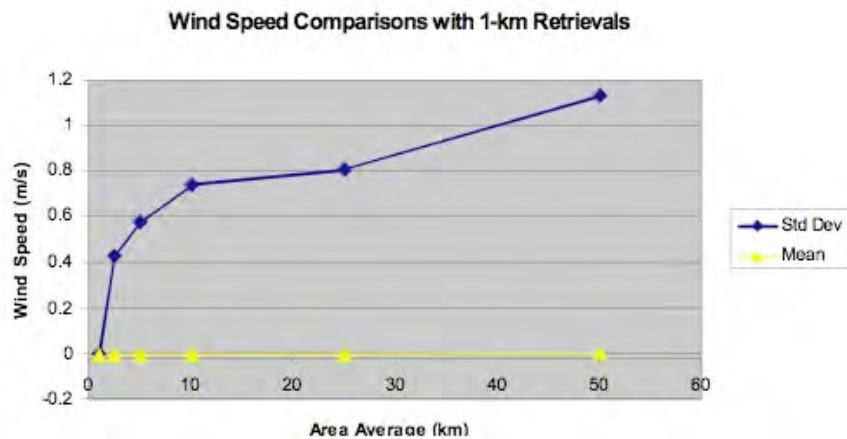


Figure 5. Comparison of differences in wind speed retrievals computed from NRCS averaged over a specified diameter area minus wind speed retrievals computed from NRCS averaged a 1-km diameter area as a function of the diameter of the averaging area.

from large area averages. When comparing point measurements of wind speed from buoys with area averages, Figure 5 provides an estimate of expected differences associated with area averages. For example, even if both a buoy and NRCS measurement averaged over a 50 km area were making perfect estimates of wind speed, the difference in their measurement would have standard deviation of over 1 m/s.

4 CONCLUSIONS

The ANSWRS system now routinely processes Radarsat and Envisat SAR imagery into high resolution wind speed maps in near real-time. The system is now running at various institutions and could, with additional effort, be made fully operational.

Comparison of Envisat SAR imagery with NOGAPS model estimates suggests that the CMOD4 model function produces wind speeds with a smaller variance with respect to model predictions than does CMOD5. However, CMOD5 produces more accurate wind speed retrievals than does CMOD4 for wind speeds above 20 m/s.

The commonly used model functions were derived by comparing wind speed and NRCS measurements averaged over areas 25 km in diameter and larger. Hence, it is possible that there could be systematic errors for wind speed retrievals made at 1 km using these model functions. We find that when comparing wind speed retrievals centered at the same point, but computed from average averages ranging in diameter from 1 to 50 km, there is no bias.

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