Ocean Surface Wind Remote Sensing Using Microwave Backscatter and Brightness Temperatures

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Abstract – This paper illustrates an improved geophysical model function (GMF) for Ku-band ocean backscatter at high winds and a preliminary geophysical model function for polarimetric brightness temperatures acquired from aircraft measurements. The implications of the geophysical model function for ocean wind velocity measurements are assessed through the analysis of NSCAT data and the simulation of satellite wind radiometer performance. The improved GMF for NSCAT appears to provide a significant better estimate of hurricane force winds than the NSCAT-1 GMF. Performance estimates for passive microwave radiometers suggest comparable accuracies of active and passive techniques from mid through high winds. Active scatterometers appear to offer a better wind direction accuracy at low winds, while passive radiometers provide a better ambiguity selection skill.

INTRODUCTION

Ocean surface wind influencing the momentum transfer and flux exchanges between upper ocean and atmosphere is a key driving force for atmosphere and ocean circulations. Many satellite microwave scatterometers and radiometers, such as Seasat Scatterometer (SASS), Earth Remote Sensing Satellite (ERS) Scatterometer, NASA Scatterometer (NSCAT) [1] aboard the Japanese Advanced Earth Observation Satellite (ADEOS), and the Special Sensor Microwave/Imager (SSM/I) [3] deployed on the Defense Meteorological Satellite Program. These satellite products have been found to have a significant impact on climate studies and weather forecasting.

However, many studies [2] have indicated that present satellite scatterometer wind products underestimate the surface wind speed at high wind regime (above 20 m$\cdot$s^{-1}). For instance, the maximum wind speed for Hurricane Lili on Oct. 19, 1996 reported in NSCAT data product is 33 m$\cdot$s^{-1}, signifcantly lower than the 50 m$\cdot$s^{-1} wind speed from aircraft reconnaissance and ship observations. Two contributing factors have been suggested for this error. One is the attenuation and scattering due to precipitation, which is frequently associated with storms and the other is the deficiency of GMF, relating the ocean radar cross section to surface wind speed and direction. This paper investigates the measurements from an aircraft scatterometer (NUSCAT) developed by the Jet Propulsion Laboratory, which was deployed on the NASA P-3 research aircraft with two flights over Hurricane Erika during the Hurricane Ocean Wind Experiment (HOWE) in September 1997 [11]. An improved GMF was developed for Ku-band dual-polarized ocean backscatter at high winds. It is shown in this paper that the NSCAT wind estimates can be significantly improved for hurricane wind force.

With a potential for significant cost savings of future satellite ocean wind missions, there has been a significant interest in the passive polarimetric technique for ocean wind measurements [4, 5, 6, 8, 10, 7]. The JPL aircraft measurements from 1993 through 1997 [8, 9, 11] have been reduced to a preliminary GMF for wind speed in the range of 3-30 m$\cdot$s^{-1}. This paper illustrates this preliminary GMF and its implications on the accuracy of wind speed and direction measurements from a satellite passive microwave sensor.

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DATA ANALYSIS

For wind-generated sea surfaces, the surface spectrum is expected to be symmetric with respect to the wind direction (ϕ_w). Denote the azimuthal observation angle of radiometer look direction with ϕ_r and the relative azimuth angle with $\phi = \phi_w - \phi_r$. The ocean co-polarized backscatters (σ_{vv} and σ_{hh}) and the polarized brightness temperatures of sea surfaces T_v and T_h are even functions of wind direction. However, the third and fourth Stokes parameters of ocean emission U and V are odd functions of ϕ [9]. Hence, expanded by the cosine and sine series of ϕ,

$$\sigma_{vv} \simeq \sum_{n=0}^{N} A_{vn} \cos n\phi \quad (1)$$

$$\sigma_{hh} \simeq \sum_{n=0}^{N} A_{hn} \cos n\phi \quad (2)$$

$$T_v \simeq \sum_{n=0}^{N} T_{vn} \cos n\phi \quad (3)$$

$$T_h \simeq \sum_{n=0}^{N} T_{hn} \cos n\phi \quad (4)$$

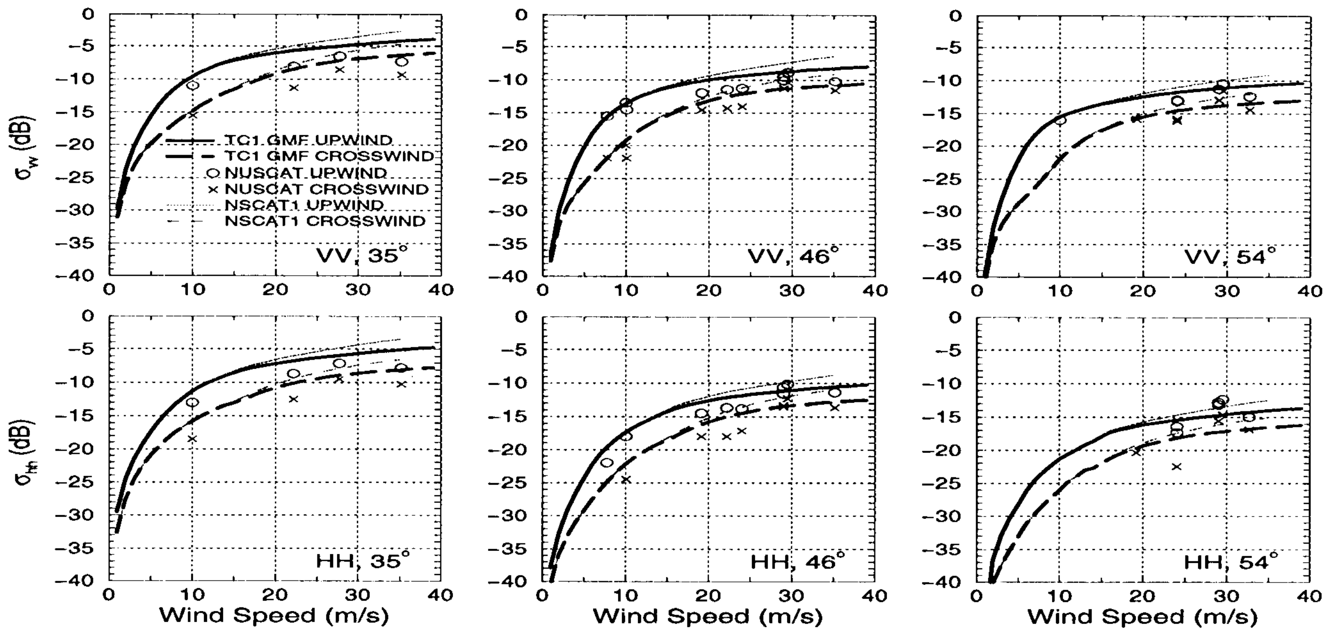

Figure 1. Upwind and crosswind backscatter from NSCAT-1 and TC-1 geophysical model functions at 35°, 45°, and 54° incidence angles. The upper three panels are for VV backscatter and the lower three panels for HH backscatter. NUSCAT measurements from Hurricane Erika [11] are included for comparison.

$$U \simeq \sum_{n=1}^{N} U_n \sin n\phi \tag{5}$$

$$V \simeq \sum_{n=1}^{N} V_n \sin n\phi \tag{6}$$

All coefficients are functions of surface wind speed, incidence angle, and frequency. There are also indications that the sea surface spectrum is influenced by the presence of large waves and the atmospheric boundary layer stability. It is therefore likely that the harmonic coefficients are also functions of surface temperatures and significant wave height.

Due to the complex interaction of electromagnetic waves and ocean surfaces, these sine and cosine series coefficients have been derived from paired satellite/aircraft ocean backscatter measurements and surface wind velocities. Fig. 1 illustrates the NSCAT-1 GMF versus wind speed. A comparison with NUSCAT measurements apparently suggests that NSCAT-1 GMF overestimates the ocean backscatter by a few dB at high winds. This supports the observations that NSCAT-1 GMF results in an underestimate of hurricane force winds (above 32 m$\cdot$s^{-1}). To overcome this error, the NUSCAT data were used to refine the NSCAT GMF at high winds with an exponential correction function suggested by [12]. The refined GMF is plotted in Fig. 1 (labeled by TC-1) for comparison.

The TC-1 GMF has been used to process the NSCAT backscatter measurements of Hurricane Lili in October 1996. Lili went through the central Bahamas on the 19th with sustained winds of near 90 knots (45 m$\cdot$s^{-1}). A ship reported an estimated wind speed of 99 knots, while located about 20 nautical miles south of the center. The estimated maximum wind speed from two NSCAT passes for Lili are 41 and 50 m$\cdot$s^{-1} with the TC-1 GMF, instead of 33 and 32 m$\cdot$s^{-1} with NSCAT-1 GMF.

The Fourier coefficients for passive microwave ocean emissions were calculated from the JPL aircraft polarimetric radiometer flight data with a minimum mean square error fit. In general, all harmonic coefficients had an increasing trend from low to moderate wind speeds, except U_2 at 65° incidence, which peaked at about 3 m/s winds. The signatures of 19 and 37 GHz data are very similar for all incidence angles. The 37 GHz channel does have a slightly stronger wind direction sensitivity than than the 19 GHz channel. However, the flights over hurricane Erika suggest that 19 GHz channel is less sensitive to precipitation than the 37 GHz channel. Fig. 2 illustrate the harmonic coefficients for three incidence angles. It is shown that there are a few Kelvin peak-to-peak signals at moderate wind speeds, but only a few tenths of one Kelvin at 2 to 3 m/s winds. The harmonic coefficient, which is most sensitive to the wind direction at low winds, is U_2 at 65° incidence. The signals appeared to be repeatable from four aircraft flights in 1994 and 1995.

The passive microwave GMF for all polarizations has been used to estimate the performance of a spaceborne

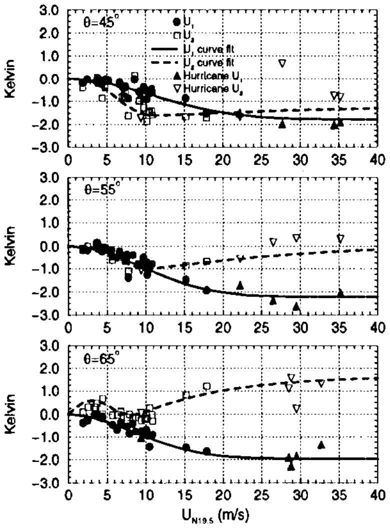

Figure 2. U_1 and U_2 from 19.35 GHz JPL wind radiometer channels versus wind speed at 10 m elevation. $U = T_{45} - T_{-45}$. (a) $\theta = 45°$, (b) $\theta = 55°$, and (c) $\theta = 65°$.

conically scanning radiometer. The projected accuracy is summarized in Table I. It is shown that 45° incidence angle offers the best performance, except at low winds where 65° incidence angle provides a better direction accuracy.

Wind Speed	45° inc.	55° inc.	65° inc.
3	1(40)	0.5(70)	0.5(30)
5	1(18)	0.7(30)	0.5(30)
8	0.8(8)	0.8(10)	0.5(20)
12	0.5(5)	0.5(8)	0.5(15)

Table I
Projected wind speed and direction accuracies for a conically scanning radiometer at 45°, 55°, and 65° incidence angles for a range of wind speed from 3 to 12 m/s. The numbers outside (inside) of the parenthesis are the rms wind speed (direction) error.

SUMMARY

The accuracy of spaceborne wind scatterometers and radiometers are investigated in this paper. Aircraft scatterometer and radiometer measurements have been uesd to improve the GMF for Ku-band ocean backscatter and a preliminary GMF for passive microwave radioemeters. The data analysis results suggest that active and passive microwave techniques offer similar performance from low to high winds.

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