Modeling of the Polarimetric Microwave Signal Due to Ocean Surface Wind Vector

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ABSTRACT

Aircraft observations of the azimuthal dependence of brightness temperature on wind direction indicate that the behavior is dominated by two sinusoidal functions. A two-scale model was developed to explain this behavior over all microwave frequencies and angles of incidence. A Fourier analysis of the data, along with a radiative transfer model of the atmosphere, provided an efficient means of simulating observations from a satellite platform for "global" conditions. This model was used to develop and test a simple wind vector retrieval algorithm. The retrieval analysis indicated that given expected noise, biases, and coupling errors for a satellite system, the wind direction can be retrieved to within 18 degrees if a combination of channels ranging from 6.8 to 37 GHz is used. These results were valid over atmospheric conditions ranging from clear skies to very heavy cloud cover.

INTRODUCTION

The ocean near-surface wind vector, which is critical for accurate storm forecasting, maritime planning and climatological studies, is strongly correlated with the magnitude and directional behavior of ocean surface emission. The affect is apparent in both vertically and horizontally polarized channels, as well as in their cross-correlation (third and fourth Stokes parameters). Observations at 10.8, 19 and 37 GHz from an aircraft platform confirmed this behavior over a broad range of wind speeds (3 to 35 m/s). The directional behavior of the brightness temperatures takes the form of a sum of sinusoidal functions of relative wind direction (RWD), where RWD is defined as the angle between the azimuthal look direction of the sensor and the upwind direction. Two harmonics in RWD are present. Upwind and downwind are distinguished by the first harmonic while the second harmonic distinguishes between upwind/downwind and crosswind. The relative strengths of these harmonics depend on frequency, elevation angle, and wind speed. Models and observations show that the directional behavior for the vertical and horizontal radiances is an even function (cosine) of the RWD while the directional behavior of the third and fourth Stokes parameters is an odd function (sine) of the RWD. This observation suggests that unambiguous resolution of wind vector is possible via microwave radiometry.

BACKGROUND

Stogryn [1] first published estimates of the horizontal and vertical brightness temperatures due to ocean waves (excluding foam) and described the surface scattering on the basis of the Kirchhoff approximation for the scattering coefficients. The Kirchhoff approximation is expected to be useful only for surface roughness whose slope is not large and whose radii of curvature are large in comparison to the electromagnetic wavelength. This condition, while met by large gravity waves, is not satisfied by small ripples or capillary waves. Several investigators extended the large scale wave model by treating the ocean surface as a composite model with the small scale roughness riding on top of the large gravity waves [1],[2],[3]. The scattering from the ripples is formulated in terms of small perturbation theory while the effect of the large scale structure is treated by a suitable geometric optics method. Clearly such an approach requires a division of the ocean surface into two major divisions of roughness scales and must consequently be viewed as non-physical. On the other hand comparisons of the Wentz [3] and Wu and Fung [2] models (only vertical and horizontal polarizations) showed considerably better agreement than that obtained using only the large-scale model. More recently the 2-scale polarimetric model of Yueh [4] (treating all four Stokes parameters) in conjunction with an ad hoc addition of hydrodynamic modulation of the small scale roughness by the large scale showed reasonably good agreement with aircraft measurements at 19 and 37 GHz. Herein, we provide comparisons of aircraft measurements at 10 and 19 GHz with a 2-scale polarimetric Tb model of the ocean surface developed at NRL. The model is similar to that developed by Yueh with the exception that (1) the coherent scattered energies are evaluated in closed form to obtain improved numerical accuracy and (2) both emission and scattering terms are included. In addition the effects of shadowing by waves is included which becomes important at large incidence angles.

The Naval Research Laboratory has participated in several airborne campaigns to collect passive polarimetric observations of the wind driven ocean surface. These experiments have been performed in conjunction with investigators from the Jet Propulsion Laboratory. NRL operated a 10 GHz polarimetric radiometer and a 22 GHz linear polarization radiometer, while JPL operated 19 and 37

GHz radiometers. The data collected during these flights has been used to validate this model.

RESULTS

We have compared the model estimates of the relative wind direction signal and the 19 and 10 GHz brightness temperatures measured during the aircraft experiments. At 19 GHz, comparisons for the vertical, horizontal, third Stokes parameter, and fourth Stokes parameter are shown in Figures 1 through 4. In these examples the earth incidence angle is 45 degrees and the surface wind speed is 9 m/s. Note that the vertical and horizontal channels have been normalized and that the relative wind direction ranges from 0 to 1800 degrees, corresponding to five azimuthal circles. The smooth curves represent the new NRL two-scale model, while the jagged curve is measured data.

Figure 1. Measured and modeled (NRL 2-scale) vertical pol. brightness temperature at 19 GHz.

Figure 2. Measured and modeled (NRL 2-scale) horizontal pol. brightness temperature at 19 GHz.

At 10 GHz, the comparisons for the third and fourth Stokes parameters are shown in Figures 5 and 6, where the surface wind speed was 15 m/s and the earth incidence angle was 65 degrees. In these figures the solid curves represent the 2-scale model results, while the points represent the experimental data. Again, the NRL model appears to mimic the observed azimuthal behavior quite well.

Small discrepancies between the measured and modeled brightness temperatures occur at the upwind and 90 degree crosswind directions, especially for the horizontal polarization. We are addressing these differences in on-going work.

Figure 3. The third Stokes Parameter as a function of relative wind direction.

Figure 4. The fourth Stokes parameter as a function of relative wind direction.

Figure 5. The third Stokes parameter at 10 GHz as a function of relative wind direction.

Figure 6. The fourth Stokes parameter at 10 GHz as a function of relative wind direction.

WIND RETRIEVAL SIMULATION

We have used the model for surface emission, along with a radiative transfer model of the atmosphere, to simulate brightness temperatures that would be observed by a space borne polarimetric radiometer. For expediency, the surface emission was based on a Fourier coefficient fit to the data presented in the previous section. The purpose of this simulation was to determine the retrieval algorithm sensitivity to atmospheric parameters and channel selection for a system observing the earth at 53 degrees earth incidence angle. The channels simulated for 6.8, 10.7, 18.7, 23.8, and 37.0 GHz, where all but the 6.8 and 23.8 GHz channels were fully polarimetric. The simulation consisted of generating two sets of "global" brightness temperatures. One set was used for retrieval algorithm development, while the other provided an independent test of the algorithm. The algorithm

was a simple D-Matrix coefficient regression to the brightness temperatures. Reasonable system errors were added to the "test" brightness temperature data set in order to provide a more realistic retrieval simulation. The added errors included system random noise, biases, polarization rotation, earth incidence angle uncertainty, and residual antenna coupling. In addition, some uncertainty was inherent in the geophysical model. For example, the foam fraction, as a function of wind speed, included an uncertainty term to account for natural variability in the occurrence of foam. This modified test data set was then run through the retrieval algorithm, and the retrieved wind direction was compared to the original direction. The results indicated that the rms wind direction error was optimal when all channels were included in the retrieval. For a 9 m/s wind, the error in retrieved direction was 15 degrees in a cloud free scene, and 18 degrees in the presence of clouds. For the cloud free case the lower frequencies did not significantly reduce the retrieval error. The presence of clouds, however, the direction error when the 6.8 and 10.7 channels were not used rose to 27 degrees.

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