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AIRBORNE PASSIVE POLARIMETRIC MEASUREMENTS OF SEA SURFACE ANISOTROPY AT 92 GHZ

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ABSTRACT

The potential for remote sensing of ocean wave direction using passive polarimetric microwave observations was investigated. A fixed-beam 91.65 GHz polarimetric radiometer was mounted on the NASA DC-8 aircraft during the Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE January - February 1993). Several experiments were performed during which the DC-8 was flown in constant bank-angle turns at $\sim$ 1.5 km altitude to obtain azimuthal scans of the sea surface at fixed observation angles. Data at 65° from nadir are consistent with previous findings using 19- and 37-GHz Special Sensor Microwave Imager (SSM/I) satellite observations and support the claim that a broadband emission mechanism is responsible for the azimuthal brightness signatures. Accordingly, a tilted-facet geometrical optics (GO) model of the surface was developed to investigate emission from deterministic and random striated surfaces. Laboratory measurements of polarimetric emission at 92 GHz from small-amplitude water-waves corroborate this model.

INTRODUCTION

Recently there has been much interest in passive remote sensing of ocean surface wind and wave direction. An investigation using satellite data from the SSM/I has shown that the surface wind vector can be determined using dual-polarized brightness temperatures (Wentz, 1992). Observations of the upwelling radiation over wind-driven ocean surfaces showed brightness temperatures that were related to wind direction. In this paper we describe a model for these azimuthal brightness signatures and discuss the potential of using fully polarimetric radiometry for ocean wind direction sensing.

It is proposed that a broadband mechanism is responsible for the upwelling brightness temperature signatures reported here (91.65 GHz) and from the 19- and 37-GHz SSM/I data (Wentz, 1992). The brightness signatures can be broken down into contributions from the first and second azimuthal Fourier harmonics. We explain the presence of each Fourier harmonic as due to ocean wave asymmetry (the first harmonic) and geometrical scattering (the second harmonic).

A tilted-facet geometrical optics (GO) model of the surface emission incorporating geometrical optics is used to explain the physical origin of the second harmonic in the azimuthal brightness signatures. Laboratory measurements of a sinusoidally striated surface corroborate the GO model and demonstrate its applicability in predicting polarized-thermal emission from relatively smooth water surfaces. A Monte-Carlo analysis of simulated one-dimensionally rough ocean surfaces using the GO model correctly predicts the phase of the second azimuthal harmonic in observations over the open ocean. Although the first-harmonic is not modelled in this analysis it is hypothesized to be due to ocean wave asymmetry and foam.

TOGA/COARE OBSERVATIONS

To characterize the polarimetric upwelling azimuthal brightness temperature at 92 GHz over an open ocean several experiments were performed during TOGA/COARE in January and February 1993. A fixed-beam polarimetric 92 GHz radiometer capable of measuring T_v, T_h and $T_U = 2Re(E_v E_h^*)$ was installed on the NASA DC-8 airborne platform. Several constant bank-angle turns were performed at $\sim$ 1.5 km altitude to obtain 360° azimuthal scans of the sea surface at fixed observation angles. Nadir video imagery and aircraft navigational information was used to provide sea surface and wind truth.

An azimuthal scan at an observation angle θ_o = 65° (Fig. 1) showed variations in T_v of ~1.3 K and T_h of ~2.5 K, with a pronounced upwind/downwind asymmetry in T_v and T_h (Kunkee and Gasiewski, 1994). Data from this scan are consistent with previous findings using 19- and 37-GHz SSM/I satellite data (Wentz, 1992), suggesting that the upwelling azimuthal signatures are the result of broadband emission.

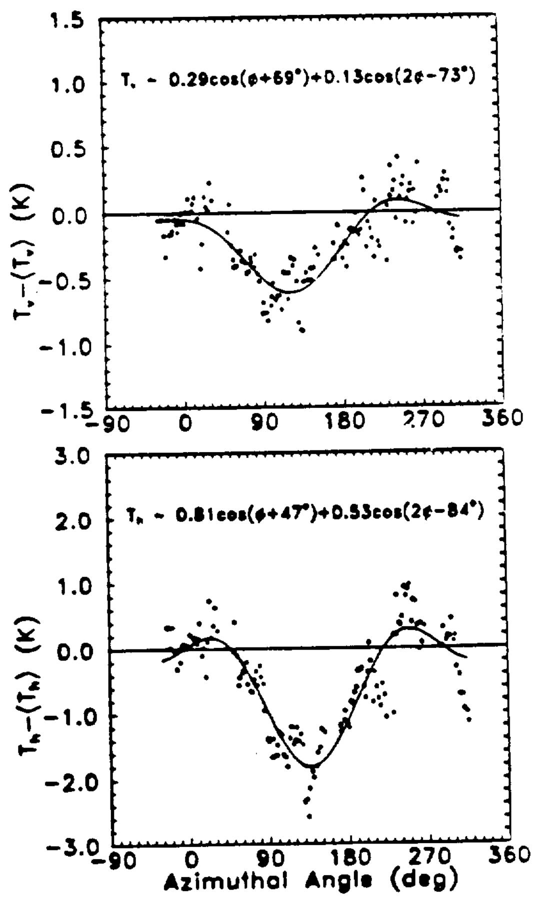

Figure 1: Measured azimuthal variation of T_v and T_h (91.65 GHz) with wind direction observed at θ_o = 65° over open ocean under light wind conditions during TOGA/COARE.

The above brightness temperature signatures can be conveniently described using the azimuthal Fourier amplitudes, B_{on} and phases, Φ_{on}, defined by:

$$T_{on}(\theta_s) = \sum_{n=0}^{\infty} B_{on}(\theta_s)\cos\left[n\phi_s + \Phi_{on}(\theta_s)\right] - T_o^{(c)}(\theta_s) \quad (1)$$

where $T_o^{(c)}$ is the calm water brightness, o is the polarization, n is the azimuthal harmonic and ϕ_s is the azimuthal observation angle with respect to the water wave vector (wave azimuthal angle). For an upwind observation $\phi_s = 0°$. Both first-order ($n = 1$) and second-order ($n = 2$) variations can be found in the TOGA/COARE data at $\theta_s = 65°$. For the vertical brightness, $T_v \sim 0.29\cos(\phi_s + 69°) + 0.13\cos[2(\phi_s - 36°)]$ and for the horizontal brightness, $T_h \sim 0.81\cos(\phi_s + 47°) + 0.53\cos[2(\phi_s - 42°)]$. Note that the brightness temperature minimum is not directly in the downwind direction with an average phase shift of $-48°$ shown. This shift is due to primarily to the presence of multiple wave trains and light winds.

The first-order azimuthal harmonic (B_{o1}) is hypothesized to result from wave asymmetry and increased amounts of ocean foam on the leeward side of the wave. Leeward-side foam will be partially hidden from the view of the radiometer during downwind observations resulting in a lower observed brightness temperature compared to the upwind observation. The first-order harmonic may also be due to ocean wave asymmetry: the leeward side of the wave is generally steeper and will thus appear brighter due to reflection of background radiation incident on the surface from the warmer near-grazing angles.

GEOMETRICAL OPTICS MODEL

The second-order harmonic B_{o2} from a striated water surface can be explained using geometrical optics (GO). A GO model of the thermal emission from a sinusoidally striated water surface was developed to investigate the azimuthal variation in the upwelling polarimetric brightness temperature (Gasiewski and Kunkee, 1993). Using the GO model the surface is composed of specularly reflecting facets, each contributing to the total upwelling radiation. The model incorporates multiple scattering up to third order.

Use of the GO model is justified at 92 GHz by considering the domain of applicability of the Kirchoff approximation (KA). Because KA is often the most direct and least time consuming method for predicting surface emission, it is unfortunate that there seems to be no unanimous decision regarding its application to surfaces of varying roughness. Wirgin (1983), claims that the KA is applicable to a sinusoidal surface at normal incidence for $h/\Lambda < 0.011(\Lambda/\lambda)$, where h and Λ are the surface amplitude and wavelength respectively, and λ is the electrical wavelength. Perhaps a more universal criteria involves the minimum local radius of curvature of the surface (Beckmann and Spizzichino 1963); this region of validity is $\min(2kr_c\cos\theta) \gg 1$ where r_c is the local radius of curvature of the surface, k is the electrical wave number and θ is the local angle of incidence. Thus, the GO model is expected to degrade at observation angles near-grazing, however, the above criteria are easily met at 92 GHz over a wide range of water surface roughness and observation angles.

Indeed, based on laboratory measurements of a sinusoidally striated water surface, Wirgin's criteria appears conservative for studies of polarimetric emission from water surfaces. To show this, direct measurements of the first three upwelling Stokes' parameters (T_v, T_h and T_U) over a rotatable water wave tank were performed at several observation angles using a precision calibrated polarimetric 92 GHz radiometer (Gasiewski and Kunkee, 1993). The measurements were used to corroborate the GO model and to establish relationships between T_v, T_h and T_U and wave angle. All experiments were performed under clear-sky background conditions; coincident radiosonde measurements of atmospheric temperature and water vapor profiles were obtained for computing sky background brightness temperatures.

Comparisons of the GO model with measurements are shown in Figs. 2 and 3 for a sinusoidally striated surface described by $z = h\sin(2\pi x/\Lambda)$ with $h/\Lambda = 0.05$ and $\theta_s = 65°$. The results verify the applicability of GO with multiple scattering for calculating polarimetric thermal radiation from relatively smooth surfaces at near-Brewster angle observation.

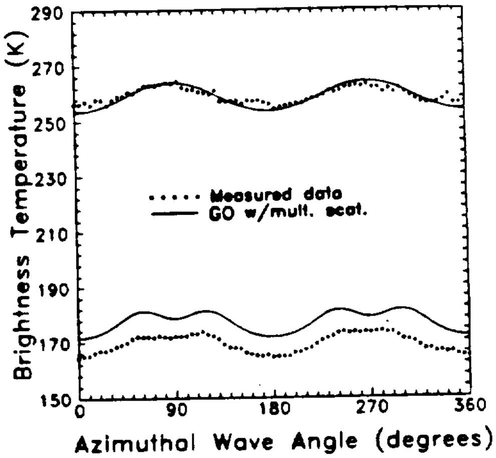

Figure 2: Measured and calculated T_v and T_h brightnesses over a sinusoidal water surface for $\theta_s = 65°$, $T_w = 288K$, $h/\Lambda = 0.05$ and SRH = 50%.

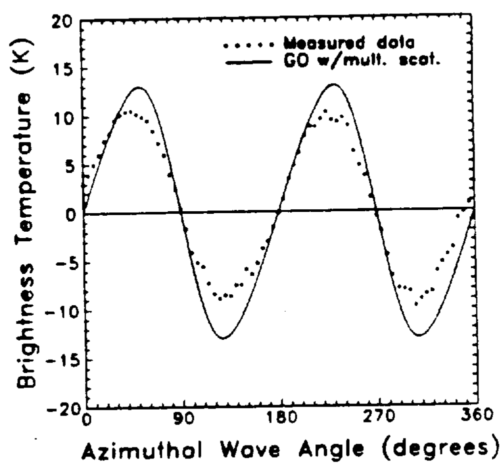

Figure 3: Measured and calculated T_U brightnesses over a sinusoidal water surface for $\theta_s = 65°$, $T_w = 288K$, $h/\Lambda = 0.05$ and SRH = 50%.

For a sinusoidal surface the GO model shows that the second-harmonic T_U brightness variations are in phase quadrature with the T_v and T_h second-harmonic magnitudes (Figs. 2, 3). Due to this phase relationship, coincident observations of T_U with T_v and T_h will facilitate the retrieval of wave and ocean surface wind direction by reducing a four-quadrant direction ambiguity to a two-quadrant direction ambiguity.

MONTE-CARLO OCEAN WAVE ANALYSIS

A wind-driven sea surface is more complex than a sinusoidal model and must be described statistically. For the open ocean, the slope distribution has variance (Cox and Munk, 1954; Wilheit, 1979):

$$\sigma_o^2(w) = 0.003 + 0.0048w \quad (2)$$

where w is the wind speed in m/s at a height of 20-m above the surface. To incorporate ocean wave statistics, a Monte-Carlo analysis was performed using a set of one-dimensional wave-covered surfaces and the GO model. The simulated ocean surfaces have wavenumber spectra with a power law of slope -3.0 and a slope variance $\sigma_o^2(7 \text{ m/s}) \approx 0.037$. Results for $\theta_s = 20°$ and frequency $f = 12$ GHz (Figs. 4, 5) show azimuthal brightness variations of magnitude and phase close to those obtained by Johnson using a diffraction model (Johnson, 1993).

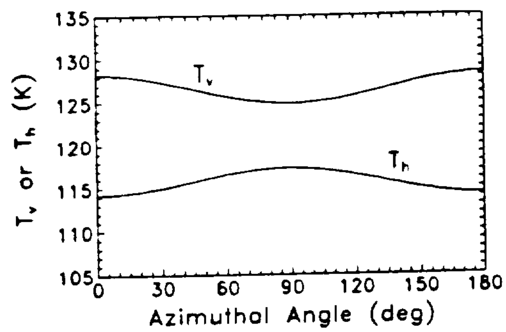

Figure 4: Calculated T_v and T_h brightnesses from a simulated ocean surface for $\theta_s = 20°$, $T_w = 300$ K, $\sigma_o^2 \approx 0.037$.

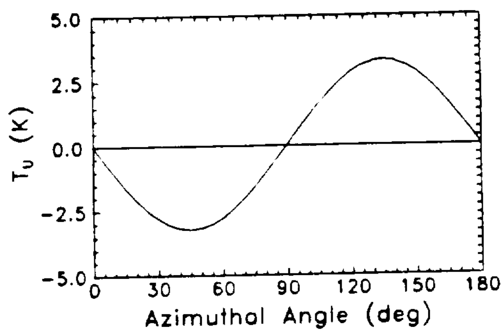

Figure 5: Calculated T_U brightnesses from a simulated ocean surface for $\theta_s = 20°$, $T_w = 300$ K, $\sigma_o^2 \approx 0.037$.

Results at 92 GHz asuming 50% surface relative humidity (SRH) and clear-air conditions are shown in Fig. 6 for an observation angle of 65°. From these data, $\Phi_{o2} = 180°$ for T_v and T_h. This is consistent with Φ_{o2} as computed from the TOGA/COARE data (after translation by a $\sim -48°$ phase correction) (Fig. 1). The calculated values of B_{o2} are several times larger than the TOGA/COARE observations. However, this model is somewhat incomplete in that ocean foam, two-dimensional slope spectra and cusping are not yet considered.

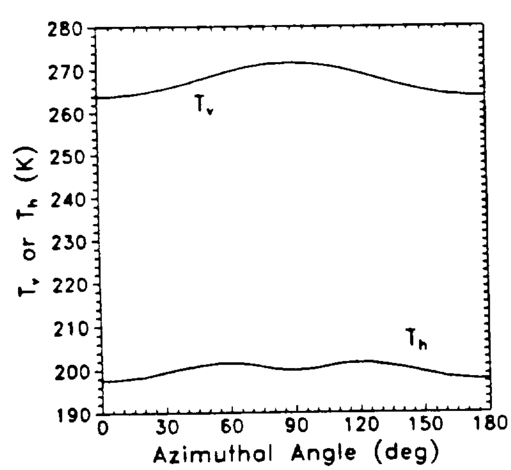

Figure 6: Calculated T_v and T_h brightnesses from a simulated ocean surface for $\theta_s = 65°$, $T_w = 290$ K, $\sigma_o^2 \approx 0.037$.

DISCUSSION AND CONCLUSIONS

Passive polarimetric observations at 92 GHz of the sea surface under light sea conditions show variations of ~1.3 K and ~2.5 K in the vertically and horizontally polarized brightness temperatures over an azimuthal scan of 360° at a constant observation angle of 65°. An upwind/downwind brightness asymmetry in T_v and T_h was observed in this data supporting the claim that ocean surface wind direction can be unambiguously observed using passive polarimetric remote sensing.

Unambiguous recovery of surface wind/wave direction on the open ocean will rely on the first-order azimuthal terms defined in (1). As expected for sinusoidal surfaces (symmetric surfaces) all B_{on} are zero for odd n, however, since real ocean waves are not symmetric this does not hold in general. The combination of $B_{o1} \neq 0$ (an upwind/downwind asymmetry) and T_U in phase quadrature with T_v and T_h will provide a way in principle to eliminate all ambiguities in the azimuthal angle of the retrieved ocean surface wind/wave direction.

The amplitude and phase of the azimuthal variations are consistent with satellite observations at 19 and 37 GHz from the SSM/I. This consistency suggests that a broadband emission mechanism is responsible for the ocean wave azimuthal signatures.

The geometrical optics model is shown to be valid in applications to water wave remote sensing at 92 GHz. Not only does the region of validity extend to near-Brewster observation angles, but results that are consistent with a diffraction model are also obtained at lower frequencies using a statistical ocean surface. The GO model also correctly predicts the phase of the second-order harmonic in the TOGA/COARE (92 GHz) observations. Better agreement with the observed second-order harmonic magnitude and accurate estimates of the first-order harmonic magnitude and phase are expected using a more complete statistical ocean surface model.

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