POLARIMETRIC BRIGHTNESS TEMPERATURES OF SEA SURFACES MEASURED WITH AIRCRAFT MICROWAVE RADIOMETERS

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Abstract - Aircraft dual-frequency (19 and 37 GHz) radiometer measurements of polarimetric sea surface brightness temperatures are reported in this paper. All measured Stokes parameters showed ‘a few Kelvin azimuth modulations with respect to the wind direction. The wind directional signals observed in the 37 GHz channel were similar to those in the 19 GHz channel. This indicates that the wind direction signals in sea surface brightness temperatures have a weak frequency dependence in the range of 19 to 37 GHz. The harmonic coefficients of the wind direction signals were derived from experimental data versus incidence angle. It was found that the first harmonic coefficients, which are caused by the up and downwind asymmetric surface features, had a small increasing trend with the incidence angle. In contrast, the second harmonic coefficients, caused by the up and crosswind asymmetry, showed significant variations in T_v and *U* data, with a sign change when the incidence angle increased from 45° to 65°. Besides the first three Stokes parameters, the fourth Stokes parameter, *V*, which had never been measured for sea surfaces before, was measured using our 19-GHz channel. The Stokes parameter *V* has an odd symmetry just like that of the third Stokes parameter *U*, but with a smaller wind direction signal than that of *U*. Theoretical interpretation based on two-scale scattering models was performed to interpret the experimental data. In summary, the sea surface features created by the near surface winds are anisotropic in azimuth direction and modulate all Stokes parameters of sea surface microwave brightness temperatures by as large as a few Kelvin in the range of incidence angles from 45° to 65° applicable to spaceborne observations.

I. INTRODUCTION

There has be an increasing interest in the application of passive microwave radiometers for ocean wind remote sensing. The near surface ocean wind, generating the momentum flux affecting ocean circulation and mixing, is the key driving force in air-sea interaction processes. Global mapping of near surface ocean winds is crucial for many oceanographic and atmospheric studies. Previous applications of passive microwave radiometers were limited to wind speed measurements based on the sensitivity of thermal emission on surface roughness created by wind forcing. Examples of such radiometers include the Scanning Multichannel Microwave Radiometer (SMMR) flown on NIMBUS-7 and SEASAT and the Special Sensor Microwave/Imager (SSM/I) deployed on the Defense Meteorological Satellite Program (DMSP) missions [1].

However, recent experimental observations [2, 3, 4, 5] indicated that ocean microwave thermal radiation could vary over azimuthal angles relative to the wind direction by a few Kelvin. The aircraft radiometer experiments conducted by the Russian scientists at the Space Research Institute measured the sea surface brightness temperatures at near normal incidence angles [2, 4]. They found a few Kelvin wind direction signal in the brightness temperatures. Unfortunately, those measurements did not cover the range of incidence angle traditionally used by spaceborne microwave radiometers (incidence angles of 48° to 60°) for large swath coverage. In contrast, SSM/I has measured the brightness temperatures at an incidence angle of 53”. Wentz’s SSM/I model function [3] indicated that T_h and T_v at both 19 and 37 GHz could vary with the wind direction by a few Kelvin.

Besides vertical and horizontal polarization measurements made by conventional radiometers, the results collected at near normal incidence by Dzura et al. [4] and the theoretical analysis based on a polarimetric Bragg scattering model by Yueh et al. [6] suggested that radiometric brightness temperatures at all polarization states are also sensitive to wind direction. To explore the potential of polarimetric radiometry for spaceborne remote sensing applications, a K-band multi-polarization radiometer (WINDRAD) was built and deployed on the NASA DC-8 aircraft with circle flights over several ocean buoys to study sea surface radio emissions by Yueh et al. [5] in November 1993. These measurements were the first experimental evidence indicating that the first three Stokes parameters of sea surface emissions are sensitive to ocean wind direction in the incidence angle range of 30° to 50°. The observed azimuthal signatures of Stokes parameters were shown to agree with the predictions of a two-scale surface emission model [7, 8]. The results of these aircraft flights indicate that passive polarimetric radiometry ha-s a strong potential for global ocean wind speed and direction measurements from space.

However, these experimental data are not yet adequate to design a spaceborne sensor for ocean wind sensing. The key parameters of a spaceborne radiometer system include the frequencies, incidence angle, and radiometric sensitivity. Wentz's SSM/I geophysical model function [3] was limited to the 53° incidence and was for only two polarizations T_v and T_h. Hence, Wentz's SSM/I model function does not allow a tradeoff study of incidence angle and polarization selection. For the cases of the data collected in November 1993 by the Jet Propulsion Laboratory's (JPL) WINDRAD, the results were three Stokes parameter measurements from 30° to 50° incidence angles. However, they were insufficient to define a geophysical model function due to the limited atmospheric and oceanic conditions encountered. In addition. the 1993 JPL data were limited to one frequency only, thus providing no information about how the signals change with frequency.

To obtain a better understanding of the frequency dependence, a Ka-band (37 GHz) polarimetric radiometer was built and integrated with the K-band (19 GHz) radiometer used in the 1993 WINDRAD experiments. The dual-frequency system was flown in July and August, 1994 over ocean buoys to obtain a more extensive measurement with varying incidence angle. The results are reported in this paper.

II. MICROWAVE POLARIMETRIC RADIOMETRY

The electromagnetic waves emitted from natural media due to random thermal motion of electric charges are in general partially polarized. To fully characterize the polarization state of partially polarized thermal radiation, four parameters I, Q, U, and V were introduced by Sir George Stokes [10]. Because conventional radiometers for earth remote sensing measure T_v and T_h, an alternate representation is to use a modified form of Stokes vector with four parameters, T_v, T_h, U, and V,

$$I_s = \begin{bmatrix} T_v \\ T_h \\ U \\ V \end{bmatrix} = c \begin{bmatrix} <|E_v|^2> \\ <|E_h|^2> \\ 2Re<E_v E_h^*> \\ 2Im<E_v E_h^*> \end{bmatrix} \qquad (1)$$

T_v and T_h are the brightness temperatures of vertical and horizontal polarizations, while U and V characterize the correlation between these two orthogonal polarizations. Note that $I(=T_v+T_h)$ represents the total radiated energy and $Q(=T_v-T_h)$ the polarization balance. Eq. (1) defines the Stokes parameters in terms of the horizontally and vertically polarized components of electric fields (E_h and E_v). The polarization vectors are related to the direction of propagation and are illustrated in Figure 1. The angular brackets denote the ensemble average of the argument, and c is a proportional constant relating the brightness temperature to the electric energy density [12].

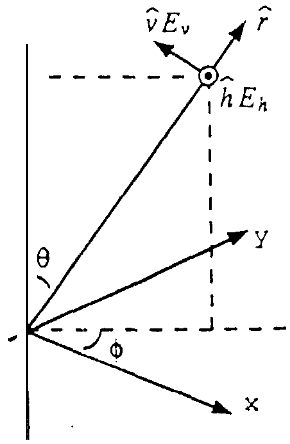

Figure 1. Polarization vectors and coordinate system. $\hat{v} = -\cos\theta\cos\phi\hat{x} - \cos\theta\sin\phi\hat{y} + \sin\theta\hat{z}$, $\hat{h} = \sin\phi\hat{x} - \cos\phi\hat{y}$, and $\hat{r} = \sin\theta\cos\phi\hat{x} + \sin\theta\sin\phi\hat{y} + \cos\theta\hat{z}$.

For wind-generated sea surfaces, the surface spectrum is expected to be symmetric with respect to the wind direction (ϕ_w). In other words, the surfaces are statistically reflection symmetric with respect to ϕ_w [9]. Let the azimuthal observation angle of radiometer look direction be denoted by ϕ_r and the relative azimuth angle by $\phi = \phi_w - \phi_r$. Yueh et al. [9] derived from Maxwell's equations using reflection symmetry that TV and T_h are even functions of ϕ and U and V are odd functions. A typical form of geophysical model functions, relating the brightness temperatures to the geophysical surface parameters, expresses the Stokes parameters in the Fourier series of the relative azimuth angle ϕ. Hence, expanded to the second harmonic of ϕ,

$$T_v \simeq T_{v0} + T_{v1}\cos\phi + T_{v2}\cos 2\phi \qquad (2)$$

$$T_h \simeq T_{h0} + T_{h1}\cos\phi + T_{h2}\cos 2\phi \qquad (3)$$

$$U \simeq U_1\sin\phi + U_2\sin 2\phi \qquad (4)$$

$$V \simeq V_1\sin\phi + V_2\sin 2\phi \qquad (5)$$

The coefficients of first harmonics account for the up/downwind asymmetric surface features, while those of second harmonics for the up/crosswind asymmetry. All coefficients are functions of near surface wind speed and other sea surface parameters.

A typical approach for Stokes parameter measurements is to carry out the power measurements at vertical and horizontal polarizations and four other polarizations, including 450-linear (E_p), $-45°$-linear (E_m), left-hand-circular (E_{lc}), and right-hand-circular (E_{rc}). Specifically, the following identities are used for measuring the third and fourth Stokes parameters:

$$2Re(E_h E_v^*) = |E_p|^2 - |E_m|^2 \qquad (6)$$

Parameter	Value	
Frequency (GHz)	19.35	37
Antenna Beamwidth (degree)	3.9	6.3
Antenna Sidelobes (dB)	-23	-33
Polarization	V, H, 45(R*), -45(L*)	V, H, 45°, -45°
Dicke Switch Rate (Hz)	125	125
Radiometer Bandwidth (MHz)	500	1200
Noise Diode Temperature (K)	103	78
System Noise Temp. (K)	550	620
Total System Noise Temp. for Scene"* (K)	803	898
RMS noise for 1.6 sec integration"* (K)	0.06	0.04
Absolute calibration (K)	<4	<4
Aircraft Altitude*** (Kft)	27, 31	27, 31
Nominal Aircraft Ground Track Speed (Knot/h)	400	400

Table I

WINDRAD key parameters. ●: Phase shifter set at 90 degrees phase shift. ● ": Assume 150 K background for 19 GHz and 200 K background for 37 G Hz. "-n: 27 Kft for 45 and 55 degree incidence and 31 Kft for 65° incidence

$$2Im(E_h E_v^*) = |E_{lc}|^2 - |E_{rc}|^2 \quad (7)$$

where

$$E_p = \frac{E_h + E_v}{\sqrt{2}} \quad (8)$$

$$E_m = \frac{E_h - E_v}{\sqrt{2}} \quad (9)$$

$$E_{lc} = \frac{E_h + iE_v}{\sqrt{2}} \quad (10)$$

$$E_{rc} = \frac{E_h - iE_v}{\sqrt{2}} \quad (11)$$

Recently, it has been demonstrated that all polarization measurements can be carried out using a single antenna and a microwave switch network to coherently combine the vertically and horizontally polarized electric fields [5]. To detect E_p anti E_m polarization components requires the coherent sum and difference of vertical and horizontal polarization field components. A microwave "Magic-Tee" was used to perform the necessary coherent operation over a 500 MHz bandwidth at 19 GHz [5] and more than 1 GHz bandwidth for the new 37 GHz radiometer. A 90-degree phase-shifter added in the path of vertical polarization channel leading from the antenna to the Magic-Tee allowed the conversion of E_p into E_{lc} and E_m into E_{rc}. By denoting the brightness temperature measurements at these four polarizations as T_p, T_m, T_{lc}, and T_{rc}, U and V can be derived from these four brightness measurements:

$$U = T_p - T_m \quad (12)$$

$$V = T_{lc} - T_{rc} \quad (13)$$

Hence, complex correlations of E_v and E_h can be obtained by using power measurements.

III. POLARIMETRIC RADIOMETER

A dual-frequency polarimetric radiometer system operating at 19 GHz (K band) and 37 GHz (Ka band) breed on the measurement principle described in the above section have been built, installed and used on the NASA DC-8 for ocean wind measurements. This dual-frequency system was an upgrade of the 19 GHz polarimetric radiometer used in the first WINDRAD experiment in" November 1993 [5], which was found to be stable and easy for polarimetric calibration. A block diagram of the 19-GHz radiometer can be found in [5], and Table I gives the characteristics of both radiometers. The new 37-GHz radiometer is similar to the 19-GHz radiometer, except that there is no 90-degree phase shifter in the 37-GHz radiometer. In the radiometers, a waveguide network is used to switch between the vertical and horizontal polarization channels from the scalar conical antenna horn. The waveguide network also combines the vertically and horizontally polarized signals in a "Magic Tee" to give T_p and T_m. This network was calibrated and adjusted using a HP851O network analyzer to provide equal losses and path lengths from the antenna to the Magic Tee.

Following the waveguide network, a conventional Dicke switched Tuned Radio Frequency (TRF) radiometer is used to measure the signal power. The detected signals are digitized using a 12-bit A/D converter and the two radiometers are controlled by a 486 personal computer. The synchronous detection is done by the computer at a 125 Hz switch rate to eliminate gain variations. A noise diode was used to measure the system noise and for temperature calibration and was calibrated with ambient and liquid Nitrogen thermal loads placed in front of the feedhorn.

IV. AIRCRAFT FLIGHT EXPERIMENTS

In July and August 1994, a set of aircraft flights were carried out with the dual-frequency polarimetric radiometer system, which was mounted on the NASA DC-8. Circle flights were performed over the National Data Buoy Center (NDBC) moored buoys deployed off the northern California coast, which provided ocean wind speed and direction measurements. The K- and Ka-band antenna horns were fixed mounted on the DC-8 windows at an angle of 80 degrees from nadir. To measure the data at 45°, 55°, and 65° incidence angles, the DC-8 was banked at 35°, 25°, and 15°, respectively. At each bank angle, DC-8 performed circle flights, allowing the radiometers to acquire data from all azimuth angles with respect to the surface wind direction. The data have been corrected for the small changes in the aircraft bank angles during the circles using the measurements from wing-wagging flights with the aircraft roll angle quickly varied within ±40°. Aircraft altitude for the circle flights at 25 and 35 degree bank angles was about 27K feet and was about 31K feet for the 15 degree bank. The flight altitude was chosen so that the location of antenna footprint would be close to the center of the circles, while DC-8 performing circle flights. This ensured that the data were collected over nearly the same area, hence reducing the uncertainty due to potential spatial surface variations.

Figures 2 to 4 illustrate a set of Stokes parameter measurements versus azimuth angles at the nominal incidence angles of 45°, 55°, and 65°, the 37 GHz T_v and T_h data were offset so that they would be near the values of the 19 GHz data for ease of visual comparison. There was a clear sky over the buoy, and the wind was 9 m/s measured by the buoy at 5 meter height, which can be translated into 10 m/s at 20 m elevation. There were a few Kelvin wind direction signals in all Stokes parameters, and the wind direction signatures at the incidence angles of 45° and 55° agree well with the data collected in the first WINDRAD experiment [5]: T_v data peaked at the upwind direction, while T_h reached a minimum; U data displayed an odd symmetry, whereas T_v and T_h data had even symmetry. However, the T_v data obtained at 65° incidence angle had a small dip at the upwind direction, unlike the 45° and 55° incidence data. The dip at the upwind direction means that the second harmonic coefficient of T_v is negative at this angle, while those of 45° and 55° incidence angles are positive.

The K- and Ka-band data plotted in Figures 2 to 4 can be used to evaluate the frequency sensitivity of the wind direction signals. It was noted that the azimuth modulations of the data acquired at these two frequencies almost overlap with each other, suggesting that the wind direction signals in all Stokes parameters have a weak frequency dependence in the frequency range of 19 to 37 GHz. This was observed in all data collected throughout the flight experiments. This could be due to the nature of sea surfaces, which are known to have a wavenumber spectrum closely following a power law, and are thus nearly self-similar at various scales like a fractal surface. Hence, although 19 and 37 GHz thermal emissions interact with different parts of the spectrum according to Bragg scattering, the length scales of surface dominating the scattering normalized by the electromagnetic wavelength, would appear similar at these two frequencies. This weak frequency dependence implies that 19 and 37 GHz radiometers would provide similar accuracies for the wind direction measurement under clear sky condition. We do, however, expect that 19 GHz channel would be less sensitive to atmospheric effects than 37 GHz channel, while 37 GHz spaceborne radiometer typically would give a better spatial resolution than 19 GHz radiometers for the same antenna size,

Immediately following the set of circle flights, which acquired the first three Stokes parameter data illustrated in Figures 2 to 4, another set was repeated to acquire the fourth Stokes parameter data, which had never been measured before for ocean remote sensing. This was designed to find out whether there were any wind direction signals in the fourth Stokes parameter, V, of sea surface emission. The phase shifter in the K-band radiometer was set to 90 degrees, enabling simultaneous T_v, T_h, and V measurements. (Note that our 37 GHz channel did not have the 90-degree phase shifter, and hence could not measure the fourth Stokes parameter.) Figure 5 illustrates the wind direction signals in V. It was found that the azimuthal modulation of V is smaller than that of U measured in the first set of circle flights. The fourth Stokes parameter also has an odd symmetry, just like the third Stokes parameter. This data set represents the first empirical measurements of the fourth Stokes parameter of sea surface brightness temperatures.

V. SUMMARY

A set of successful dual-frequency airborne radiometer flights were carried out to investigate the wind direction sensitivity of the Stokes parameters of microwave emissions from sea surfaces. The aircraft was banked at three different angles to acquire the data in the incidence angle range of 45° to 65”. There were as large as a few Kelvin signals observed in all Stokes parameters. Preliminary assessment of the frequency sensitivity, incidence angle dependence, and wind speed dependence was performed. It was found that the wind direction signals have a broad frequency spectrum from 19 to 37 GHz. The up and downwind asymmetry of sea surface brightness had a small increasing trend versus incidence angle, while the up and crosswind asymmetry may have a dramatic variation with incidence angle. The observed magnitudes of azimuthal wind direction signals in T_v and T_h, though weak compared with the direction-independent terms (T_{v0} and T_{h0}), are easily measurable with present microwave radiometers. In addition, the third and fourth Stokes parameters, U and V, which have an odd symmetry with respect to the wind direction, hence free of the zero harmonic term, are also measurable with a single antenna plus microwave switch network design. The results indicate that spaceborne passive microwave radiometers have a strong potential for ocean wind remote sensing.

However, further flight experiments are required to gather data at low wind (3 to 5 m/s) and high wind (above 15 m/s) to allow a more complete evaluation of the wind speed dependence of wind direction signals in sea surface brightness temperatures. The effects of other environmental variables, including air and sea surface temperatures (SST), significant wave height, and atmospheric water content, also need to be investigated. The permittivity of sea surfaces is a function of SST, meaning that a change of SST will lead to a change of surface emissivity and the magnitudes of all harmonic coefficients. In addition, the air and sea surface temperature difference affects the stability of surfaces and the onset of breaking waves. The whitecaps caused by breaking waves are known to be a significant microwave radiation source. The large *scale* waves and swells would affect the local incidence angle and the friction velocity or wind stress of sea surfaces, which directly influences the magnitude of short-scale wind waves and therefore the modulation of microwave emission from sea surfaces. Atmospheric liquid water and water vapor in addition to other constituents, will attenuate the microwave emission from the surface, and the atmospheric downwelling reflection from the surface has a negative effect on the wind direction signals in the surface emission. The effects of these variables need to be quantified to understand the limitation of passive microwave radiometry and to develop techniques applicable to reduce these effects for ocean wind remote sensing.

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