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MICROWAVE REMOTE SENSING OF OCEAN SURFACE WIND SPEED AND RAIN RATES OVER TROPICAL STORMS

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ABSTRACT

The value of using narrowly spaced frequencies within a microwave band to measure wind speeds and rain rates over tropical storms with radiometers is reviewed. The technique focusses on results obtained in the overflights of Hurricane Allen during 5 and 8 of August, 1980.

Introduction

On 5 and 8 August, 1980, a C-Band Stepped Frequency Microwave Radiometer (SFMR) overflow Hurricane Allen for the purpose of measuring rain rate and ocean surface wind speed. The SFMR was placed in a mode whereby it could sequentially step between frequencies of 4.5, 5.0, 5.6, and 6.6 GHz. The strategy of the experiment was to recognize that the rain column is only weakly attenuating at C-Band, thus providing continuous observations of the wind-driven ocean surface, even for heavy rain rates. The frequency stepping technique was devised as a means to separate dispersive atmospheric emission from the nondispersive ocean surface emission. The envelope of four-frequency brightness temperatures will increase and decrease in proportion to the percentage of surface foam, and is therefore a measure of the surface wind speed. The relative differences in brightness temperature is a measure of the rain opacity, which is at least proportional to the square of the electromagnetic wavelength.

The preliminary results were reported in a brief paper(1). Because of space limitations, the retrieval scheme was presented without derivation. A more detailed derivation will be given here, including a brief discussion of the results that have already been reported.

In the time period since the original results were reported, the activity has concentrated on upgrading the algorithm, and resolving calibration issues that surfaced in the detailed analysis of the data. Deadline pressures for the publication of this paper have precluded presentation of graphics; however, the results will be presented during the oral delivery of the paper.

Derivation of the Algorithm

As usual, all first principle algorithms used for the analysis of microwave radiometer data begin with the radiative transfer equation, which is given by:

$$T_B = (1-\varepsilon)\, T_C\, e^{-2\tau_\infty} + T_{AIR} + (1-\varepsilon)\, T_{AIR}\, e^{-\tau_\infty} + \varepsilon\, T_S\, e^{-\tau_\infty} \quad (1)$$

where:

T_B = brightness temperature
ε = surface emissivity
τ_∞ = atmospheric opacity
T_S = ocean surface temperature
T_C = residual 2.7K cosmic background

The quantity T_{AIR} is the equivalent brightness temperature of the atmospheric column which, in the absence of scattering, is given by

$$T_{AIR} = \int_{\tau(o)}^{\tau(h)} T(z)\; e^{-\tau(z)}\; d\tau(z)$$

Where z is a distance above the surface, h is the height at which observations are conducted, $T(z)$ is the true air temperature at height z, and $\tau(z)$ is the opacity at z.

If we conduct measurements at high altitudes so that $\tau(h) \approx \tau_\infty$, and replace $T(z)$ by some average temperature $\langle T \rangle$, then it easily follows that

$$T_{AIR} = \langle T \rangle\, [1 - e^{-\tau_\infty}] \quad (2)$$

We now rearrange (1) to express T_B in the following form:

$$T_B = T_C\, e^{-2\tau_\infty} + T_{AIR}\, [1 + e^{-\tau_\infty}] + \varepsilon\, [T_S\, e^{-\tau_\infty} - T_C\, e^{-2\tau_\infty} - T_{AIR}\, e^{-\tau_\infty}] \quad (3)$$

Substituting (2) into (3) gives

$$T_B = T_C\, e^{-2\tau_\infty} + \langle T \rangle\, [1 - e^{-2\tau_\infty}] + \varepsilon\, [(T_S - \langle T \rangle) + (\langle T \rangle - T_C)\, e^{-\tau_\infty}]\, e^{-\tau_\infty} \quad (4)$$

As a first iteration, we assume that $T_S \approx \langle T \rangle$, in which case, the surface emissivity becomes

$$\varepsilon \cong \frac{\left[\frac{\langle T\rangle - T_C}{\langle T\rangle}\right] - \left[\frac{\langle T\rangle - T_B}{\langle T\rangle}\right] e^{2\tau_\infty}}{\frac{\langle T\rangle - T_C}{\langle T\rangle}} \tag{5}$$

We now ass ι e that the opacity due to rain varier with electromagnetic frequency to some power k, and that the emissivity is constant over the bandwidth of the measurements. Thus, if f_1 is the lower frequency, and f_2 is the upper frequency, (5) can be expressed as two simultaneous equations to eliminate ε and solve for τ_R, the opacity due to rain at frequency f_1. The result is:

$$e^{-\tau_R} = \left[\frac{\langle T\rangle - T_B(f_2)}{\langle T\rangle - T_B(f_1)}\right]^{\left[\frac{1}{2\,[(f_2/f_1)^k - 1]}\right]} \tag{6}$$

Where $T_B(f_2)$ is the measured brightness temperature at the upper frequency and $T_B(f_1)$ is that at the lower frequency. In the original paper, the exponential k was empirically determined through a best fit to the surface truth. This ad hoc procedure is not necessary if a third frequency is utilized. The surface emissivity is determined by solving for the opacity using (6), and substituting the result into (5). Wind speed and rain rate are then empirically derived from the retrieved values of ε and τ_R. With ε_o as the emissivity of smooth water, the following linear relationship between increased brightness temperature ΔT_B and wind speed W was assumed:

$$\Delta T_B = (\varepsilon - \varepsilon_o)\, T_S = K_1\, W \tag{7}$$

where K_1 was assumed to be 0.7KM•sec^{-1}. The rain rate R was assumed to be a linear function of τ_R, such that

$$R = K_2\, \tau_R \tag{8}$$

A value of K_2 = 320 mm: ·r ^{1} was assumed for the retrievals, which was later found to be high by approximately a factor of 2.

Summary of Initial Results

The first of many passes through Hurricane Allen was north to south. The radiometric brightness temperatures for 4.5, 5.0, 5.6, and 6.6 GHz are shown in figure 1. Heavy rain rates in the northern eye wall (point A) result in a large

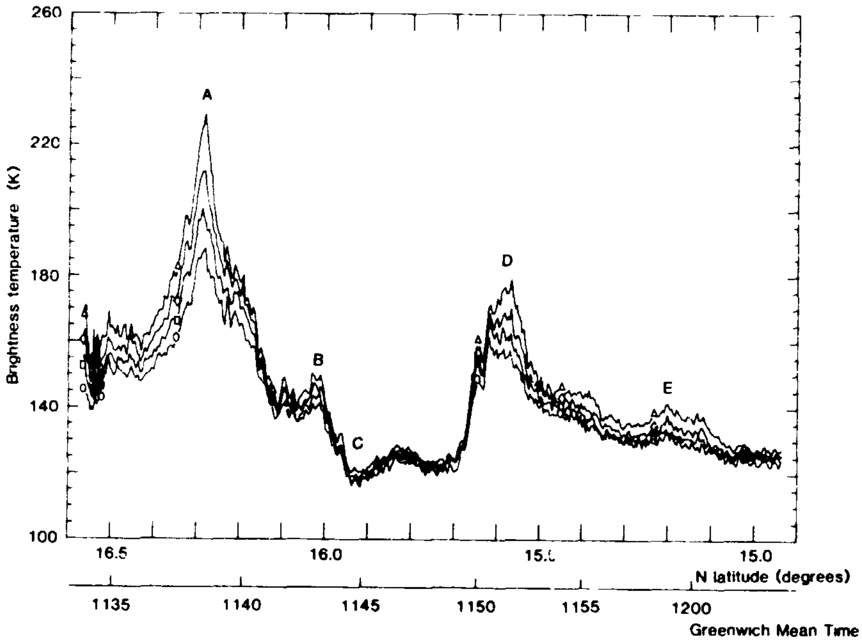

Fig. 1. Radiometer brightness temperature at four frequencies between 4.5 and 6.6 GHz. Higher brightness temperatures are associated with higher frequencies.

separation between the curves for 4.5 and 6.6 GHz. Point B locates the presence of an inner eye wall, and point C is the center of the eye where data from all frequencies merge, indicating no rain. Some rain is indicated in the southern eye wall, (point D). The variation of the envelope is indicative of the variation in ocean surface wind speed at points along the pass. Retrievals of wind speed and rain rate are shown in figures 2 and 3, respectively. The discrete points represent in situ measurements which were used to determine the exponent k that describes the wavelength dependency of the opacity.

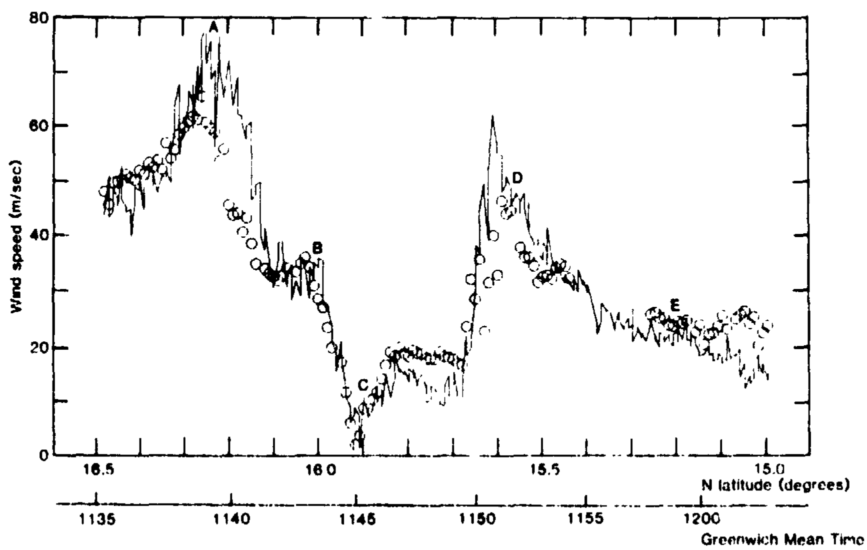

Fig. 2. Surface wind speed derived from magnitude of radiometer brightness temperature (continuous line) and from the P-3 flight-level inertial navigation system (cycles).

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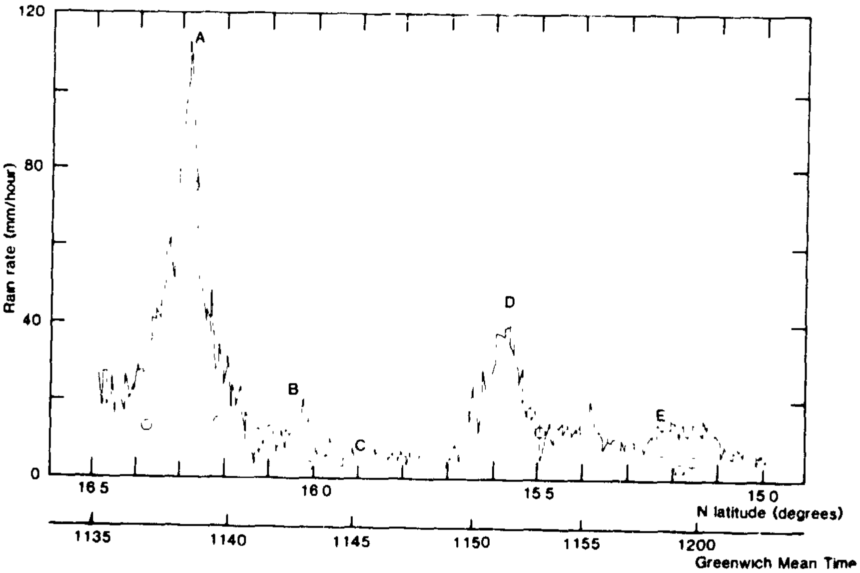

Fig. 3. Rain rate derived from magnitude of radiometer brightness temperature (continuous line) and from the radar composite obtained from the P-3 (circles).

The major conclusion to be drawn from these results is that the SFMR can measure wind speeds exceeding 70 m sec^{-1}, and rain rates exceeding 50 mm $\cdot$ hr^{-1}. A potential technique of observing hurricanes from safe altitudes was therefore demonstrated.

Present Status of Data Analysis

Over a score of passes through Hurricane Allen have been analyzed by the NASA Langley Research Center using a two frequency algorithm. The activity at the University of Massachusetts has focussed on advancing the algorithm and resolving calibration issues that were discovered in the detailed analysis of the data. The algorithm has been modified to include more detail, such as atmospheric lapse rate, and a variable wavelength dependency of rain attenuation based on published data. Work is well underway to develop a three-frequency algorithm to retrieve not only rain rate, and ocean surface wind speed, but also the wavelength dependency factor, k. This is done by introducing a third frequency f_3, and interacting equation (6) to retrieve k.

The calibration issue has been resolved, and self-consistent retrievals of rain rate and wind speed are achieved by using various combination of frequency pairs.

Concluding Remarks and Generic Issues

The major impact of this research is that a means is now available to probe hurricanes at safe altitudes above the storm, rather than routinely sending aircraft into the turbulent and dangerous boundary layer. In addition, the retrieval algorithm is so simple that real time processing is possible to relay first order estimates of rain rate and ocean surface wind speed to a central weather facility. Thus, meteorologists can quickly assess the status of the storm and perhaps predict its path. More research flights are needed to better refine the algorithm. For example, research is needed to relate rain opacity to rain rate; and it is not clear at this time that there is a simple linear relationship between wind speed and increased brightness temperature. There is also a fundamental need to relate the remote sensing measurement to ocean surface wind stress. Finally, there is a need to determine whether or not the stepped frequency technique can be used to infer rainfall over land. There is a potential of doing this by observing relative differences in brightness temperature between frequencies, and ignoring the envelope, which is presumably the spatial variation in the emissivity of land.

At the present time, more aircraft flights are needed in connection with high quality surface truth.

References

Jones, W. L., P. G. Black, V. E. Delnore, and C. T. Swift, 1981: Airborne microwave remote sensing measurements of Hurricane Allen. Science, 214, 274-280.