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Observations of Thermal and Precipitation Structure in a Tropical Cyclone by Means of Passive Microwave Imagery near 118 GHz

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ABSTRACT

An imaging microwave radiometer with eight double-sideband channels centered on the 118-GHz oxygen resonance was flown on a high-altitude aircraft over a tropical cyclone in the Coral Sea. The measurements clearly resolved an eyewall of strong convection and a warm core within the eye. Brightness temperatures observed within the eye were approximately 10 K warmer than those observed in clear air 100 km or more away. This warming extended somewhat beyond the eyewall in the highest (most opaque) channel. The temperature profile in the eye, central pressure, and convective cell-top altitudes are inferred from the data.

. Introduction

A tropical low developed in the Coral Sea, approximately 500 km east-northeast of Townsville, Australia, in the first week of February 1993. It was declared Tropical Cyclone Oliver on 6 February, and for the next several days it moved slowly southward. This system provided an excellent opportunity for study by National Aeronautics and Space Administration (NASA) aircraft-borne instruments based in Townsville while participating in the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). This paper describes the observations made by the Massachusetts Institute of Technology Millimeter-wave Temperature Sounder (MTS) from a NASA ER-2 high-altitude aircraft, which flew over the eye of Tropical Cyclone Oliver twice on 7 February. A preliminary discussion of this data was presented by Schwartz et al. (1994). Spencer et al. (1994) described measurements of Oliver by another instrument on the ER-2, the Advanced Microwave Precipitation Radiometer.

The MTS is a cross-track scanning microwave spectrometer with eight double-sideband channels within 2 GHz of the oxygen resonance at 118.75 GHz, supplemented by a 107° wide-angle video camera. The 118.75-GHz Dicke radiometer consists of a stationary scalar feed horn and fixed subreflector with a 7.5° beamwidth viewing a scanned mirror. All views are chopped at 25 Hz against an ambient temperature Dicke reference load. Symmetric sidebands from 330 to 2030 MHz of the resonance are mixed into a common intermediate frequency (IF) from which eight channels are filtered and synchronously detected. Fourteen spots between −46.8° and +46.8° from nadir, a heated target, and an ambient temperature calibration target are viewed during each 5.5-s scan. Resolution of a horizontal surface from 20 km is 2.6 km at nadir. Along the flight track it is degraded for views away from nadir by the secant of the viewing angle and across the track by the secant squared, with a scan every 1.1 km for a nominal aircraft velocity of 400 knots. Actual resolution depends upon the altitude being imaged. Eight channels are filtered from the common IF and synchronously detected. This instrument, and its use in the profiling of atmospheric temperature and precipitation, has been described by Gasiewski et al. (1990).

Absorption within 2 GHz of the line is primarily due to oxygen, which is extremely well mixed in the atmosphere, permitting retrieval of physical temperature profiles from thermal atmospheric radiances in the absence of precipitation. The eight MTS channels have double-sideband passbands symmetrically spaced from 470 to 1880 MHz from the line center, with widths ranging from 170 to 290 MHz. The opacity due to oxygen of a standard tropical atmosphere varies from 4 to 6 Np (nepers) in the passband of the 470-MHz channel while only from 0.9 to 1.1 Np in the 1880-MHz channel. (One neper is an attenuation by $1/e$.) When viewing nadir from a 20-km altitude (60-hPa pressure), the MTS channels provide the clear-air temperature weighting functions shown in Fig. 1. The component reflected from the surface, shown here for a flat ocean, is significant for the lower altitude weighting functions. Absorption and scattering by water vapor, cloud water, and precipitation may significantly perturb

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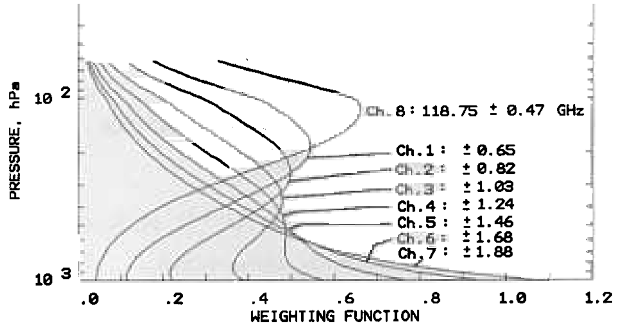

FIG. 1. Temperature weighting functions in a tropical model atmosphere.

these weighting functions. Figure 2 compares the absorption due to oxygen and water vapor at various altitudes in a standard tropical atmosphere to that due to various size distributions of liquid and solid hydrometeors.

Tropical humidities are such that, at the earth's surface, absorption due to water vapor is typically stronger than that due to oxygen, even at the 118-GHz oxygen line center. However, above 5-km altitude, water vapor contributes less than 0.05 Np km^{-1} in the MTS passband. The degree to which liquid water and ice perturb observed radiances depends upon their size distribution, density, and altitude. Such perturbations of upwelling brightness at a particular altitude will be attenuated, at the very least, by oxygen absorption in overlying layers before reaching the receiver. Perturbers at altitudes below the bulk of a weighting function will not have a large effect on the radiance observed in the corresponding channel. Absorption by cloud liquid water is only weakly dependent on particle size and so is primarily a function only of cloud density. Absorption due to ice is generally negligible. Rain and ice distributions with mean radii larger than 100 μm and densities of 0.1 g m^{-3} or larger are effective scatterers. Most cirriform clouds are negligible perturbers of upwelling radiances near 120 GHz, but scattering from large, dense graupel in the tops of convective cells produces dramatic decreases in the radiances observed in transparent MTS channels. Such scattering results in the replacement of warm upwelling radiation from the lower atmosphere by scattered cosmic background radiation, resulting in perturbations as large as 200 K (Gasiewski et al. 1990). An indication of cell-top height may be obtained from the degree to which these perturbations diminish for the more opaque channels. Liquid hydrometeors, which both absorb and scatter significantly, typically produce less dramatic cooling of observed brightnesses than those caused by glaciated cells. Thus, the MTS provides an "altitude-sliced" probe of precipitation cell structure, which is often obscured in visible or infrared observations by overlying clouds.

2. Instrument calibration

The MTS was calibrated by viewing two blackbody targets at the end of each 5.5-s scan—an ambient target that typically drops to 260 K during a 5-h flight and a 335-K heated target. The temperatures of these targets were monitored with thermocouples. The time-dependent linear system gain and offset were estimated for each channel. Typically the calibration counts vary slowly, with gradual changes in instrument gain and changes in the temperatures of the ambient target and the unheated Dicke reference target. A 25-scan-wide triangular filter was applied to the calibration counts to reduce noise. Occasionally the system exhibited sharp discontinuities in gain, generally correlated across all of the 118.75-GHz channels. Breakpoints, which calibration filters must not cross, were marked manually during preprocessing, allowing the estimated gain to retain these sharp discontinuities.

Small departures from linearity of the instrument response are evident in observations of an absorber immersed in liquid nitrogen, as well as in zenith observations from a 20-km altitude when the MTS has been flown in an upward-looking configuration. Such cold space measurements, with radiances departing from those of the calibration targets by more than 260 K, are very sensitive to problems in calibration. Errors of several degrees have been noted in radiances for the cold space measurements for some of the channels, and work is underway to apply calibration corrections derived from these uplooking measurements to the downlooking measurements. No such corrections have been made in the data presented here. However, corrections to the downlooking data would be expected to be on the order of 2 K or less, and our primary interest here is in the horizontal variation of the measurements, not their absolute value.

Portions of the data from the cyclone flight contain interference that results in quasi-periodic bands in the imagery. The bands maintain their orientation with the aircraft through turns and banks, ruling out a geophysical explanation of their presence. This interference has varying peak-to-peak amplitude reaching several degrees, is well correlated in all channels, and has a typical (possibly aliased) period of one to a few scans. These bands are readily discernible by eye, but have proved difficult to characterize in the frequency domain because of their closeness to the scan frequency, which is the highest observable frequency along the flight track and the highest uniform sampling rate. Sharp discontinuities in brightness of the transparent channels observed while crossing the eyewall also have high frequency components, but the most opaque channel is only minimally perturbed by the eyewall, permitting instrument interference to be discerned from geophysical signal. Interference was removed by first subtracting from each channel the high frequency component of the most opaque channel, then low-pass filtering