Passive Microwave Imagery of a Tropical Storm near 118 GHz
Thermal and Precipitation Structure

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ABSTRACT

An Imaging microwave radiometer with eight double-sideband channels centered on the 118.75-GHz (1-) oxygen resonance was flown on a NASA ER-2 high altitude aircraft over a tropical cyclone in the Coral Sea, east of Australia. An eyewall of strong convection and a warm core within the eye are clearly visible. Brightness temperatures observed within the eye are approximately 10K warmer than those observed in clear air 100-km away. This warming extends somewhat beyond the eyewall in the highest (most opaque) channel. Two passes three hours apart may reveal a slight weakening of the convective activity. This flight provides the first known calibrated high-resolution 118.75-GHz imagery of a tropical storm. Temperature profiles and cloud-top altitudes may be inferred from the data.

INTRODUCTION

A tropical low developed in the Coral Sea, approximately 500-km ENE of Townsville, Australia in the first week of February, 1993, was declared Tropical Cyclone Oliver on February 6, and for the next several days moved slowly southward. This system provided an excellent opportunity for study by 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-(MIT) Millimeter-wave Temperature Sounder (MTS) from a NASA ER-2 high-altitude aircraft which overflew the eye of Cyclone Oliver twice on February 7.

DESCRIPTION OF THE INSTRUMENT

The MTS is an imaging microwave spectrometer with eight double-sideband channels within 2-GHz of the oxygen (1-) resonance at 118.75-GHz, and a 107° wide-angle video camera. The 118.75-GHz Dicke radiometer consists of a stationary scalar feed horn and a fixed subreflector with a 7.5° beamwidth viewing a scanned mirror. Fourteen spots between +/-46.8° from nadir, a heated and an ambient temperature calibration load are viewed in each 5.5-second scan. The eight channels are filtered from the common IF and synchronously detected. The use of this instrument for the profiling of atmospheric temperature and precipitation has been discussed 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 a nonscattering atmosphere. The eight MTS channels have double-sideband passbands symmetrically spaced from 470- to 1880-MHz of the line center (Table 1). When viewing nadir from ~20-km altitude, they provide clear-air temperature weighting functions which peak, successively, at altitudes from 15-km to the earth's surface. Water vapor and liquid water, when present, also provide significant contributions to absorption. Liquid or solid hydrometeors larger than 1 mm in diameter are effective scatterers.

Table 1. *MTS Passbands*

MTS Channel number	Sideband Center frequency (GHz)	Sideband Width (MHz)
8	118.75 ± 0.47	210
1	118.75 ± 0.65	170
2	118.75 ± 0.82	240
3	118.75 ± 1.03	270
4	118.75 ± 1.24	270
5	118.75 ± 1.46	250
6	118.75 ± 1.68	270
7	118.75 ± 1.88	290

Thin cirrus clouds, though optically opaque, contribute only small perturbations to observed brightnesses. However, scattering from ice in the tops of convective cells produces dramatic decreases in radiances observed in the transparent channels. Warm, upwelling radiation from the lower atmosphere is replaced by scattered cosmic background radiation, resulting in perturbations as large as 200 K (Gasiewski, 1990). Thus the MTS provides a probe of precipitation cell structure through clouds as well as clear-air temperature soundings.

CYCLONE OLIVER FLIGHT

The TOGA COARE Intensive Observing Period, from November 1992 through February 1993, was an intensive study of the western Pacific warm pool system. ER-2 flight 93-061 was a five-hour mission which contained two passes over the eye of Cyclone Oliver as well as multiple crossings of associated convective cells on the east side of the system. The first crossing of the eye was west-to-east, at 17:00 GMT, and the second, back along approximately the same line east-to-west, was at 20:00 GMT. The aircraft (pressure) altitudes were 19.7 km and 20.0 km on the two passes (Figure 1).

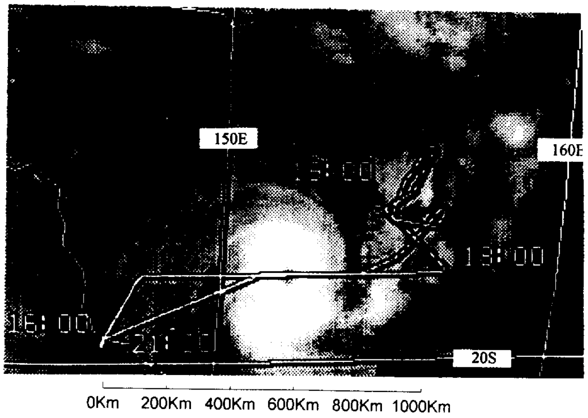

Figure 1.
GMS IR 7 FEB 93036 18:34:00 with ER-2 Flight Track
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INSTRUMENT CALIBRATION

The MTS is calibrated by viewing two black-body loads at the end of each 5.5-sec scan: an ambient load which typically drops to 260K during a six hour flight, and a 335K heated load. The temperatures of these loads are monitored with thermocouples. Linear system gain and offset are estimated for each channel. Typically the calibration counts slowly vary with gradual changes in instrument gain, and with changes in the temperatures of the ambient load and the unheated Dicke reference load. A 25-scan-wide triangular filter was used to reduce noise in the calibration counts. Occasionally the system exhibits sharp discontinuities in gain, generally correlated across all of the 118.75-GHz channels. Breakpoints, which calibration filters may not cross, are 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 observations of cold space from 20 km when MTS has been flown in an upward-looking configuration. The cold space measurements, with radiances departing from those of the calibration loads by more than 260K, are extremely sensitive to problems in calibration. Errors of several degrees have been noted in retrieved radiances for the cold space measurements for some of the channels, and work is underway to apply calibration corrections derived from these measurements to measurements of upwelling radiances. No such corrections have been made in the data presented here.

Imagery of the radiances from portions of the cyclone flight contained interference in the form of quasiperiodic bands near the nyquist rate of the scan frequency. Peak-to-peak amplitude approached several degrees. These bands were readily discernible by eye, but proved difficult to characterize in the frequency domain because of their closeness to the scan frequency, the highest uniform sampling rate. This interference was best removed by lowpass filtering the images along the direction of flight. Each scan was averaged with the mean of its nearest neighbors. Image resolution along the flight path is somewhat degraded by this process, but is still far better than the cross-scan resolution at scan angles far from nadir.

MTS DATA IMAGES

In producing imagery of storms, the deviations of a given channel and scan angle's radiances from those of nearby clear air are typically most useful. A baseline was set in a minimally perturbed region 250 km west of Oliver's eye (Figure 2). This baseline contains temperature profile information, including the limb-cooling, and its subtraction results in images of ΔT_B's showing the combined dramatic effects of scattering from graupel in the tops of convective cells, and the more subtle effects of scattering and absorption by liquid hydrometeors, and of changes in the temperature profile as a function of pressure.

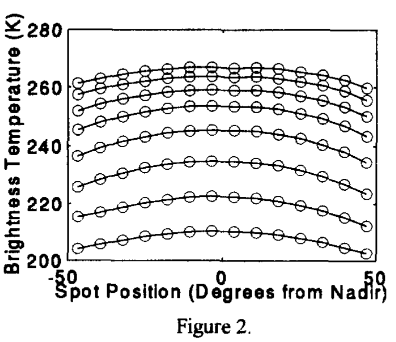

Figure 2.
Clear Air Brightnesses, 250-300 km West of the Eye

The two images of the eye of Cyclone Oliver clearly show the structure of the eyewall with dramatic drops in the brightness in the transparent channels (Figures 3, 4). The most opaque channel (8), has a weighting function which peaks above the cloud tops of the eyewall and it is unperturbed by their presence. The eye appears to be slightly smaller in the second crossing than in the first, with somewhat less intense convection in the eyewall, but the significance of these observations is questionable. The second pass misses the southern portion of the eyewall where convection, as indicated by sharp drops in the brightness temperatures of the transparent channels, appears to be most intense. The storm did appear to be somewhat weakened when observed on February 8 (NASA, 1993). In the clear eye, warming of radiances is observed through all channels. This warming is a combined result of warmer physical temperatures of the "warm-core" storm as well as the reduced atmospheric pressure which causes the weighting functions of all channels to shift to somewhat lower altitudes. These phenomena have been observed, *in situ*, in other tropical storms (Hawkins and Imbembo 1975). Such microwave warmings in the opaque oxygen band near 55-GHz were used to estimate winds in Hurricane June using the thermal wind equation (Grody, *et al.* 1979). The ~10 K warming evident here suggests that the 50-km spatial resolution of the AMSU-A temperature sounder on future weather satellites will be able to monitor the strength of ordinary hurricanes comparable to Oliver.

Variations in water vapor density and, in the most transparent channels, in sea surface roughness, also perturb the brightnesses observed in the eye (Rosenkranz *et al.*, 1978). The combined data set from the suite of instruments on the ER-2, as well as those on a NASA DC-8 which made several flights through Oliver, provides an unprecedented opportunity to sort out these effects.

CLOUD TOP ALTITUDE RETRIEVAL

A muiltilayer feed-forward neural network has been developed to retrieve convective cell-top altitudes from MTS data (Spina, 1994). Data from the February 7, 1993 flight has been processed with this net to produce cloud-top altitude imagery (Figure 5). These are preliminary results. The training set consisted of the peaks of cells and of near-nadirial views only, so retrieved altitudes on the flanks of clouds and at large scan angle should be discounted; also, the training set included no truly tropical conditions, and definitely no hurricanes, so conditions in Oliver may be somewhat outside of the training space. These considerations aside, the neural network has been demonstrated to be a definite improvement over previously-used estimators of cell top altitude using microwave radiometry.

Work is in progress to verify these retrieved altitudes with other measurements. Estimates based upon the MTS video imagery, such as image transit time (linear with altitude) or parallax analysis may be possible in the low light conditions of the second eye pass, but will be impossible in the predawn darkness of the first. Unfortunately, the DC-8 with its lidar and radar was not flown in conjunction with the ER-2 on this date. Data from the closest DC-8 passes will be pursued.

Figure 3.
First Eye Crossing, 16:55 - 17:09

Figure 4.
Second Eye Crossing, 19:54 - 20:07

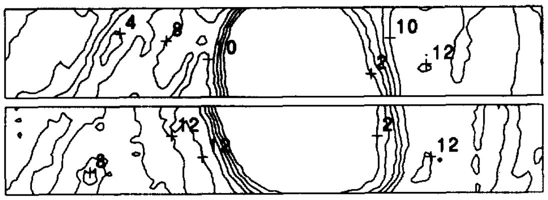

Figure 5.
Neural Net Retrieval of Cloud-Top Altitude, 2 km Contours

CONCLUSIONS

MTS data from the February 7, 1993 flight over Cyclone Oliver provides a wealth of information on the morphology of the storm. These observations provide the first calibrated, high-resolution 118.75-GHz images of a tropical cyclone. The temperature and cloud-top profiling capabilities provided by the successively more opaque MTS channels and the ability to image scatterers through clouds make this data a valuable addition to the combined data set.

REFERENCES

Gasiewski, A.J., J.W. Barrett, P.G. Bonanni and D.H. Staelin. "Aircraft-based Radiometric Imaging of Tropospheric Temperature and Precipitation Using the 118.75-GHz Oxygen Resonance." *Journal of Applied Meteorology* 29 (1990): 620-632.

Gasiewski, A.J. and D.H. Staelin. "Statistical Precipitation Cell Parameter Estimation Using Passive 118-GHz O_2 Observations." *Journal of Geophysical Research* 94 (1989): 18,367-18,378.

Grody, N.C., C.M. Hayden, W.C.C. Shen, P.W. Rosenkranz and D.H. Staelin. "Typhoon June Winds Estimated From Scanning Microwave Spectrometer Measurements at 55.45 GHz." *Journal of Geophysical Research* 84 (1979): 3689-3695.

Hawkins, H.F. and S.M. Imbembo. "The Structure of a Small, Intense Hurricane - Inez 1966." *Monthly Weather Review* 104 (1976): 418-442.

Rosenkranz, P.W., D.H. Staelin and N.C. Grody. "Typhoon June (1975) Viewed by a Scanning Microwave Spectrometer." *Journal of Geophysical Research* 83 (1978): 1857-1868.

Spina, M.S., M.J. Schwartz, D.H. Staelin and A.J. Gasiewski. "Application of Multilayer Feedforward Neural Networks to Precipitation of Cell-Top Altitude Estimation," in International Geoscience and Remote Sensing Symposium, 1994.

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