

## NOTES

**Nimbus-7 37 GHz Radiances Correlated with Radar Rain Rates over the Gulf of Mexico**

ROY W. SPENCER,\* BARRY B. HINTON\* AND WILLIAM S. OLSON\*\*

\*Space Science and Engineering Center and \*\*Department of Meteorology, University of Wisconsin-Madison, 53706

16 April 1983 and 19 August 1983

## ABSTRACT

In a comparison between 37 GHz brightness temperatures from the Nimbus 7 Scanning Multichannel Microwave Radiometer and rain rates derived from the WSR-57 radars at Galveston, Texas and Apalachicola, Florida, it was found that the brightness temperatures explained 72% of the variance of the rain rates. The functional form relating these two types of data was significantly different from that predicted by models of radiative transfer through plane-parallel clouds. Most of the difference can be explained in terms of the partial coverage of footprints by convective showers. Because residual polarization is always present, even for large obscuring storms over land and water, it is hypothesized that emission by nonspherical hydrometeors is at least partly responsible for the observed polarization.

**1. Introduction**

The transfer of 37 GHz microwave radiation through rain over the ocean has usually been modeled with horizontally infinite clouds of spherical hydrometeors (e.g., Savage, 1976; Weinman and Guetter, 1977; Rodgers *et al.*, 1979; Olson, 1983; Huang and Liou, 1983). Typically, the results of these experiments show that the emission from rain raises the observed brightness temperature above that of the ocean surface, which appears relatively cold because of its low emissivity, until the rain rate reaches 5 to 10 mm h<sup>-1</sup>. The brightness temperature decreases gradually at higher rain rates to an asymptotic limit for rain rates greater than about 20 mm h<sup>-1</sup>. This decrease above 5 to 8 mm h<sup>-1</sup> is partly due to scattering of upwelling radiation, as well as emission at lower temperatures. As the rain cloud becomes more dense at higher rain rates, the radiative emission seen by a downward looking radiometer originates from increasingly higher (colder) levels.

Over the tropics and warmer regions, however, the ~500 km<sup>2</sup> footprint of the 37 GHz channel of the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR, Gloersen and Hardis, 1978) is probably seldom filled with rain (except occasionally in the special case of tropical cyclones). This is because of the relatively small size of individual showers and the multicellular nature of shower complexes. This effect had been observed during the GATE (GARP Atlantic Tropical Experiment) when the Nimbus 5 ESMR (Electrically Scanning Microwave Radiometer), a 19.35 GHz instrument, was used to estimate rainfall and the results were compared to radar measurements (Medrow *et al.*, 1982; Austin and Geotis, 1978). It was found that the satellite underestimated the rain rates by 40

to 50% when compared to the radar estimates. It was also found that the microwave sensor footprint filling estimated by radar could not alone account for the differences between the radar and satellite measurements.

We present observations that reveal the departures of observed 37 GHz radiation from plane parallel theory for warm season showers over the Gulf of Mexico, and discuss some possible explanations for the observed discrepancies.

**2. SMMR and radar observations**

Coincident radar and SMMR 37 GHz observations were analyzed over the Gulf of Mexico within the 230 km radius scans of the WSR-57 radars operated by the U.S. National Weather Service (NWS) at Galveston, Texas on five days and at Apalachicola, Florida on one day (Table 1). Reflectivities from radar Plan Position Indicator (PPI) microfilm records were manually digitized on a 20 km grid and converted to average rain rates for each 20 × 20 km bin (see Spencer *et al.*, 1983a). The possible errors in these radar measurements of rain rate are numerous. For the particular radars and storm types in this study the uncertainty is estimated to be ±60%. This estimate is based upon the operational nature of the WSR-57's, the use of only six discrete reflectivity display levels, and the manual digitization of microfilm images of variable quality. Nevertheless, the radars and SMMR have similar temporal and spatial sampling characteristics; i.e., they both observe instantaneously over spatially continuous areas.

Data from approximately 35 storms were included. Images were generated from both the digitized rain rates and the SMMR observations on the University

TABLE 1. Dates and times of SMMR and radar data used in this study.

Radar	Date	SMMR observation time (GMT)	Radar observation time (GMT)
Galveston, TX	16 April 1979	1801	1801
Galveston, TX	27 June 1979	1755	1756
Galveston, TX	7 July 1979	1735	1734
Galveston, TX	9 July 1979	0638	0639
Galveston, TX	13 July 1979	1744	1745
Apalachicola, FL	17 July 1979	0530	0538

of Wisconsin-Madison Man-computer Interactive Data Access System (McIDAS, Suomi *et al.*, 1983). The SMMR images were adjusted for navigation errors using the brightness temperature contrast of land-water boundaries. These errors were always less than 20 km, and after correction are within 5 km. The radar and SMMR images were sampled on a 20 km grid and geographically matched pairs of rain rate and brightness temperature were plotted (Fig. 1). The brightness temperatures are seen to increase as the bin averaged rain rates increase. A sixth power function of the 37 GHz brightness temperature (the curve shown in Fig. 1) has a correlation coefficient of 0.85, revealing that the SMMR horizontally polarized 37 GHz observations can account for 72% of the variance of the radar rain rates. The differences between the observed brightness temperatures and those predicted by plane-parallel theory (Olson, 1983, which assumes a rain filled sensor footprint) are marked, especially at low rain rates.

The differences between plane-parallel theory and observation are also substantial for the 37 GHz polarization (defined here as the vertical minus horizontal brightness temperature) as a function of rain rate (Fig. 2). The polarization of the radiation emanating from the ocean surface is typically 50–60°C after modification by the intervening atmosphere, which is taken into account by the model. The model indicates that the polarization should drop nearly to zero if the field of view is covered with a rain layer with rate above 5 mm h<sup>-1</sup>. These results are typical of most other investigations. A notable exception is the Huang and Liou (1983) general solution for the transfer of thermal radiation in scattering atmospheres, including the polarization effects of Mie particles. At 37 GHz they found that scattering results in *negative* polarization when the rain rate exceeds 7 mm h<sup>-1</sup>, reaching -2°C at 20 mm h<sup>-1</sup>. The observations (also in Fig. 2) reveal much larger, positive polarizations.

We first tried to explain these differences between plane-parallel theory and observation with partial footprint filling by the showers. The same rain systems were further analyzed from the PPI photographs. The fractional coverage of each 20 km bin by rain was estimated, as well as the average rain rate for the raining

portion of that bin. We used the theoretical relation between the horizontally polarized brightness temperature and rain rate to estimate the brightness temperature that should emanate from the raining portion of the bin. The nonraining portion was assigned a brightness temperature which was the value predicted by the model (166 K) and that observed to be typical of rain free portions of the Gulf. These two temperatures were area averaged. The result is plotted as a function of bin-average rain rate in Fig. 3. The relationship implied by these data is somewhat closer to the observed relationship between rain rate and brightness temperature, but some large differences remain. It was found that the difference seen here is relatively independent of the  $Z - R$  relationship used to derive the rain rates from the radar reflectivities.

An additional factor resulting in some discrepancy between the observed and theoretical relationships shown in Figs. 1 and 2 is rain cell geometry. The in-

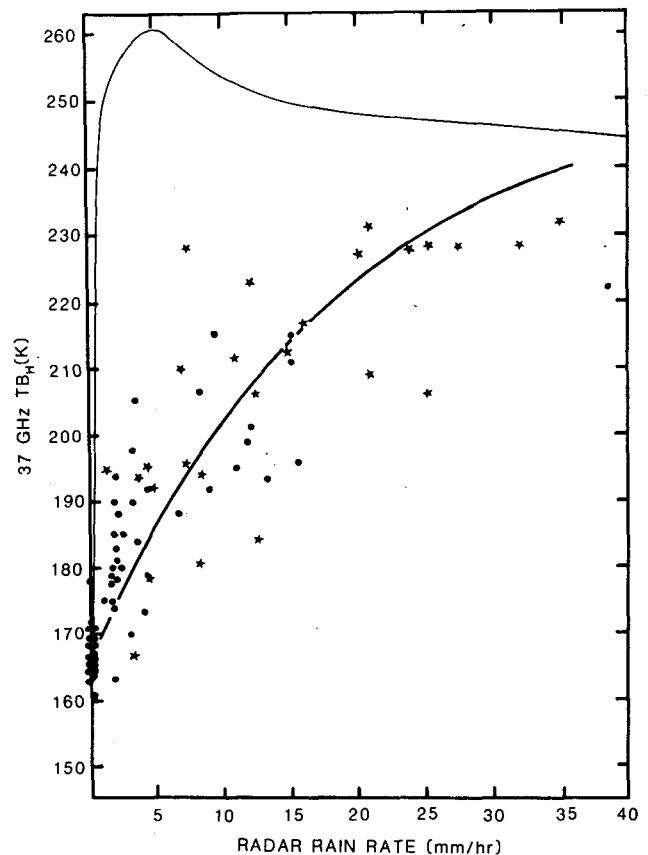


FIG. 1. Observed 37 GHz horizontally polarized brightness temperatures from the Nimbus 7 SMMR versus radar rain rates from the Galveston radar (dots) and Apalachicola radar (stars), manually digitized and assigned to 20 × 20 km bins. The line through the data points is a least squares fit of a function proportional to the sixth power of the brightness temperatures. The upper curve depicts the theoretical results of Olson (1983) for rain filled fields of view, and is representative of the results of many other investigators. The area averaged rain rates are estimated to be accurate to ±60%.

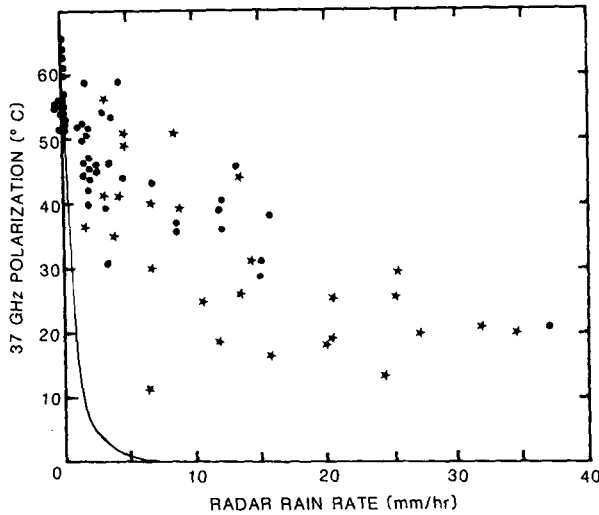


FIG. 2. Observed 37 GHz polarization (vertical minus horizontal brightness temperatures) versus the corresponding Galveston and Apalachicola radar rain rates. The curve in the lower left is the theoretical result of Olson (1983) for rain filled fields of view.

tensity of radiation upwelling from a model rain cloud of finite horizontal extent over the ocean is typically less than that upwelling from a plane-parallel cloud with the same height and rainfall rate. Weinman and Davies (1978) modeled rain cells with finite cloud geometry. Their results show that this effect is greatest for relatively small rain cells (less than  $\sim 6$  km diam) or relatively light rain rates (less than  $\sim 5$  mm  $h^{-1}$ ). The radar observations revealed that these are infrequently satisfied conditions. The average storm size was 15 km and the average storm rain rate was 15 mm  $h^{-1}$ , values at which the "finite cloud" effects are almost negligible.

If all the residual polarization at high rain rates were due to patches of the radiometrically cold ocean surface being in view, then the observed horizontally and vertically polarized brightness temperatures should both be lower than the theory predicts for radiation emanating from thick rain layers. This was not the case for the largest storms observed. A line of large (up to 80 km diam), intense thunderstorms observed by the Apalachicola, Florida radar had tops exceeding 14 km. Simultaneous SMMR 37 GHz observations revealed vertically polarized brightness temperatures up to 252 K (with 20°C polarization) in these storms, coincident with the heaviest rain rates which exceeded 30 mm  $h^{-1}$  averaged over 400 km<sup>2</sup>. Fig. 4 shows the observed 37 GHz vertically polarized brightness temperature—rain rate relationship for the showers observed by the Apalachicola and Galveston radars, along with the relationship derived from plane-parallel theory for rain filled footprints. The observed 37 GHz brightness temperatures of the Apalachicola storms are at least 5°C higher than the theory predicts at the highest rain rates. Corrections for the most obvious sources of errors in

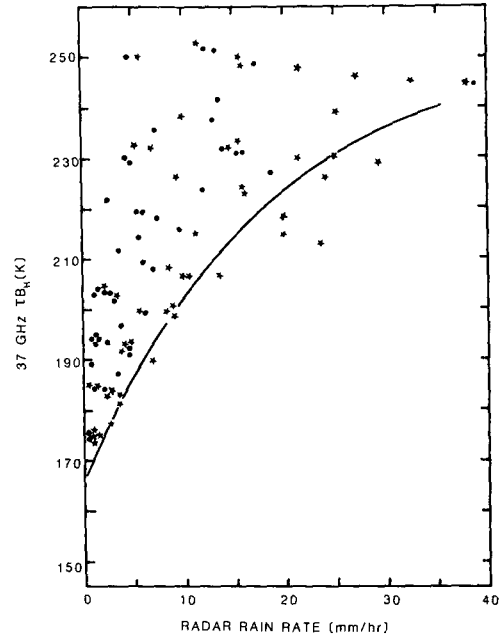


FIG. 3. Model 37 GHz horizontally polarized brightness temperatures estimated from the areal weighting of the brightness temperatures from Olson's model by the radar observed fractional covering of 20 x 20 km bins by rain and no rain, as a function of bin averaged rain rate. See Fig. 1 for details.

the model assumptions would lead to even a larger temperature difference. A more appropriate model that would include the great depth of the rain layer and the presence of ice would have produced much lower brightness temperatures, and the discrepancy between the model and observations would probably have exceeded 20°C. Spencer *et al.* (1983b) showed SMMR 37 GHz observations of heavy thunderstorms over land that exhibited vertically polarized brightness temper-

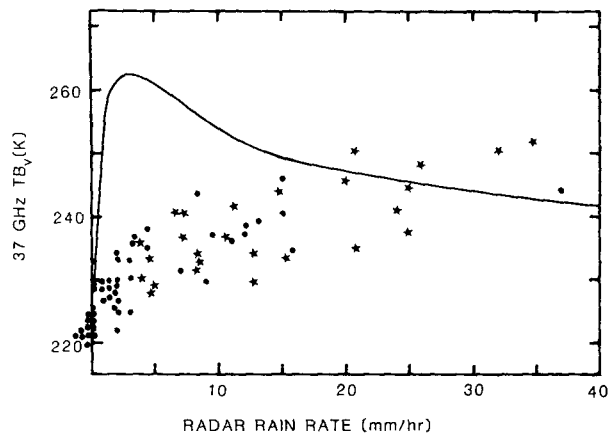


FIG. 4. Observed 37 GHz vertically polarized brightness temperatures from the Nimbus 7 SMMR and radar rain rates from the Galveston radar (dots) and Apalachicola radar (stars) manually digitized and assigned to 20 x 20 km bins. An eighth power least squares fit to the data has a correlation of 0.82. See Fig. 1 for details.

atures as low as 174 K, with 11°C polarization compared to 5–8°C polarization for the surrounding land. A more extensive sample of 37 GHz brightness temperatures of tropical convection scattered over a  $5 \times 10^5$  km<sup>2</sup> area in the Pacific (not shown) was compared to GOES-West infrared and visible pictures. The highest brightness temperature regions corresponded to deep convective activity. Again, these rain cells had polarizations above 10°C, with vertically polarized temperatures between 255 and 258 K. Thus, there is substantial evidence for a significant polarization of the radiation emanating from the tops of rain layers that is independent of the ocean surface contribution.

Two possible explanations for the observed polarization are scattering and emission of polarized radiation from nonspherical hydrometeors. Nearly all of the models of the upward transfer of passive microwave radiation through rain clouds to a downward looking radiometer, that we are aware of, contain the assumption that the raindrops are spheres that emit radiation isotropically. Huang and Liou (1983) have shown that scattering by spherical drops results in a slight negative polarization. However, raindrops, especially the larger ones, are not spheres but have a preferred flattened shape, with the short axis oriented vertically. The scattering properties of these drops have been studied extensively by communications engineers who have observed and modeled the marked differential attenuation effect these drops have on polarized microwave communication signals. A comprehensive review of much of this work is provided by Oguchi (1981). It is also possible that ice plates in the upper portions of the storms are partly responsible for the observed polarization. How the scattering and emission effects combine to produce the 10 to 20°C polarization that we observe with the widest and deepest (and thus most obscuring) storms we cannot say. These effects, however, should be addressed before useful quantitative rain estimates can be made from theoretically-based algorithms.

### 3. Conclusions and implications

From the aforementioned considerations, we conclude that *the footprint observed by the Nimbus-7 37 GHz radiometer is seldom covered by rain*. The same statement concerning footprint filling would be even more applicable to the 18 GHz channel since its footprint is approximately four times the size of the 37 GHz footprint. Additionally, due to the radar evidence for large numbers of optically thick rain showers (greater than 5 mm h<sup>-1</sup>), we conclude that *the primary cause of variations in observed 37 GHz brightness temperatures over the ocean is footprint filling by relatively opaque showers*. This contrasts with a simple application of plane-parallel theory in which the brightness temperatures vary only with the rain opacity at low rain rates (less than 5 mm h<sup>-1</sup>). Finally, because there

is always 10–20°C polarization present with the largest storms (even over land) *scattering and emission by precipitation probably contributes to polarization of the satellite-sensed radiation*.

Observations of showers at 37 GHz over the ocean contain much the same information as the radar-derived rain rates averaged over 20 × 20 km areas for approximately 35 storms observed on six days. The relationship between brightness temperature and rain rate in this limited group of observations is quite different than that given by plane parallel theory. The relatively high correlation between rain rate and the sixth power of brightness temperature (0.85) suggests that footprint filling (and possibly other) effects are naturally correlated with footprint-averaged rain rate. Thus, it may not be necessary to invoke multispectral satellite techniques (e.g., visible and infrared; see Smith and Kidder, 1978) to estimate the footprint filling independently, unless rainfall information is sought on a spatial scale finer than that provided by the microwave sensor.

Additional modeling of typical size and shape distributions of tropical showers within the radiometer field of view, and the scattering and emission characteristics of the raindrops within these showers over the ocean, should help to explain the observed brightness temperature—rain rate relationship. We suggest that modifications of plane-parallel models are needed before they can provide accurate estimates of rain rate, particularly in regions where the radiometer's relatively large field of view is seldom filled with rain. Alternatively, an empirical algorithm based upon large numbers of SMMR and radar comparisons over coastal waters covered by these radars should provide useful estimates of oceanic rain rate. If the observed relationship (or one like it) holds up over the tropics and other showery regions, it should prove more useful than the theoretical relations until they are modified to deal adequately with beam filling, the presence of ice, the variable depth of the rain layer, and precipitation-induced polarization of radiation.

*Acknowledgments.* This work benefited from discussions with Dr. David Martin and Professor James Weinman. Funding for this study was provided by the National Oceanic and Atmospheric Administration National Earth Satellite Service through Grant NA-80-SAC-00742. We wish to thank Per Gloersen and William Abbott of the Goddard Space Flight Center for their generous provision of SMMR data. The manuscript was typed by Angela Crowell and Jody Edwards.

### REFERENCES

- Austin, P. M., and S. G. Geotis, 1978: Evaluation of the quality of precipitation data from a satellite-borne radiometer. Final Report under NASA Grant NSG 5024. Department of Meteorology, MIT 30 pp.

- Gloersen, P., and L. Hardis, 1978: *The Nimbus-7 Users' Guide*. National Aeronautics and Space Administration, 213-245.
- Huang, R., and K.-N. Liou, 1983: Polarized microwave radiation transfer in precipitating cloudy atmospheres: Applications to window frequencies. *J. Geophys. Res.*, **88**, 3885-3893.
- Medrow, W., E. Raschke and E. Ruprecht, 1982: Rainfall rates derived from Nimbus-5 observations analyzed against radar rainfall. *Preprints Symp. uber Strahlungstransportprobleme und Satellitenmessungen in der Meteorologie und der Ozeanographie, Lohr, Dtsche. Wetterdienst, Offenbach am Main, Fed. Rep. of Germany*, 71-73.
- Oguchi, T., 1981: Scattering from hydrometeors: A survey. *Radio Sci.*, **16**, 691-730.
- Olson, W. S., 1983: Estimation of rainfall rates in tropical cyclones by passive microwave radiometry. Ph.D. dissertation, Dept. of Meteorology, University of Wisconsin, 200 pp.
- Rodgers, E., H. Siddalingaiah, A. T. C. Chang and T. Wilheit, 1979: A statistical technique for determining rainfall over land employing Nimbus 6 ESMR measurements. *J. Appl. Meteor.*, **18**, 978-991.
- Savage, R. C., 1976: The transfer of thermal microwaves through hydrometeors. Ph.D. dissertation, Dept. of Meteorology, University of Wisconsin, 147 pp.
- Spencer, R. W., D. W. Martin, B. B. Hinton and J. A. Weinman, 1983a: Satellite microwave radiances correlated with radar rain rates over land. *Nature*, **304**, 141-143.
- , W. S. Olson, Wu Rongzhang, D. W. Martin, J. A. Weinman and D. A. Santek, 1983b: Heavy thunderstorms observed over land by the Nimbus-7 Scanning Multichannel Microwave Radiometer. *J. Climate Appl. Meteor.*, **22**, 1041-1046.
- Suomi, V. E., R. Fox, S. S. Limaye and W. L. Smith, 1983: McIDAS III: A modern interactive data access and analysis system. *J. Climate Appl. Meteor.*, **22**, 766-778.
- Weinman, J. A., and R. Davies, 1978: Thermal microwave radiances from horizontally finite clouds of hydrometeors. *J. Geophys. Res.*, **83**, 3099-3107.
- , and P. J. Guetter, 1977: Determination of rainfall distributions from microwave radiation measured by the Nimbus-6 ESMR. *J. Appl. Meteor.*, **16**, 437-442.