

MEASUREMENT OF RAINFALL PATH INTEGRATED ATTENUATION AT NADIR:
A COMPARISON OF RADAR AND RADIOMETER METHODS AT 13.8 GHz

S. L. Durden, Z. S. Haddad, E. Im, F. K. Li, A. B. Tanner, and W. J. Wilson

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109

Submitted to: *Radio Sci.*

Date submitted: March 22, 1994

Abstract

An approach for reducing the ambiguity in the retrieved rainfall profile from spaceborne rain radar is to use the path integrated attenuation as a constraint. Two approaches for measuring the path integrated attenuation have been proposed: radar surface reference technique and microwave radiometry. We have compared these two techniques for estimating the 13.8 GHz path integrated attenuation in rainfall using data acquired by the ARMAR airborne rain radar during TOGA COARE in the Western Pacific Ocean in early 1993. For one-way attenuations of approximately 4 dB or less the two methods produce estimates that are generally very close, while at larger attenuations the radiometer is saturated and cannot be used.

1 Introduction

Retrieval of the rainrate profile from spaceborne radar measurements has proved to be a difficult problem because of the presence of attenuation at the higher frequencies planned for these systems [Meneghini and Nakamura, 1990]. One approach for reducing the ambiguity in the retrieved profile is to use the path integrated attenuation (PIA) as a constraint [Meneghini and Nakamura, 1990; Marzoug and Amayenc, 1991]. Two approaches have been considered for measuring the PIA. In the surface reference technique [Meneghini et al., 1983], the radar is used. A measurement of the ocean surface in a clear area is compared with measurements in the raining area, and the difference between the two yields the PIA. This method assumes that the ocean cross section in the clear area and within the rain are identical. There has been concern, however, that this may not be the case [Meneghini et al., 1992]. Bliven and Giovanangeli [1993] showed that rain can generate capillary waves, and Tsimplis and Thorpe [1989] showed that rain can damp short gravity waves. Additionally, the ocean cross section is sensitive to the surface wind, and there is no guarantee that the wind conditions in the clear area and in the rain are the same. A second approach to retrieving PIA is via a microwave radiometer, with one or more frequencies [Weinman et al., 1990]. It is the purpose of this paper to show results from TOGA COARE [Webster and Lukas, 1992], comparing the radar and radiometer techniques. These results are relevant to the Tropical Rainfall Measuring Mission (TRMM) to be launched in the late 1990's [Simpson et al., 1988]. This mission will include both a multifrequency microwave radiometer and the first spaceborne rain radar.

2 Data Acquisition

The Airborne Rain Mapping Radar (ARMAR) has been developed for the purpose of supporting future spaceborne rain radar systems, including the radar for TRMM, to be flown in the late 1990's. ARMAR flies on the NASA DC-8 aircraft and measures reflectivity at the TRMM radar frequency of 13.8 GHz. It operates in a downward looking, cross-track scanning geometry. Nadir-looking, non-scanning measurements can also be acquired. A number of capabilities not included on the TRMM radar have been included on ARMAR to improve its ability to support the TRMM radar and to allow it to serve as a testbed for future spaceborne systems. These include dual-polarization, frequency diversity, and Doppler (when frequency diversity is not used). While operating as a radar, a small fraction of time is spent measuring brightness temperature in a radiometer mode at the same frequency and viewing geometry as the radar mode. ARMAR characteristics are shown in Table 1. Further details on ARMAR can be found in Durden et al. [1994] and Tanner et al. [1994].

ARMAR participated in all 13 flights of the DC-8 in TOGA COARE over the Western Pacific Ocean in January and February of 1993, observing rainfall systems ranging from isolated convective cells to stratiform rain to tropical cyclones. For this study we have examined 15 flight legs acquired during 12 different flights. This corresponds to 2781 measurements in rainfall. Each radar measurement consists of an average of approximately 100 independent samples, giving a radar measurement standard deviation of approximately ± 0.5 dB. Each radiometer measurement has a precision of about 1 K.

3 Estimation of PIA

For the radar approach, we examined the nadir surface cross section throughout each flight leg. The reference cross section used in attenuation estimation for each rain area was the surface cross section measured in the closest preceding clear area, where clear areas were defined as having brightness temperatures lower than 152 K. Based on this definition, the average attenuation on our clear measurements was estimated at 0.4 dB. This was added to our measurements to give the "true" clear condition cross section. The surface reference one-way PIA is found from

$$PIA_{rad} = (\sigma_{clear}^0 - \sigma_{rain}^0)/2. \quad (1)$$

Estimation of the PIA using the nadir radiometer measurement is more complicated. It has been shown [Wilheit et al, 1977] that the brightness temperature increases with attenuation and then saturates, reaching a maximum that is somewhat below the medium's physical temperature. At very high rainrates, and particularly if ice is present, the brightness temperature decreases with increasing attenuation because of scattering. For a single frequency radiometer, accurate estimates of attenuation

can only be made when the brightness temperature is well below the saturation temperature, where scattering is a minor contribution. Hence, we have used a simple radiative transfer model to compute the brightness temperature T_b , given the profile of atmospheric attenuation. The equation for T_b is [Fujita et al., 1985]:

$$T_b = T_b(o) \exp\left(-\int_0^H \gamma(l)dl\right) + \int_0^H \gamma(l)T(l) \exp\left(-\int_l^H \gamma(s)ds\right)dl \quad (2)$$

where $T_b(0) = (1 - \epsilon)T_b^{sky} + \epsilon T_{sea}$ and

$$T_b^{sky} = \int_0^H \gamma(l)T(l) \exp\left(-\int_0^l \gamma(s)ds\right)dl$$

Here, γ is the absorption coefficient, T is the atmosphere physical temperature, and T_{sea} is the ocean surface physical temperature. Equation (2) cannot be directly inverted for the path attenuation. We have therefore taken the approach of using (2) to compute T_b for a variety of attenuation profiles and then developing an inverse relation from these calculations. Figure 1 shows the results for 113 different profiles, including uniform attenuation below the freezing level, and attenuations concentrated in the lower, middle, and upper regions of the atmosphere below the freezing level. The freezing level was taken to be around 4.5 km, and attenuation above the freezing level was assumed to be negligible. Only cases with $T_b < 260$ K are shown, since this is close to the temperature where the radiometer begins to saturate and lose sensitivity to attenuation. To derive a simple inversion algorithm, a quadratic was fit to the data in Figure 1:

$$PIA_{mr} = 0.34 + 0.000192(T_b - 125)^2 \quad (3)$$

where the subscript mr stands for microwave radiometer. This fit is quite accurate, yielding a correlation coefficient of 0.97.

4 Discussion

We applied both the radar and radiometer techniques to determining the one-way PIA over the 15 flight legs of ARMAR TOGA COARE data. Figure 2 shows an example of the radar and radiometer derived attenuations along a single 10 minute flight leg on 8 February 1993. Generally, the two estimates are quite close. A few points where the radar estimate is much higher than the radiometer estimate are noted. Also, it should be noted that the radar estimate shows much more variability than the radiometer estimate. Figure 3 shows the radar estimated PIA versus the radiometer estimated PIA for all 15 flight legs. For comparison purposes, the straight line $PIA_{rad} = PIA_{mr}$ is also shown. For PIAs less than about 4 dB, the two estimates agree. We note that of the 2781 measurements, 2231 of them

did have radiometer attenuations less than 4 dB, so the two methods agree for 80% of our data. The mean difference $PIA_{mr} - PIA_{rad}$ is only 0.06 dB, and the rms difference between the two techniques is 0.7 dB. We believe that the rms difference is primarily due to fluctuations in the radar estimate, as was noted in Figure 2. Fluctuations in the radar estimate were also noted by Meneghini et al. [1992]. In their data and in ours the ocean cross section even in clear conditions can vary by 1 dB or more, likely due to changes in the surface wind speed. This inherent variability in the radar estimate lead Meneghini et al. [1992] to recommend that the surface reference technique not be used for very low attenuations, and our measurements support this recommendation. This variability is also likely the cause for the few outlier points that can be seen at low attenuations. A key point in our work is the finding that the mean difference between the two techniques is very close to zero. Since a modification of the surface by rainfall would be expected to produce a bias in the radar technique, these data suggest that the effect of rain modifications is small at lower attenuations and rainrates. For attenuations greater than 4 dB as measured by the radiometer (20% of our data), the radar attenuation can be up to 25 dB. For these large attenuations the radiometer is saturated; attenuations of 5 dB and 25 dB yield nearly the same brightness temperature.

The PIA measurements in Figures 2 and 3 can be converted to a path averaged rainrate using $k = 0.03R$ [Olsen et al., 1978], where k is the absorption coefficient in dB/km and R is in mm/h. By assuming that the attenuation occurs over a 4.5 km path, the path averaged rain rate in mm/h is 7.4 times the PIA in dB. Thus, according to the radar technique, path averaged rainrates of well over 100 mm/h were observed on a number of occasions. High surface winds in convective storms could have reduced the nadir surface cross section, causing the surface reference technique to overestimate the PIA by several dB. Even if this is the case, the PIA in several cases is at least 15 dB, corresponding to path averaged rainrates near 110 mm/h.

5 Conclusions and Future Plans

We have compared the radar surface reference technique with microwave radiometry for estimating the 13.8 GHz path integrated attenuation in rainfall. For one-way attenuations of approximately 4 dB or less the two methods produce estimates that are generally very close. At large attenuations (> 4 dB) the radiometer is saturated and cannot be used. The radar technique, however, has the potential of providing accurate estimates at these large attenuations. While the effects of wind and rain on the surface did not appear to bias the radar technique in this study, they are still a potential problem at high attenuations and rainrates. As data from the other TOGA COARE aircraft become available, we will re-examine some of the high attenuation cases in an effort to answer questions regarding the effects

of rain and wind on the surface reference technique. In particular, attenuation at 10 GHz is roughly half of that at 13.8 GHz, and we will use 10 GHz radiometer data to extend the range of the radiometer technique.

Acknowledgment

The research described here was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

References

- Bliven, L. F. and J.-P. Giovanangeli, An experimental study of microwave scattering from rain- and wind-roughened seas, *Int. J. Remote Sensing*, vol. 14, pp. 855-869, 1993.
- Durden, S. L., E. Im, F. K. Li, W. Ricketts, A. Tanner, and W. Wilson, ARMAR: An airborne rain mapping radar, *J. Atmos. Oceanic Tech.*, in press, 1994.
- Fujita, M., K. Okamoto, H. Masuko, T. Ojima, and N. Fugono, Quantitative measurements of path-integrated rain rate by an airborne microwave radiometer over the ocean, *J. Atmos. Oceanic Tech.*, 2, 285-292, 1985.
- Marzoug, M., and P. Amayenc, Improved range profiling algorithm of rainfall rate from a spaceborne radar with path-integrated attenuation constraint, *IEEE Trans. Geosci. Remote Sensing*, 29, 584-592, 1991.
- R. Meneghini and K. Nakamura, Range profiling of the rain rate by an airborne weather radar, *Remote Sens. Environ.*, 31, 193-209, 1990.
- R. Meneghini, J. Eckerman, and D. Atlas, Determination of rain rate from a spaceborne radar using measurements of total attenuation, *IEEE Trans. Geosci. Remote Sensing*, 20, 34-43, 1983.
- R. Meneghini, T. Kozu, H. Kumagai, and W. C. Boncyk, A study of rain estimation methods from space using dual-wavelength radar measurements at near nadir incidence over ocean, *J. Atmos. Oceanic Tech.*, 9, 364-382, 1992.
- Olsen, R. L., D. V. Rodgers, and D. B. Hodge, The aR^b relation in the calculation of rain attenuation, *IEEE Trans. Antennas Propagat.*, 26, 318-329, 1978.
- Simpson, J., R. F. Adler, and G. R. North, A proposed tropical rainfall measuring mission (TRMM) satellite. *Bull. Am. Met. Soc.*, 69(3), 278-295, 1988.

Tanner, A., S. L. Durden, R. Denning, E. Im, F. K. Li, W. Ricketts, W. Wilson, Pulse compression with very low sidelobes in an airborne rain mapping radar, *IEEE Trans. Geosci. Remote Sensing*, in press, 1994.

Tsimplis, M., and S. A. Thorpe, Wave damping by rain, *Nature*, 342, 893-895, 1989.

Webster, P. J. and R. Lukas, TOGA COARE - The coupled ocean atmosphere response experiment, *Bulletin of the American Meteorological Society*, 73(9), 1377-1416, 1992.

Weinman, J. A., R. Meneghini, and K. Nakamura, Retrieval of precipitation profiles from airborne radar and passive radiometer measurements: Comparison with dual-frequency radar measurements, *J. Appl. Meteor.*, 29(10), 981-993, 1990.

Wilheit, T. T., A. T. C. Chang, M. S. V. Rao, E. B. Rodgers, and J. S. Theon, A satellite technique for quantitatively mapping rainfall rates over the oceans, *J. Appl. Meteor.*, 16, 551-560, 1977.

Figure Captions

Figure 1. Solutions of the radiative transfer equation (2) for 120 attenuation profiles for the case of a nadir-looking 13.8 GHz radiometer.

Figure 2. Example of radar and radiometer attenuations along a single flight leg at nadir. The horizontal axis is the number of minutes from the start of the leg. Data were acquired 8 February 1993.

Figure 3. Plot of the measured radar PIA versus the measured radiometer PIA for 15 flight legs in TOGA-COARE at nadir incidence.

Table 1: ARMAR System Characteristics

Operating Frequency	13.8 GHz
Surface Horizontal Resolution	800 m
Vertical 3 dB Resolution	55 m
Polarization	HH,VV,HV
Antenna Beamwidth	3.8°
Antenna Scan Angle	±20°
Transmitter Power	200 W
Transmit Chirp Duration	5-45 μ sec
Pulse Repetition Frequency	1-8 kHz
Chirp Bandwidth	4 MHz
A/D Sampling Rate	10 MHz
A/D Resolution	12 bits





