Measurement of Rainfall Path Attenuation Near Nadir:

A Comparison of Radar and Radiometer Methods at 13.8 GHz

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Abstract

Rain profile retrieval from spaceborne radar is difficult because of the presence of attenuation at the higher frequencies planned for these systems. One way to reduce the ambiguity in the retrieved rainfall profile is to use the path integrated attenuation as a constraint. Two techniques for measuring the path integrated attenuation have been proposed: the radar surface reference technique and microwave radiometry. We compare these two techniques using data acquired by the ARMAR 13.8 GHz airborne radar and radiometer during TOGA COARE in the Western Pacific Ocean in early 1993. The two techniques have a mean difference close to zero for both nadir and 10^o incidence. The RMS difference is 1.4 dB and is reduced to 1 dB or less if points where the radiometer was likely saturated are excluded. Part of the RMS difference can be attributed to variability in the ocean surface cross section due to wind effects and possibly rain effects. The results presented here are relevant for the Tropical Rainfall Measuring Mission, which will include a 13.8 GHz precipitation radar.

1 Introduction

Retrieval of the rainrate profile from spaceborne radar measurements is a difficult problem because of the presence of attenuation at the higher frequencies planned for these systems. For example, the Tropical Rainfall Measuring Mission (TRMM) [Simpson et al., 1988] will carry a 13.8 GHz Precipitation Radar (PR). Attenuation at 13.8 GHz can be several dB/km in heavy rain [Olsen et al, 1978]. One way to reduce 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 techniques 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 assumption may not be valid because of the effect of rain and wind on the ocean surface [Meneghini et al., 1992; Atlas, 1994]. A second technique for retrieving PIA is microwave radiometry [Weinman et al., 1990]. The TRMM Microwave Imager (TMI) will operate at 10, 19, 22, 37, and 85 GHz and could potentially be used to estimate the 13.8 GHz PIA, although its viewing geometry is different from that of the PR. Like the surface reference technique, radiometry also has some potential problems, including saturation at larger PIA. It is the purpose of this paper to show results from TOGA COARE [Webster and Lukas, 1992], comparing the radar and radiometer techniques at 13.8 GHz.

2 Data Acquisition

The data used in this study were acquired by the NASA/JPL Airborne Rain MApping Radar (ARMAR). This system has been developed for the purpose of supporting future spaceborne rain radar systems, including the TRMM PR. ARMAR flies on the NASA DC-8 aircraft and measures reflectivity at the TRMM radar frequency of 13.8 GHz. It normally operates in a downward looking, cross-track scanning geometry and has dual-polarization and Doppler capabilities. While operating as a radar, a small fraction of time is spent measuring brightness temperature in a radiometer mode at the same frequency, viewing geometry, and resolution as the radar mode. ARMAR characteristics are shown in Table 1, and additional details can be found in Durden 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.

3 Estimation of PIA

To estimate the PIA from microwave radiometer measurements, we derived a simple algorithm based on the results of modeling using the Eddington radiative transfer code of Kummerow [1993]. This code allows the atmosphere to be divided into horizontal layers. The input to the code specifies layer thickness, temperature, relative humidity, cloud liquid water, precipitation liquid water, and precipitation

ice. Additional inputs are the surface temperature and the surface wind speed, used for computation of the ocean emissivity. The 13.8 GHz brightness temperature T_b and PIA were computed for the model atmosphere shown in Table 2 for a variety of rainrates R (up to 30 mm/h), cloud liquid water L (up to 1 g/m^3), and surface wind speed (up to 10 m/s). The drop size distributions of both Marshall and Palmer [1948] and Sekhon and Srivastava [1971] were used. The temperature in each layer decreased linearly with altitude. The relative humidity was 90%, and the surface temperature was 301 K. A simple function relating PIA and brightness temperature was fit to the model calculations:

$$A_{mr} = 10.2 - 2.0 \ln(277.5 - T_b), \quad T_b \leq 276\text{K} \tag{1}$$

where A_{mr} is the one-way 13.8 GHz microwave radiometer estimated PIA in dB and T_b is the 13.8 GHz brightness temperature in K. The RMS fit error was 0.19 dB. This functional form was also used by Weinman et al. [1990]. Equation (1) represents a simple algorithm for estimating PIA from brightness temperature; it is plotted in Figure 1.

For the radar surface reference technique (SRT), we use the radar ocean cross section σ^o throughout each flight leg. The surface cross section is found by extracting the maximum return from range bins in the vicinity of the surface (as determined by the aircraft altitude). It is expected that a similar approach would be used for processing the TRMM PR data. The reference cross section used in attenuation estimation for each rain area is the average cross section measured in the closest preceding clear area, although clear areas following rain could also be used. For the TRMM PR, clear areas would likely be determined using the radar return in all range bins above the surface. Absence of signal in all bins would indicate a clear area. In the case of ARMAR a simpler technique can be used since the ARMAR radiometer operates with exactly the same viewing geometry as the radar. We define clear areas as those areas having a radiometric brightness temperature below 140 K. This will include areas that are cloudless, as well as areas with clouds and perhaps even light rain. This definition is

necessary because the DC-8 often repeatedly flew tracks over the same storm system, turning around near the edge of the system but not necessarily over areas that were cloudless. Applying the Eddington radiative transfer model to a cloudless tropical atmosphere and smooth ocean, the PIA is 0.16 dB and T_b is around 130 K. The threshold T_b of 140 K corresponds to a PIA of around 0.3 dB, also based on calculations with the Eddington code. It follows that areas with T_b less than 140 K should have PIA ranging from about 0.16 dB to about 0.3 dB, and we take 0.25 dB as a typical value. The true clear area cross section σ_c^o is found by adding the typical two-way attenuation, 0.5 dB, to our measured σ^o. A_{srt}, the surface reference one-way PIA in dB, is found from

$$A_{srt} = (\sigma_c^o - \sigma_r^o)/2 \tag{2}$$

where σ_r^o is the ocean surface cross section in rain. The error in A_{srt} caused by the presence of clouds and light rain in the reference clear area should be less than about 0.1 dB.

4 Results and Discussion

Figure 2 shows an example of the nadir radar and radiometer derived attenuations along a single 10 minute flight leg on 8 February 1993. Generally, the two estimates are close, except for a few high attenuation points. Figure 3 shows the nadir surface reference one-way PIA versus the radiometer estimated one-way PIA for all 13 TOGA COARE flights. A total of 8457 points are shown. For comparison, a straight line with unity slope, $A_{srt} = A_{mr}$, is also shown. Note that points with brightness temperatures over 276 K are not shown. These accounted for about 13% of the data.

Most points in Figure 3 lie relatively close to the line $A_{srt} = A_{mr}$. For large attenuations, however, the radiometer is saturated, and the scatter becomes large. This saturation effect can be seen in Figure 1. The PIA versus brightness temperature curve becomes nearly vertical as T_b increases above 260 K, reducing the radiometer sensitivity and making the radiometer retrieval more sensitive to measurement errors. When all points in Figure 3 are considered, the RMS difference is 1.4 dB, and the mean

difference between the two techniques is small (radar estimate is 0.20 dB greater than radiometer). If we consider only points with T_b less than 260 K (PIA $<$ 5 dB), the RMS difference is reduced to 0.8 dB, and the mean difference is reduced to 0.15 dB. Thus, removal of the points where the radiometer is likely saturated reduces but does not eliminate the difference between the two methods. Another possible contributor to the observed difference is errors in the radiometer estimate due to deviation of the true atmosphere or ocean emissivity from those used in the Eddington calculations. However, a potentially larger contributor is variability in the radar estimate. An example of the variability in the radar estimated PIA can be seen in Figure 2, when compared to the relatively smooth radiometer estimate. Variability in the radar estimate was also noted by Meneghini et al. [1992], leading to their recommendation that the surface reference technique not be used for very low PIA. Our data support this recommendation. In clear air conditions, we found that the nadir ocean cross section for the entire 13 flights has a standard deviation of approximately 1.5 dB, likely due to varying wind and wave conditions. When examined over a more limited time or area the cross section standard deviation is somewhat less, but still enough to cause relatively large errors at low PIA.

In addition to wind and wave effects, Atlas [1994] and others have presented evidence that heavy rain damps ocean waves, smoothing the ocean surface. At nadir this would increase σ^o, causing the radar PIA to be underestimated. In fact, the mean radar estimate is slightly higher than the radiometer estimate. Consequently, we do not have direct evidence of the effect of rain on the ocean. However, it is possible that rain enhancement of σ^o in some areas is combined with wind reduction in others, so that the two effects together contribute to the RMS difference between radar and radiometer methods. It is also possible that the 13.8 GHz radiometer saturates at rain rates too low to produce wave damping. This led us to examine 10.7 GHz radiometer data acquired by the Advanced Microwave Precipitation Radiometer (AMPR) [Spencer et al., 1994] on the NASA ER-2 aircraft, which occasionally flew the same track as the DC-8, although at a much higher altitude. We used Eddington radiative transfer

model calculations to derive an equation similar to (1), but relating the 13.8 GHz PIA to the brightness temperature at 10.7 GHz. The equation was applied to several heavy rain cases in which the ER-2 and DC-8 were nearly collocated. In some of these cases the 13.8 GHz PIA estimated by the ARMAR radar and the AMPR radiometer are very close. However, in other cases the radar estimated PIA is much larger. In these cases the large radar attenuation occurs over a very small area, and the disagreement between radar and radiometer may be caused by the relatively large 10.7 GHz radiometer footprint, which is approximately three times the size of the radar footprint. Errors in radiometer derived rainfall due to this partial beam-filling problem have been studied previously [Graves, 1993].

The analysis of ARMAR radar and radiometer data was repeated for 10^o incidence angle for all TOGA COARE flights. For points with $T_b < 276$ K, the RMS difference is 1.4 dB and the mean difference is 0.16 dB. For $T_b < 260$ K the RMS difference is 1.0 dB, and the mean difference is 0.12 dB. These values are similar to the nadir case. The variability of the clear condition ocean σ^o at 10^o is 1 dB, which is less than that at nadir. However, this may be offset by increased variability in the radiometer estimate due to the off-nadir viewing geometry. In the nadir case both the upwelling and reflected downwelling contributions to the brightness temperature come from within the antenna beam. However, at 10^o, the downwelling component originates outside the antenna beam and is specularly reflected into the beam. The radar, in contrast, is sensitive to extinction only within the antenna beam at both nadir and 10^o.

PIA measurements at 13.8 GHz in convective rain can be converted to a path averaged rainrate using $k = 0.048R^{.99}$ [Olsen et al., 1978], where k is the extinction coefficient in dB/km and R is the rainrate in mm/h. By assuming that the attenuation occurs over a 4.7 km path, the path averaged rain rate in mm/h is approximately 4.5 times the PIA. The peak radar estimated PIA was 30 dB, which corresponds to a path averaged rain rate of 135 mm/h. Several instances of PIA between 15 and 20 dB were noted. These correspond to rainrates between 67 and 90 mm/h, which are reasonable for tropical

convective rainfall.

5 Conclusions

We have compared the radar surface reference technique with microwave radiometry for estimating the 13.8 GHz path integrated attenuation in rainfall. The two methods have a mean difference close to zero for both nadir and 10^o incidence. The RMS difference is 1.4 dB and is reduced to 1 dB or less if points where the radiometer was likely saturated are excluded. Part of the RMS difference can be attributed to variability in the ocean surface cross section due to wind effects and possibly rain effects. A bias, such as would be caused by rain effects alone on the ocean surface, was not found, possibly because smoothing of the surface due to rain often took place near areas with roughening due to wind. Another possiblity is that the effect of rain was not seen because of 13.8 GHz radiometer saturation. We were not able to reliably extend the study to heavier rainfall using a 10.7 GHz radiometer because of potential beam-filling effects in the radiometer footprint. This will also be a problem in the case of TRMM, since the 10.7 GHz TMI channel has a much larger footprint than the Precipitation Radar.

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Figure Captions

Figure 1. One-way 13.8 GHz path integrated attenuation versus 13.8 GHz brightness temperature, as calculated from Equation (1).

Figure 2. Example of radar and radiometer one-way PIA 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 one-way PIA versus the measured radiometer PIA for all TOGA-COARE flights, nadir incidence. Also shown, for comparison, is the line with unit slope.

Table 1: ARMAR System Characteristics

Operating Frequency	13.8 GHz
Surface Horizontal Resolution	800 m
Vertical 6 dB Resolution	80 m
Polarization	HH,VV,HV
Antenna Beamwidth	3.8^o
Antenna Scan Angle	$\pm 20^o$
Transmitter Power	200 W
Transmit Chirp Duration	5-45 μsec
Pulse Repetition Frequency	1-8 kHz
Chirp Bandwidth	4 MHz
A/D Sampling Rate	10 MHz
A/D Resolution	12 bits
Number Independent Samples	>100
Radiometer ΔK	1K

Table 2: Atmospheric Model

Layer Altitude (km)	Layer-Top Temperature (K)	Cloud Liquid Water (g/m^3)	Precipitation Liquid (mm/h)	Precipitation Ice (mm/h)
0.0-1.5	292	0	R	0
1.5-4.7	273	L	R	0
4.7-5.7	267	0	0	$R/2$

Note: R ranges from 0 to 30 mm/h, L ranges from 0 to 1 g/m^3