NASA/CR-203879

Final Report to TRMM
NAS5-32780

A. R. Jameson
RJH Scientific, Inc.
5904 Richmond Hwy., Ste. 401
Alexandria, VA 22303

The proposed effort consisted of three elements all having to do with the measurement of rain and clouds using microwaves. Briefly they were (1) to examine recently proposed techniques for measuring rainfall rate and rain water content using data from ground-based radars and the TRMM microwave link in order to develop improved ground validation and radar calibration techniques, (2) to develop dual-polarization, multiple frequency radar techniques for estimating the rain water content and cloud water content separately in order to better interpret the vertical profiles of Z measured by the TRMM Precipitation Radar and to develop a technique to measure quantities relevant to understanding the vertical distribution of latent heating by clouds and rain and (3) to investigate theoretically and experimentally the potential for biases in TRMM Precipitation Radar reflectivity factors (Z) because of spatial inhomogeneities in the precipitation. As explained below, all of these topics have been addressed and the associated research has led to several referred publications. These publications are listed at the end of this brief report, and copies of the cover papers are attached. Details (not repeated here) may be found in these articles.

As part of earlier TRMM research, several methods were developed for remotely estimating rain water content and rainfall rate using dual-polarization, multi-frequency microwave techniques (Jameson 1993; Jameson and Caylor 1994; Jameson 1994a; Jameson 1994b) using advanced polarization radars and microwave links. It was hoped that the TRMM microwave link would become operational, providing unique multi-frequency and dual-polarization microwave measurements in rain at the NASA Facility at Wallops Island, Virginia. That did not come to pass in the time frame of this proposal although the link is now undergoing final tests for such measurements. In lieu of these data, some measurements from the CaPE experiment in Florida in 1991 were processed and are included in the polarization component of an overview article "Evolution of Radar Rainfall Measurements: Steps and Mis-steps" co-authored with Dr. David

Atlas (Distinguished Scientist Emeritus, GSFC) and Prof. Daniel Rosenfeld (Hebrew University of Jerusalem). This publication appears as the lead article in a book just published by UNESCO as listed at the end of this report.

The factor limiting detailed study of these techniques was a lack of data. Proposals to NASA to acquire the necessary data primarily using NASA/JPL ARMAR radar were declined. Consequently, attempts were made to use some of the ARMAR aircraft observations. In general, however, these were not suited for this research because of the nearly nadir viewing angles in rain. However, in the course of exploring this data option, my colleague, Dr. Steven Durden at JPL, and I noticed the remarkable occurrence of linear depolarization even when looking down in rain. This led to the publication of an article co-authored with Steve Durden entitled "A Possible Origin of Linear Depolarization Observed at Vertical Incidence in Rain" that appeared in the *Journal of Applied Meteorology* in February 1996. Specifically, observations by two different nadir pointing airborne radars with some polarization capabilities have detected surprisingly large linear depolarization ratios at times in convective tropical rain. This depolarization can be explained if the rain is considered to be a mixture of a group of apparent spheres and another group of drops that are distorted in the horizontal plane perpendicular to the direction of propagation of the incident wave. If confirmed in future observations, this suggests that at times the larger raindrops are oscillating, in part, because of collisions with smaller drops. Since many of the interpretations of radar polarization measurements in rain by ground-based radars presume that the raindrops shapes correspond to those of the well-known, so-called 'equilibrium' drops, the present observations may require adjustments to some radar polarization algorithms for estimating rainfall rate, for example, if the shape perturbations observed at nadir also apply to measurements along other axes as well.

In addition, I worked with Dr. Ziad Haddad on research designed to help improve rainfall retrieval using the TRMM radar. This led to the publication of an article co-authored with Drs. Z. Haddad , E. Im and S.L. Durden (all of JPL) entitled "Improved Coupled Z-R and k-R Relations and the Resulting Ambiguities in the Determination of the Vertical Distribution of Rain from the Radar Backscatter and the Integrated Attenuation" that appeared in the *Journal of Applied Meteorology* in December 1995.

With regard to item (2) above, research led to the publication of an article entitled "Using Multiparameter Radars to Estimate the Attenuation and Water Content of Clouds" that appeared in the *Journal of Applied Meteorology*, September 1995. In summary it was reported that the attenuation of microwaves is caused not only by precipitation but also by clouds. Consequently, the presence of liquid cloud can affect estimates of rainfall rate computed from attenuation and reflectivity factors measured at higher frequencies typically used for spaceborne and airborne radars. Cloud attenuation also affects ground-based radar measurements of rainfall at frequencies as low as 5 GHz.

This paper suggests an approach for determining the attenuation due to cloud (A_C) and for estimating the cloud water content (W_C) even in moderate rain by using radars operating at two frequencies with one of them capable of dual-linear (horizontal-vertical) polarization measurements. This analysis suggests that useful 'instantaneous' estimates of A_C and W_C should be possible when an upper frequency of 13.8 GHz is used in conjunction with a lower frequency. These measurements could also be used to derive cloud attenuation statistics, potentially useful for developing techniques to help compensate for the effect of cloud attenuation on spaceborne, airborne and ground-based radar estimates of rainfall.

While this algorithm appears promising, it is particularly challenging to devise approaches to test this technique not only because the necessary instruments do not yet exist but also because of a lack of a standard for comparison. Although a complete test appears out of reach at this time, it should be possible at least to explore the validity of certain aspects of the technology. One possible approach using measurements over extended volumes is discussed at the end of this paper.

The final research topic led to some important insights regarding the structure of rainfall that is now being pursued in greater depth under new funding from the National Science Foundation. Specifically, research into this topic with Prof. A. B. Kostinski at Michigan Technological University led to an article entitled "Non-Rayleigh Signal Statistics Caused by Relative Motion during Measurements" that appeared in the *Journal of Applied Meteorology* in October 1996. It was reported that in order to reduce fluctuations, remote sensing devices such as radars and radiometers typically sample many times before forming an estimate. When mean values are stationary during this sampling period, the fluctuations in the amplitudes and intensities obey the same probability density functions (pdf's) as those for each sample contributing to the estimate. However, it is shown in this work that when mean values change from sample to sample (i.e., pulse to pulse for most radars), the pdf's of the amplitudes and intensities differ from those corresponding to the samples. Such changes can be inherent to the scatterers as, for example, the scatter of microwaves from an ocean surface, or they can be induced by factors such as antenna motion across gradients.

With respect to meteorological radars, it is routinely argued that the Central Limit Theorem leads inexorably to zero-mean Gaussian distributions of the two components of the electric field phasor backscattered from precipitation because of the large number of independent scatterers in the sampling volume. Consequently, the net amplitudes and intensities obey Rayleigh and exponential probability density distributions, respectively. While apparently true for each pulse (sample) even when the reflectivity across the beam is not uniform, we show that, in general, the underlying statistics of the amplitudes and intensities are no longer Rayleigh nor exponential. This occurs because the number of scatterers and intensities change from sample to sample as, for example, when a radar beam moves while the mean intensity is changing. Consequently, non-Rayleigh statistics and deviations from Gaussian distributions are probably much more common than previously appreciated.

A statistical model is developed and confirmed from detailed Monte Carlo drop simulations of a radar sampling as the beam moves through a cloud. Theory and these model simulations show that the resultant pdf's of the amplitude and intensity are mixtures of the pdf's from each sample contributing to the estimate. This mixture of pdf's also produces increased variance. Because of the general nature of these findings, it is likely that the effects of sampling through changing conditions (namely, biases and increased variances) probably also apply to many other types of remote sensing instruments including those using square law detectors. Fortunately, *this turns out not to be the case for the TRMM radar.* The reason is that the radar is steered electronically so that it uses what may be called 'block' averaging (Appendix) in which the beam is held stationary while each estimate is made. On the other hand, *the TRMM radiometers are not electronically steered and, therefore, may be subject to the non-Rayleigh effects described in this work.*

Aside from these important conclusions, attempts to advance this type of research led Prof. Kostinski and I to explore further the spatial (temporal) structure of rain. This led to the final paper entitled "Fluctuation Properties of

Precipitation. Part I: On Deviations of Single-Size Drop Counts from the Poisson Distribution" that appeared in the *Journal of the Atmospheric Sciences* on September 1997. Specifically, the traditional statistical description of the spatial and temporal distributions of cloud droplets and raindrops is the Poisson process that tends to place the drops as uniformly as randomness allows. Yet, the clumpy nature of clouds and precipitation is apparent to most casual observers. Is such clumpiness consistent with the Poisson statistics? Here we explore the possibility of deviations from the Poisson distribution using temporal raindrop counting experiments. Disdrometer measurements during the passage of a squall line strongly indicate that a mixture of Poisson distributions (Poisson mixture) provides a better description of the frequency of drop arrivals per unit time in variable rain than does a simple Poisson model. Poisson mixture generally yields distributions different from Poissonian. While the validity of the Poisson mixture model to smaller scales requires much finer temporal resolution than available in this study, these results do show that one must carefully interpret the statistical and physical meaning of average drop concentrations when the measurements are collected through variable rain, whether observed by airborne or ground-based instruments. Statistically, the variance in the measurements is greatly increased, due to the added variability from the rain field, thus minimizing the reduction of the variance normally achieved by increasing the sample size (N). In fact, in some cases the variance of relevant distributions scales as N^2 rather than N, thereby making the relative fluctuations independent of N. Consequently, the sampling criteria proposed by Cornford in 1967 are not necessarily generally applicable. Moreover, we conjecture that in most clouds the distribution of drop concentrations in small volumes may be more aptly described by a Poisson mixture rather than by a pure Poisson distribution. This may have significant implications with regard to the droplet growth and the evolution of rain. Already this research has led to new insights of obvious concern to TRMM into the meaning and measurement of drop size distributions in continuing research funded by the National Science Foundation and, therefore, not reported here.

REFERENCES

Jameson, A.R., 1994: On the estimation of rainfall parameters using spaceborne and airborne nadir pointing radars. *J. Appl. Meteor.*, **33**, 230-244.

Jameson, A.R., and I.J. Caylor, 1994: A new approach to estimating rain water content by radar using propagation differential phase shift. *J. Atmos. and Oceanic Technol.*, **11**, 311-322.

Jameson, A.R., 1994a: An alternative approach to estimating rainfall rate by radar using propagation differential phase shift. *J. Atmos. and Oceanic Technol.*, **11**, 122-131.

Jameson, A.R., 1994b: Measuring rain water content by radar using propagation differential phase shift. *J. Atmos. and Oceanic Technol.*, **11**, 299-310.

Jameson, A.R., 1993: Estimating the path average rain water content and updraft speed along a microwave link. *J. Atmos. and Oceanic Technol.*, **10**, 478-485.

PUBLISHED PAPERS FUNDED UNDER THIS CONTRACT

Kostinski, A.B. and A.R. Jameson, 1997: Fluctuation properties of precipitation. Part I: Deviations from the Poisson distribution in precipitation. *J. Atmos. Sci.,* **54**, 2174-2186.

Jameson, A.R. and A.B. Kostinski, 1996: Non-Rayleigh signal statistics caused by relative motion during measurement. *J. Appl. Meteor.,* **35**, 1846-1859.

Atlas, D., D. Rosenfeld, and A.R. Jameson, 1997: Evolution of radar rainfall measurement: Steps and mis-steps. in *Weather Radar Technology for Water Resources Management,* eds. B. Braga and O. Massambani, UNESCO Press, Montevideo, pp.1-60.

Jameson, A.R. and S.L. Durden, 1996: A possible origin of linear depolarization observed at vertical incidence in rain. *J. Appl. Meteor.*, **35**, 271-277.

Jameson, A.R., 1995: Using multiparameter radars to estimate the attenuation and water content of clouds. *J. Appl. Meteor.,* **34**, 2046-2059.

Haddad, Z.S., A.R. Jameson, E. Im, and S.L. Durden, 1995: Improved correlated Z-R and k-R relations and the resulting ambiguities in the determination of the vertical distribution of rain from the radar backscatter and the integrated attenuation. *J. Appl. Meteor.*, **34**, 2680-2688.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1997	Contractor Report

4. TITLE AND SUBTITLE
Final Report to TRMM

5. FUNDING NUMBERS
NAS5-32780
Code 910.1

6. AUTHOR(S)
Arthur R. Jameson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS (ES)
RJH Scientific, Inc.
5904 Richmond Highway, Suite 401
Alexandria, VA 22303

8. PEFORMING ORGANIZATION REPORT NUMBER
RJH–1004–001–Final

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS (ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
CR–203879

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 43
Report available from the NASA Center for AeroSpace Information,
800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The effort involved three elements all related to the measurement of rain and clouds using microwaves:

1) Examine recently proposed techniques for measuring rainfall rate and rain water content using data from ground-based radars and the TRMM microwave link in order to develop improved ground validation and radar calibration techniques;

2) Develop dual-polarization, multiple frequency radar techniques for estimating rain water content and cloud water content to interpret the vertical profiles of radar reflectivity factors (Z) measured by the TRMM Precipitation Radar; and

3) Investigate theoretically and experimentally the potential biases in TRMM Z measurements due to spatial inhomogeneities in precipitation.

The research succeeded in addressing all of these topics, resulting in several refereed publications. addition, the research indicated that the effects of non-Rayleigh statistics resulting from the nature of the precipitation inhomogeneities will probably not result in serious errors for the TRMM radar Measruements, but the TRMM radiometers may be subject to significant bias due to the inhomogeneities.

14. SUBJECT TERMS
radar, rain, microwave, ground truth, TRMM, polarization, dual-polarization radar, latent heating, radar reflectivity factors, spatial inhomogeneities

15. NUMBER OF PAGES
6 plus attachments

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL