REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
May 5, 1995

3. REPORT TYPE AND DATES COVERED
Final Report 4/1/92 - 3/31/95

4. TITLE AND SUBTITLE
Measurements of Natural Surfaces at Millimeter Wavelengths

5. FUNDING NUMBERS
DAAL03-92-G-0101

6. AUTHOR(S)
Robert E. McIntosh, Principal Investigator
James B. Mead, Research Associate Professor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Massachusetts
Knowles Engineering Buildgin
Amherst, MA 01003

DTIC
SELECTE
JUL 10 1995
S B D

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. ARO
AMXRO-ICA
4300 S. Miami Blvd.
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 29360.3-GS

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

During the three years covered by this contract, we achieved a number of important results in millimeter-wave radar hardware development, measurements, and data analysis. Important results include demonstrating the equivalence of coherent and noncoherent polarimetric measurement techniques; the development of a Kalman filter to improve the convergence of noncoherent polarimetric measurements; the development of a single-antenna 95 GHz polarimetric radar; measurement of the polarimetric response of deciduous and coniferous trees at 35, 95 and 225 GHz; and development of polarimetric scattering models for anisotropic scattering volumes. Among the most significant accomplishments of the last three years were the snow measurement campaigns of 1992-1994 which resulted in a large volume of fully polarimetric data at 35, 95 and 225 GHz. In addition to yielding long records of the diurnal variation in radar cross-section, these data showed for the first time that anisotropy in the snow pack has a major impact on the polarimetric response throughout the millimeter band. Finally, we have initiated a significant effort to archive all polarimetric data gathered during this project in the FINRACS database.

14. SUBJECT TERMS

DTIC QUALITY INSPECTED 3

15. NUMBER OF PAGES

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

FINAL REPORT:
Measurements of Natural Surfaces at Millimeter Wavelengths

ARO grant number: DAAL03-92-G-0101

Robert E. McIntosh, Principal Investigator

James B. Mead, Research Associate Professor

University of Massachusetts

Microwave Remote Sensing Laboratory

Amherst, MA 01003

Submitted to

Army Research Office

May 16, 1995

1. Introduction

The Microwave Remote Sensing Laboratory of the University of Massachusetts has actively pursued a millimeter-wave measurement program for the past nine years. During this time we have built radars operating at 35, 95, 215, and 225, and have developed polarimetric measurement techniques to study the backscatter properties of a variety of natural surfaces. During the three years covered by this contract (April 1992-March 1995), we achieved a number of important results in hardware development, measurements, and data analysis. Important results include demonstrating the equivalence of coherent and noncoherent measurement techniques; the development of a Kalman filter to improve the convergence of noncoherent polarimetric measurements; the development of a single-antenna 95 GHz polarimetric radar; modification of an existing 35 GHz FM-CW radar to allow fully polarimetric measurements; measurement of the polarimetric response of deciduous and coniferous trees at 35, 95 and 225 GHz; and development of polarimetric scattering models for anisotropic scattering volumes.

Among the most significant accomplishments of the last three years were the snow measurement campaigns of 1992-1994 which resulted in a large volume of fully polarimetric data at 35, 95 and 225 GHz. In addition to yielding long records of the diurnal variation in radar cross-section, these data showed for the first time that anisotropy in the snow pack has a major impact on the polarimetric response throughout the millimeter band. Finally, we have initiated a significant effort to archive all polarimetric data gathered during this project in the FINRACS (file of normalized radar cross-sections) database.

2. Statement of Problem Studied

In the proposal for this research project, we identified three primary goals: 1) To extend our field measurements to include a wider variety of natural surfaces and frequencies; 2) to assess the applicability of recently developed single and dual parameter polarimetric models; and 3) to experimentally compare coherent and noncoherent measurement techniques. In addressing the first goal, we made a concerted effort to extend our measurements to new surfaces, such as asphalt, grasses, and croplands, and greatly improved the quality and volume of our measurements of snow. We also extended our polarimetric measurement capability to 35 GHz by modifying an existing radar. In addressing the second goal, we gained a better understanding of the limitations of our one- and two-parameter models, especially through analysis of snow measurements. This led to the development of more complex models of up to four parameters that could describe scattering from anisotropic media. The third goal was addressed early in the project, by carrying out a series of measurements on foliage using a specially configured 95 GHz radar.

In addition to the millimeter-wave research supported by ARO, projects sponsored by other government agencies have greatly enhanced our millimeter-wave measurement capability. In the last three years we have developed a sophisticated cloud profiling radar system, which incorporates two fully polarimetric radars operating simultaneously from the same antenna at 33 and 95 GHz. We have also upgraded our 95 GHz dual-antenna radar to operated from a single antenna. Furthermore, funding from DOE and NSF has allowed us to make a significant contribution in ground-based and airborne millimeter-wave cloud studies. None of these latter contributions would have been possible without the initial support of ARO in funding the development of high-power millimeter-wave radars and polarimetric techniques.

3. Summary of Important Results

In the following paragraphs, we give brief summaries of the important accomplishments made during this funding period.

3.1 Snow Measurement Campaigns of 1992-94

During the winters of 1989-91 Western Massachusetts received comparatively little snowfall, which limited the amount of millimeter-wave polarimetric data gathered during those years. The winters of 1992-93 and 1993-94 reversed this trend, yielding record levels of snow, and allowing us to make extensive measurements at 35, 95 and 225 GHz. Data gathered during 1992-93 were the first to be carried out with a totally automated system. Compute controlled sweeps of the snow field were carried out at 60-80° incidence, every half hour throughout the day and night, for continuous periods of up to eight days. In addition, with the help of researchers from CRREL, we gathered a large set of snow microstructure samples using a liquid polymer technique developed at CRREL. This data set was extended in 1994, which included modifications to the 35 GHz radar to make fully polarimetric measurements, and included more detailed meteorological information to allow us to estimate snow pack parameters on finer time scales.

One of the most interesting features of this data was the sensitivity of the polarimetric response to anisotropies in the snow pack. Fresh snow cover is usually anisotropic, since it is comprised of needles, plates, and dendrites which fall with their broad axes horizontal. Through measurements and modelling, we have shown that this anisotropy can strongly influence the magnitude and phase of the correlation between horizontally and vertically polarized fields. These results have resulted in more sophisticated three- and four parameter models for the normalized Mueller matrix of snow cover, which reduce to the previously derived one- and two-parameter models for the isotropic case. Analysis of this data is continuing: At UMass, we are attempting to apply classification schemes to the measured Mueller matrix to identify different classes of snow; in addition, we have been working with researchers from MIT and CRREL to apply a more sophisticated vector radiative transfer model to see if it can account for the effects of anisotropy.

3.2 Demonstration of the equivalence of coherent and noncoherent measurement techniques

Polarimetric measurements of natural surfaces are usually expressed in terms of the Mueller matrix, which describes the average polarimetric response of a distribution of scatterers. This is usually achieved using a coherent radar which samples the complex scattering matrix of the scene under view by transmitting a pair of orthogonally polarized pulses in rapid succession. Noncoherent measurement techniques have also been developed which require transmitting three or more polarization states. Noncoherent techniques are especially useful above 100 GHz, where rapid polarization switching and phase coherence are difficult to achieve.

In order to demonstrate the equivalence of these two measurement techniques, we modified our existing dual antenna 95 GHz radar to simultaneously measure the target Mueller matrix using the coherent and noncoherent schemes. We did this by measuring three sets of orthogonal polarization pairs, namely, vertical/horizontal polarization; right and left hand circular polarization; and $\pm$ 45° linear polarization. The individual pairs were used to coherently compute three independent estimates of the Mueller matrix, while the noncoherently-derived matrix was computed by combining all six polarizations. We conclude three things: 1) the coherent and noncoherent techniques are equivalent when the measurements are made properly; 2) the coherent technique suffers from decorrelation effects due to target motion and phase noise; and 3) coherent measurement can be corrected by making an independent estimate of target decorrelation by transmitting two identically polarized pulses. These results were reported in a paper which will appear shortly in *Radio Science.*

As part of this effort, we also developed a Kalman filter to force the noncoherently-derived Mueller matrix to conform to constraints set by reciprocity. This technique was shown to reduce the error in Mueller matrix estimates, and was subsequently reported in *IEEE Trans. on Antennas and Propagation.*

3.3 Hardware Development

At the beginning of this project, we had two polarimetric radars, one operating at 225 GHz and another operating at 95 GHz. Our only 35 GHz radar was a 35 GHz FM-CW radar that could measure co- and cross-polarized backscatter, but required us to manually rotate the radar to measure at a different transmit polarization. All three radar were upgraded to improve measurement quality, reduce size and weight, and to allow full automation of the measurements. The 225 GHz radar was originally packaged in separate transmit and receive enclosures to allow bistatic measurements. Since most of our measurements were made monostatically, we decided to repackage the radar into a single enclosure. This reduce the size of the radar by almost half, and eliminated the need to align the transmit and receive antennas for different target ranges. The 95 GHz radar was originally configured with separate transmit and recieve antennas, which made it large and heavy. With funding from DOE, we were able to reconfigure this radar to operate from a single antenna, by the addition of a sophisticated polarization switching network and t/r diplexer. This change resulted in better polarization purity and stability, and eliminated the problems of beam alignment which plagues dual antenna systems.

Before the 1993-94 snow measurement campaign we realized that we could modify the existing 35 GHz FM-CW radar to make noncoherent polarimetric measurements using components that were already available in our lab. This involved modifying a spare 95 GHz lens antenna to operate at 35 GHz, and installing a motor drive to rotate the polarization of the transmit antenna. Polarimetric measurements were achieved by transmitting a series of six linear polarizations, and using our Kalman filter technique to solve for the Mueller matrix. This scheme proved feasible for snow cover measurements and allowed us to make simultaneous three frequency polarimetric measurements of snow cover for the first time in 1994.

3.4 Data Archiving

In the mid-1980s we developed a computer database, termed FINRACS, to gather as much of the published radar cross-section data as we could find in the open literature. We have since modified FINRACS to allow inclusion of polarimetric data, in the form of Mueller matrices, and have upgraded the software to run on UNIX workstations and IBM-compatible PCs. Most of the polarimetric data gathered during the course of this project have been entered into FINRACS, and are available to interested users via the internet. We have also published a joint report with the University of Michigan which contains a large volume of the polarimetric data gathered during the last five years.

4. List of Publications (last three years)

1. J.B. Mead, P.S. Chang, S.P. Lohmeier, P.M. Langlois, R E. McIntosh, "Polarimetric Observations and Theory of Millimeter-wave Backscatter from Snowcover", *IEEE Trans. on Antennas and Propagation*, v. 41, no. 1, 1993, pp. 38–46.
2. A. L. Pazmany and R. E. McIntosh, "The use of estimation techniques to reduce noncoherent polarimetric measurement errors",*IEEE Trans. on Antennas and Propagation*, v. 42, no. 9, 1994, pp. 1325–1328.

3. J. B. Mead, A.L. Pazmany, P.S. Chang, R.E. McIntosh, "A Comparison of Coherent and Noncoherent Polarimetric Radar Techniques at 95 GHz," accepted for publication, 1995, *Radio Science.*

4. P.S. Chang, J. B. Mead, R.E. McIntosh (UMass); B. Davis (CRREL); "Polarimetric Backscatter from Fresh and Metamorphic Snowcover at Millimeter Wavelengths, submitted to *IEEE Trans. Antennas and Propagation*, 1994, revised, April, 1995.

5. P. Chang, S. Lohmeier, R. McIntosh, J. Mead, (UMass); R. Hartikka, A. Nashashibi, K. Sarabandi, P. Siqueira, and F. Ulaby (UMich); *Handbook of Millimeter-wave Polarimetric Radar Response of Terrain, Vol.'s I and II*, March, 1995, 485 pages.

5. UMass personnel supported by this program:

- Robert E. McIntosh, Professor.
- James B. Mead, Research Associate Professor.
- Eric Knapp, MS, 1993. Now working as an engineer in our laboratory.
- Paul S. Chang, Ph.D.,1994. Now working at NOAA/NESDIS.
- Stephen P. Lohmeier, MS, 1992. Now working toward Ph.D.
- Jeff Baker, graduate student since 1993.
- Delwyn Moller, (supported in 1992).
- Geoff Hopcraft, (supported in 1992).
- Greg Sadowy, (supported in 1993).