MILLIMETER-WAVE MEASUREMENTS AND MODELLING OF THE SCATTERING PHASE FUNCTION OF INHOMOGENEOUS MEDIA

Fawwaz T. Ulaby

ARO Contract DAAL03-90-G-0203
Project Director: Fawwaz T. Ulaby

July 1, 1991

THE UNIVERSITY OF MICHIGAN
Radiation Laboratory
Department of Electrical Engineering
and Computer Science
Ann Arbor, Michigan 48109-2122
USA

MILLIMETER-WAVE MEASUREMENTS AND MODELLING OF THE SCATTERING PHASE FUNCTION OF INHOMOGENEOUS MEDIA

Fawwaz T. Ulaby

ARO Contract DAAL03-90-G-0203
Project Director: Fawwaz T. Ulaby

July 1, 1991 APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1, 1991

3. REPORT TYPE AND DATES COVERED
FINAL: 1 Sept 1990 - 20 April, 1991

4. TITLE AND SUBTITLE
MILLIMETER-WAVE MEASUREMENTS AND MODELLING
OF THE SCATTERING PHASE FUNCTION OF INHOMOGENIOUS MEDIA

5. FUNDING NUMBERS
DAAL03-90-G-0203

6. AUTHOR(S)
Fawwaz T. Ulaby

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
1301 Beal Ave.
Ann Arbor, MI 48109-2122

8. PERFORMING ORGANIZATION REPORT NUMBER
027731 - F

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 28358.1-GS-EQ

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)*

ARO Contract DAAL-03-90-G-0203 provided funds for the purchase of equipment to upgrade the University of Michigan's Millimeter-Wave Radar Systems. The 35 and 94 GHz channels were modified to operate in two modes: (a) totally coherent polarimetric mode and (b) coherent-on-receive polarimetric mode. The totally coherent mode is used for laboratory measurements to obtain the complete scattering matrix of the object of interest. The coherent-on receive mode is used under field conditions to measure the Mueller matrix and degree of polarization *in situ*. Experiments were conducted to verify that both modes provide identical results under laboratory conditions.

14. SUBJECT TERMS
Millimeter Waves, Radar Scattering, Terrain Characterization

15. NUMBER OF PAGES
8

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

1. INTRODUCTION

The University of Michigan has designed and built Millimeter-Wave radar systems for characterizing the scattering properties of terrain. These systems use a vector network analyzer as the signal processor. The systems have been used successfully under laboratory conditions to measure the polarimetric response of a variety of targets, including small trees. Under field conditions, however, the systems were incapable of providing accurate measurements because of the temporal movements of the target (tree leaves and branches) during the multipolarization data acquisition period (approximately 1 second). To overcome this problem, we proposed to ARO to convent the system to the incoherent-on-receive data acquisition mode which is insensitive to target motion. The conversion necessitated changes in the radar antennas, the RF circuitry, and the software program.

With the funds made available through ARO Contract DAAL-03-90-G-0203, we were able to implement the necessary modifications and verify that the two modes of operation provide identical results under laboratory conditions. The details of these results are given in Appendix A which is a copy of a paper that was presented at the 1991 AGARD Symposium in Ottawa, Canada.

2. INSTRUMENTATION

The instrumentation purchased through funds from this contract included:

Harmonic Multiplier, Spacek Lab Co.	$5,400.00
RF Amplifier, Miteq Corp.	5,447.61
RF Mixer, Militech Corp.	3,611.91
Mode Injector, Atlantic Microwave	642.01
MMW Amplifier, Avantech Corp.	9,252.81
MMW Mixer 1, Militech Comp.	5,502.87
MMW Mixer 2, Militech Comp.	6,200.00
Mixer Splitter, Alpha Corp.	6,272.79
	$42,340.00

3. PUBLICATIONS

Millimeter Wave Polarimetric Scatterometer Systems: Measurement and Calibration Techniques, Y. Kuga, K. Sarabandi, A. Nashashibi, F.T. Ulaby and R. Austin. 1991 AGARD Symposium, Ottawa, Canada.

4. PARTICIPATING PERSONNEL

Since this contract was specifically intended for the purchase of equipment, no personnel were supported by this contract.

5. INVENTIONS

None.

APPENDIX A

Millimeter Wave Polarimetric Scatterometer Systems: Measurement and Calibration Techniques, Y. Kuga, K. Sarabandi, A. Nashashibi, F.T. Ulaby and R. Austin. 1991 AGARD Symposium, Ottawa, Canada.

MILLIMETER WAVE POLARIMETRIC SCATTEROMETER SYSTEMS: MEASUREMENT AND CALIBRATION TECHNIQUES

Y. Kuga, K. Sarabandi, A. Nashashibi, F. T. Ulaby and R. Austin
University of Michigan
The Radiation Laboratory
Department of Electrical Engineering and Computer Science
3228 EECS Building
Ann Arbor, Michigan 48109-2122

SUMMARY

The target and system phase-stability during the time to measure the scattering matrix is a major problem for millimeter wave polarimetric radars. This is particularly true for network analyzer-based systems. To circumvent this phase-stability problem, we have developed new fully polarimetric radars at 35 and 94 GHz. The system is based on a relatively inexpensive network analyzer and is capable of operating in either the coherent or the incoherent polarimetric measurement mode. In the coherent mode, the scattering matrix can be measured within 2 ms. In the incoherent mode, the average Mueller matrix is measured directly by transmitting four different polarizations and measuring the Stokes vector of the backscattered signal. To compare the performance of the true measurement modes, the average Mueller matrix and the statistics of the phase difference of the two co-polarized signals were measured for a rhododendron tree and for a metallic tree. The average Mueller matrices obtained from the coherent and incoherent polarimetric measurement modes were similar. The target motion during the data acquisition period did not change the average Mueller matrix in the incoherent measurement mode. The probability density function of the phase difference of the two co-polarized signals computed from the average Mueller matrix is essentially the same as the one measured with the coherent polarimetric measurement mode.

1 INTRODUCTION

Increasing interest has been expressed in recent years for understanding the statistical properties of data obtained with fully polarimetric radars for remote sensing applications [Ulaby and Elachi, 1990]. At centimeter wavelengths, polarimetric data has been found to be useful for land-use classification [Van Zyl et. al., 1987] and for measuring the biophysical properties of forest canopies [McDonald et. al., 1990]. For the MMW region, however, it is still not clear what type of information can be extracted from polarimetric radar, over and above the magnitude information provided by conventional radar systems. Unlike the microwave region, the complexity and the cost of building a fully polarimetric radar at millimeter-wave frequencies is still very expensive, and progress has been rather slow, which is due, in part, to the limited availability of experimental data.

At microwave frequencies the traditional approach used for measuring the polarimetric radar response of a given target is based on the direct measurement of the target's scattering matrix, $\mathcal{S}$. For distributed targets, such as terrain surfaces, multiple measurements of $\mathcal{S}$ are made, corresponding to statistically independent samples, each measurement is used to compute its corresponding Mueller matrix $\mathcal{L}$, and then an ensemble average is performed to obtain an estimate of the average Mueller matrix, $<\mathcal{L}>$. Whereas the scattering matrix measurement technique is appropriate at microwave frequencies, it is difficult to implement at millimeter wavelengths because it requires that both the system and target phases remain stable during the time it takes to measure $\mathcal{S}$. This is particularly true for network analyzer-based polarimetric radars [Ulaby et. al., 1990].

To circumvent this phase-stability problem, we have developed new fully polarimetric radars at 35 and 94 GHz. The system is based on relatively inexpensive network analyzer and is capable of operating in either the coherent or the incoherent polarimetric measurement mode. In the coherent mode, the scattering matrix can be measured within 2 ms. In the incoherent mode the average Mueller matrix is measured directly by transmitting four different polarizations and recording the horizontally polarized and vertically polarized components of the backscattered field. This paper includes a detailed analysis of the two measurement modes, and provides comparisons of data measured using the two modes for a rhododendron tree and an artificially made metallic tree.

2 NWA BASED POLARIMETRIC RADARS

The fully polarimetric radar configuration based on the vector network analyzer (NWA) is easy to construct and is widely used for remote sensing investigations [Ulaby et. al., 1990]. These systems usually are operated in the swept frequency mode over a given bandwidth. The minimum sweep time, which depends on the number of frequency points and the type of NWA, is typically between 100 to 400 ms. The decorrelation time of the MMW wave scattered from trees, on the other hand, can be shorter than 10 ms [Narayanan et. al., 1988]. Hence, when using the fully coherent measurement configuration, it is necessary that all four components of the scattering matrix be measured within a few milliseconds in order to obtain accurate data. If the $V-$ and $H-$ polarized signals are transmitted sequentially in the swept frequency mode, it will take at least 0.5 to 1 second to get a complete scattering matrix, including the data transfer time between the NWA and the computer. Obviously, the NWA-based MMW radar used in the swept frequency mode is not suited for coherent polarimetric measurements.

There are two ways to overcome the shortcoming of the traditional swept-frequency NWA based polarimetric radar. The first approach is the incoherent polarimetric measurement technique. With this technique the swept frequency mode can still be used for the NWA operation but the radar transmitter must be modified to transmit four independent polarizations. The data processing and calibration are substantially more complicated than those associated with the coherent polarimetric technique. The second approach is the coherent polarimetric measurement technique using Coupled/Chop mode and point by point external triggering of the NWA. We have developed both coherent and incoherent polarimetric radars based on these techniques at 35 and 94 GHz. The radar front end and data acquisition system are the same for both systems. The only difference is the operating mode of the NWA and the data processing. It is, therefore, possible to obtain polarimetric data of the same targets coherently and incoherently. The block diagram of the MMW radar system and the 35 GHz front end are shown in Figs. 1 and 2. The block diagram of the 94 GHz is essentially the same as that of the 35 GHz system. In the following section the details of the coherent and incoherent systems will be discussed.

2.1 Coherent Polarimetric Radar

The coherent polarimetric radar has many advantages over the incoherent polarimetric radar. For example, with the coherent polarimetric radar the statistical data including the phase difference between the two copolarized channels, can be easily obtained. Another advantage is the significantly simpler signal processing and calibration processes compared to those of the incoherent polarimetric radar. As discussed in the previous section, the NWA-based radar operated in the swept frequency mode is not suited for coherent polarimetric measurements. In this section, we will describe a new technique which utilizes a relatively inexpensive NWA (HP8753C) that allows the acquisition of coherent polarimetric data at a much faster rate. With this system it is possible to measure the scattering matrix within 2 ms at 35 and 94 GHz.

The Hewlett-Packard network analyzer, HP8753C, has two independent receiving channels which can be used in the Coupled/Chop mode. It also has a point by point external triggering capability in the swept frequency mode. These functions are ideally suited for the coherent polarimetric radar. For example, the simultaneous acquisition of V and H channels can be done by operating A and B inputs in the Coupled/Chop mode. The point by point external triggering can be used for transmitting V and H sequentially and synchronizing a polarization control circuit to create different polarizations. At present, HP8753C does not support the external point by point triggering in the CW mode but a near CW mode can be created in the swept frequency mode by choosing the output frequency bandwidth to be 1Hz. The minimum time to get a complete scattering matrix is approximately 2 ms in the present system. The polarization of the transmitted MMW signal is controlled by a Faraday rotator whose switching time is less than 5 μs. Using the maximum number of points provided by the HP8753C, it is possible to obtain 800 scattering matrices within 3.2 s without transferring data into a computer.

The separation of signal from unwanted noise, such as antenna coupling, is accomplished by the hardware gating circuit in the IF path as shown in Fig. 2. The transmitted pulse length is 20 ns and the pulse-repetition-rate is 5 MHz. Although it is not necessary to scan the RF frequency band in the coherent polarimetric mode, additional independent samples can be realized by averaging the backscattering coefficient over the RF bandwidth [Ulaby et. al., 1988]. A bandwidth of 1 GHz at 35 GHz, for example, offers 5 to 10 independent samples per spatial observation for the tree measurements.

The calibration of the coherent system is straightforward. Because the system has more than 23 dB of isolation between the V and H channels, a simple calibration technique that requires a sphere and a depolarizing target is used [Sarabandi et. al., 1990].

2.2 Incoherent Polarimetric Radar

In the incoherent polarimetric radar technique, the Mueller matrix of the target is measured directly by transmitting four independent polarizations and receiving the Stokes vector of the scattered signal. Because the correlation between the $V-$ and $H-$ polarized signals is inherently included in the received Stokes vector, the measurement time between the different incident polarizations can be much longer than the decorrelation time of the target. The incoherent polarimetric technique also permits the use of MMW sources that do not have good phase-stability in the transmitter section [Mead, 1990]. A desired polarization can be created by placing two quarter-wave plates in front of the transmitting antenna and by adjusting the orientation angle of each wave plate relative to the incident polarization.

The received Stokes vector for a given incident polarization is usually obtained by two different approaches, incoherent and coherent-on-receive techniques. The incoherent receive technique, which often is employed in optics measures the intensity of six different receive polarizations, but the phase measurement is not required. The Stokes vector is obtained by taking appropriate ratios of the receive intensities, as shown in Appendix A.

The receiver of the coherent-on-receive technique is similar to that of the coherent polarimetric radar. The coherent-on-receive method requires the measurement of the magnitudes of the $V-$ and $H-$ polarized receive signals and the phase difference between them, but it does not have to measure the phase angle relative to the transmitted signal, as is the case with the coherent polarimetric radar. The Stokes vector can be computed from the magnitudes of the V and H components of the received signal and the phase difference between them as shown in Appendix A. Because it is relatively easy to measure the phase difference between the V and H channels, our system is based on the coherent-on-receive technique.

Calibration of incoherent polarimetric radar systems involves two steps [Mead, 1990]. In the first step, the receiver distortion matrix is obtained by placing a wire grid polarizer in front of the receiving antenna at three different positions. In the second step, the exact polarization properties of the transmitter are determined by measuring the backscatter from a point target with known scattering matrix using the calibrated receiver.

3 EXPERIMENTAL DATA

To demonstrate that the coherent and incoherent polarimetric measurement techniques do indeed provide identical information for distributed targets, experiments were conducted using a rhododendron tree and a metallic structure resembling a short tree. Photographs of these targets are shown in Fig. 3. The metallic structure is used for creating a target return with strong correlation between the S_{vv} and S_{hh} components. To create many independent samples and also to show that the incoherent polarimetric technique can provide accurate results even if the data acquisition time is much longer than the target decorrelation time, the trees were rotated at slow (0.67 rpm) and fast (1.33 rpm) speeds during the data-collection process.

Table 1 shows the average Mueller matrices of the rhododendron and metallic trees obtained by the coherent and incoherent polarimetric radar techniques. The Mueller matrices are normalized with respect to the L_{11} component to show the relative magnitude of the matrix elements. The average Mueller matrix of the coherent polarimetric radar technique was computed from the 8000 scattering matrices obtained over the 34-35 GHz band. Because of the slow data-acquisition speed in the incoherent polarimetric radar, the average Mueller matrix is obtained from only 500 samples, including those due to frequency averaging over the 1-GHz RF bandwidth.

The sum of the Mueller matrix elements L_{33} and L_{44}, which is a function of the correlation between S_{vv} and S_{hh}, is higher for the metallic tree than for the rhododendron tree. Although the polarimetric signature computed from the average Mueller matrix is useful for showing the characteristics of the target, it is not easy to directly relate the target characteristics to the values of the Mueller matrix elements.

Figure 4 shows the probability density function of the phase difference between the two co-polarized channels (ϕ_c = phase of S_{vv} - phase of S_{hh}) obtained with the coherent polarimetric radar. As expected, $p(\phi_c)$ of the metallic tree is much narrower than that of the rhododendron tree, showing strong correlation between S_{vv} and S_{hh}.

Unlike the coherent polarimetric radar, the information obtained with the incoherent polarimetric radar is limited to the average Mueller matrix and it is not possible to measure the probability density function $p(\phi_c)$ directly. Due to a recent theoretical derivation, however, the phase statistics of ϕ_c can be estimated from the average Mueller matrix [Sarabandi, 1991]. The probability density function $p(\phi_c)$ is given by

$$p(\phi_c) = \frac{\lambda_{11}\lambda_{33} - \lambda_{13}^2 - \lambda_{14}^2}{2\pi B^2}\left\{1 + \frac{D}{B}\left[\frac{\pi}{2} + \tan^{-1}\left(\frac{D}{B}\right)\right]\right\}$$

where

$$\lambda_{11} = \frac{L_{11}}{2}, \qquad \lambda_{33} = \frac{L_{22}}{2},$$

$$\lambda_{13} = \frac{L_{33} + L_{44}}{4}, \qquad \lambda_{14} = \frac{L_{34} - L_{43}}{4},$$

$$D = \lambda_{13}\cos\phi_c + \lambda_{14}\sin\phi_c,$$

$$B = \left[\lambda_{11}\lambda_{33} - D^2\right]^{\frac{1}{2}}.$$

The function $p(\phi_c)$ is completely specified in terms of the elements of the average Mueller matrix $\mathcal{L}_m$.

The average Mueller matrix given in Table 1 and the probability density function of the phase difference shown in Fig. 4 are obtained from the same target by two different polarimetric measurement techniques. If the probability density function given by Eq. 1 is correct, $p(\phi_c)$ estimated from the average Mueller matrix must be similar to the one shown in Fig. 4. Figure 5 shows the probability density function computed from the average Mueller matrix obtained by the incoherent polarimetric radar. The agreement between Figs. 4 and 5 is excellent for both trees.

4 CONCLUSION

The work described in this paper has demonstrated that the average Mueller matrices obtained using the coherent and incoherent polarimetric measurement techniques are essentially identical. The advantage of the coherent polarimetric radar over the incoherent polarimetric radar is its ability to measure the statistical distributions of the magnitudes and relative phases of the scattering matrix elements. The incoherent polarimetric radar, however, is particularly useful if the target decorrelation time is much faster than the data acquisition time.

REFERENCES

[1] Ulaby, F.T., and C. Elachi, *Radar Polarimetry for Geoscience Applications*, Artech House Inc., Massachusetts, 1990.

[2] Van Zyl, J.J., H.A. Zebker, and C. Elachi, "Imaging Radar Polarization signatures: Theory and Observation," *Radio Science*, 1987, Vol. 22, pp. 529-543.

[3] Sarabandi, K., F.T. Ulaby, and M.A. Tassoudji, "Calibration of Polarimetric Radar Systems with Good Polarization Isolation," *IEEE Trans. on Geosci. Remote Sensing*, 1990, GE-28.

[4] Ulaby, F.T., T.F. Haddock, and R.T.. Austin, "Fluctuation Statistics of Millimeter-Wave Scattering from Distributed Target," *IEEE Trans. on Geosci. and Remote Sensing*, 1988, Vol. 26, pp. 268-281.

[5] McDonald, K.D., M.C. Dobson, and F.T. Ulaby, "Using MIMICS to Model *L*- Band Multiangle and Multitemporal Backscatter from a Walnut Orchard," *IEEE Trans. on Geosci. and Remote Sensing*, 1990, Vol. 28, pp. 477-491.

[6] Mead, J.B., "Polarimetric Measurements of Foliage and Terrain at 225 GHz," (PH.D. Thesis, Univ. of Mass., 1989).

[7] Ulaby, F.T., M.W. Whitt, and K. Sarabandi, "AVNA-based Polarimetric Scatterometers," *IEEE Antennas Propagation Magazine*, 1990.

[8] Sarabandi. K., "Derivation of Phase Statistics of Distributed Targets from the Averaged Mueller Matrix," Technical Report 026511-T, 1991, Radiation Laboratory, University of Michigan, Ann Arbor, MI.

[9] Narayanan, R.M., C.C. Borel, R.E. McIntosh, "Radar Backscattering Characteristics of Trees at 215 GHz," *IEEE Trans. on Geosci. and Remote Sensing*, 1988, Vol. 26, pp. 217-218.

APPENDIX A

COHERENT-ON-RECEIVE TECHNIQUE

Complete polarimetric characterization of the scattering properties of a distributed target can be obtained by measuring either the scattering matrix $\mathcal{S}$ or the Mueller matrix $\mathcal{L}_m$. Measurement of the scattering matrix requires accurate phase measurements. Also 4 elements of $\mathcal{S}$ must be obtained within the decorrelation time of the target which is in the order of milliseconds at MMW frequencies. The scattered electric field $\mathbf{E}^r$, in terms of the scattering matrix $\mathcal{S}$ and the incident electric field $\mathbf{E}^i$, is given by

$$\mathbf{E}^r = \frac{e^{ikr}}{r}\mathcal{S}\mathbf{E}^i \qquad (A.1)$$

$$\mathbf{E}^r = \begin{bmatrix} E_v \\ E_h \end{bmatrix} \quad \mathbf{E}^i = \begin{bmatrix} E_v \\ E_h \end{bmatrix} \quad \mathcal{S} = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \qquad (A.2)$$

To obtain $\mathcal{S}$, we need to send $[E_v, 0]^t$ and $[0, E_h]^t$, and measure E_v and E_h simultaneously.

The polarized wave can also be expressed in terms of the Stoke's vector $\mathbf{F}_m$ which is defined as

$$\mathbf{F}_m = \begin{bmatrix} I_1 \\ I_2 \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_v|^2 \\ |E_h|^2 \\ 2\mathrm{Re}[E_v E_h^*] \\ 2\mathrm{Im}[E_v E_h^*] \end{bmatrix} \qquad (A.3)$$

then (A.1) in terms of Stokes vector becomes

$$\mathbf{F}_m^r = \frac{1}{r^2}\mathcal{L}_m \mathbf{F}_m^i \qquad (A.4)$$

$$\mathcal{L}_m = \begin{bmatrix} |S_{vv}|^2 & |S_{vh}|^2 & \mathrm{Re}(S_{vh}^* S_{vv}) & -\mathrm{Im}(S_{vh}^* S_{vv}) \\ |S_{hv}|^2 & |S_{hh}|^2 & \mathrm{Re}(S_{hh}^* S_{hv}) & -\mathrm{Im}(S_{hv} S_{hh}^*) \\ 2\mathrm{Re}(S_{vv} S_{hv}^*) & 2\mathrm{Re}(S_{vh} S_{hh}^*) & \mathrm{Re}(S_{vv} S_{hh}^* + S_{vh} S_{hv}^*) & -\mathrm{Im}(S_{vv} S_{hh}^* - S_{vh} S_{hv}^*) \\ 2\mathrm{Im}(S_{vv} S_{hv}^*) & 2\mathrm{Im}(S_{vh} S_{hh}^*) & \mathrm{Im}(S_{vv} S_{hh}^* + S_{vh} S_{hv}^*) & \mathrm{Re}(S_{vv} S_{hh}^* - S_{vh} S_{hv}^*) \end{bmatrix} \qquad (A.5)$$

where $\mathcal{L}_m$ is called the Mueller matrix.

The totally incoherent method does not require phase measurements. With this method, the 4 elements of Stokes vector are obtained by receiving 6 polarizations (V, H, 45, 135, LHC, RHC). For example, the third element of Stokes vector U is given as a ratio of intensities at 45 linear to 135 linear. For a given incident polarization, therefore, we can obtain a column of the Mueller matrix. To get the complete Mueller matrix, we need to repeat this process for 4 independent incident polarizations. Altogether, at least 24 magnitude only measurements are required to obtain the complete Mueller matrix. Although the phase measurement is not required with the incoherent method, it is necessary to receive all 6 polarizations. The elements of the Stokes vector, in terms of 6 polarizations and a set of 4 independent incident polarizations, given by:

$$I_1 = \frac{W_v}{W_h + W_v} \qquad (A.6)$$

$$I_2 = \frac{W_h}{W_h + W_v} \qquad (A.7)$$

$$U = \frac{W_{45} - W_{135}}{W_{45} + W_{135}} \qquad (A.8)$$

$$V = \frac{W_{LHC} - W_{RHC}}{W_{LHC} + W_{RHC}} \qquad (A.9)$$

$$I_v = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, I_h = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, I_{45} = \begin{bmatrix} 1/2 \\ 1/2 \\ 1 \\ 0 \end{bmatrix}, I_{LHC} = \begin{bmatrix} 1/2 \\ 1/2 \\ 0 \\ 1 \end{bmatrix} \qquad (A.10)$$

where W is the received intensity of polarization.

If a receiver is able to measure the phase between the V and H channels, it is possible to do the incoherent method without measuring 6 polarizations. This method is called the coherent-on-receive (COR) technique. The elements of the Stokes vector can be expressed as

$$I_1 = |E_v|^2 \qquad (A.11)$$

$$I_2 = |E_h|^2 \qquad (A.12)$$

$$U = 2|E_v||E_h|\cos\delta \qquad (A.13)$$

$$V = 2|E_v||E_h|\sin\delta \qquad (A.14)$$

where δ is the phase difference between V and H channels.

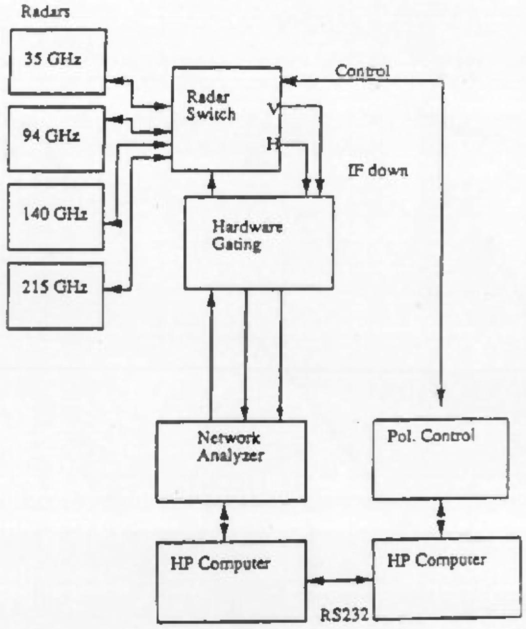

Figure 1 Block Diagram of the MMW Polarimetric Radar.

35 GHz Radar (Fully Polarimetric)

<u>Transmitter</u>

IF bandwidth	up to 2 GHz
Power	+23 dBm
Antenna	6" Lens (beamwidth 4.2 degrees)
Polarization	Any polarization

<u>Receiver</u>

Dual Channel	V and H
Mixers	Fundamental mixing
Antenna	6" Lens (beamwidth 4.2 degrees)

<u>Polarimetric data</u>

Incoherent (coherent-on-receive)
Mueller matrix

Coherent
Scattering amplitude matrix

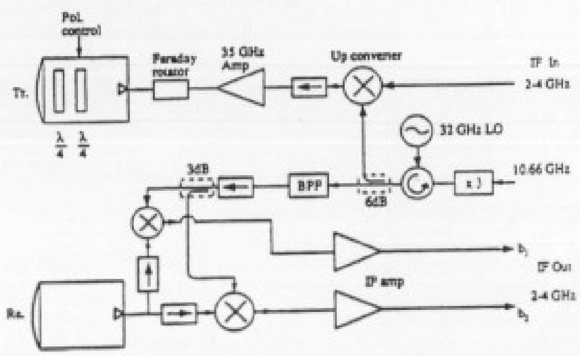

Figure 2 Block Diagram of the 35 GHz Radar Frontend.

Figure 3 Photographs of the Metallic Tree and Rhododendron Tree.

Rhododendron Tree (Target in motion)

Incoherent Polarimetric Measurement Mode (500 samples)

Fast Motion

$$\begin{bmatrix} 1 & 0.16 & -0.006 & 0.007 \\ 0.186 & 0.828 & -0.017 & 0.017 \\ 0.04 & 0.059 & 0.735 & 0.056 \\ -0.059 & -0.023 & -0.019 & 0.472 \end{bmatrix}$$

Slow Motion

$$\begin{bmatrix} 1 & 0.231 & -0.052 & 0.012 \\ 0.126 & 1.035 & -0.021 & 0.049 \\ -0.038 & 0.082 & 0.697 & 0.003 \\ -0.013 & -0.015 & -0.064 & 0.619 \end{bmatrix}$$

Coherent Polarimetric Measurement Mode (8000 samples)

$$\begin{bmatrix} 1 & 0.159 & -0.002 & -0.006 \\ 0.179 & 0.823 & -0.003 & -0.018 \\ 0.0 & -0.01 & 0.683 & -0.023 \\ -0.033 & -0.001 & 0.003 & 0.596 \end{bmatrix}$$

Metallic Tree (Target in motion)

Incoherent Polarimetric Measurement Mode (500 samples)

Fast Motion

$$\begin{bmatrix} 1 & 0.089 & 0.02 & 0.03 \\ 0.094 & 0.74 & 0.02 & 0.001 \\ 0.026 & 0.011 & 0.888 & 0.105 \\ -0.028 & -0.007 & -0.126 & 0.619 \end{bmatrix}$$

Coherent Polarimetric Measurement Mode (8000 samples)

$$\begin{bmatrix} 1 & 0.06 & 0.0 & 0.0 \\ 0.06 & 1.16 & 0.009 & 0.004 \\ 0.011 & 0.002 & 0.973 & -0.053 \\ 0.008 & 0.002 & 0.049 & 0.89 \end{bmatrix}$$

Table 1. Average Mueller matrices of rhododendron and metallic trees measured with coherent and incoherent polarimetric measurement modes.

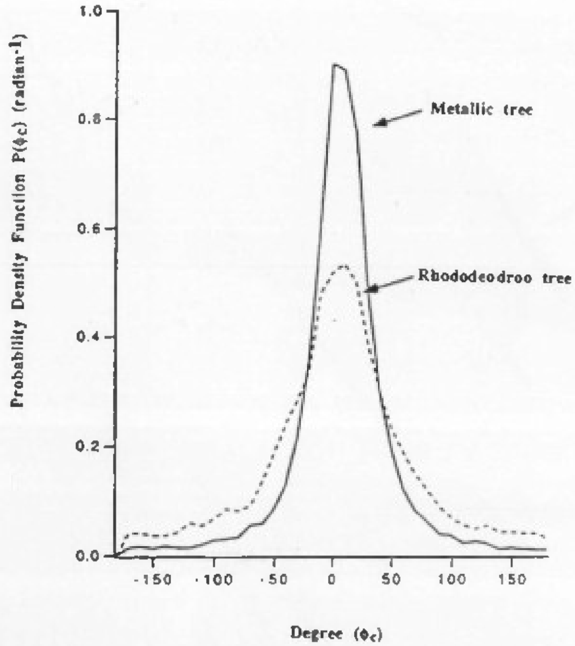

Figure 4 Probability Density Function Measured by the Coherent Polarimetric System.

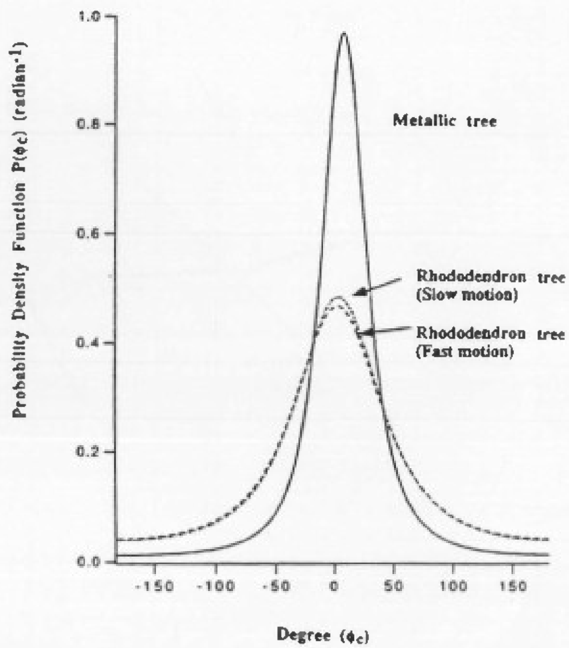

Figure 5 Probability Density Function Computed from the Average Mueller Matrix.