MEASUREMENT OF MODIFIED MUELLER MATRIX OF RANDOM MEDIA USING A MULTI-POLARIZATION POWER-MEASURING SCATTEROMETER

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1. Introduction

Radar polarimetry has become a new subject of studies in the field of microwave remote sensing in these years (Refs. 1, 2). A synthetic-aperture radar (SAR) coupled with polarimetry is expected to expand capabilities of imaging radars for earth observations significantly. A number of airborne and spaceborne polarimetric SAR programs, including JPL's SIR-C, are progressing.

Ground-based polarimetric signature studies have also started in recent years. Ground-based studies with accurate ground-truth are quite important for modeling radar targets and to understand well SAR images obtained from aircraft or spacecraft. Most of the polarimetric signature studies are utilizing vector network analyzer systems or scatterometers with a phase measurement capability (Ref. 2).

This paper presents a ground-based experiment for studying polarimetric signatures of random media. We have developed a method to measure the modified Mueller matrix of random media by using a multi-polarization, power-measuring (not phase-measuring) scatterometer. The paper describes the principle of the measurement method and the measuring system, and discusses backscatter measurements on a random scatterer made of randomly-oriented thin dielectric rods and on coniferous trees.

2. Measurement Method

Backscattered waves from random media are in general elliptically-polarized for any incident waves with a specified polarization. While observing a random medium, a backscattered field behaves as a random variable (cf. fading), and its polarization state changes also. We can thus consider the backscattered fields to be "partially polarized." Partially polarized fields are well described by the Stokes vector: $[g] = [g_0, g_1, g_2, g_3]$.

Applying a technique used in radio astronomy, we can measure a Stokes vector by using six antennas, with polarizations of linear horizontal (H), linear vertical (V), 45°-inclined linear (D), 135°-inclined linear (X), left-handed circular (L) and right-handed circular (R). A Stokes vector is given by

$$[g] = \left[\frac{Wh'}{Arh'} + \frac{Wv'}{Arv'},\ \ \frac{Wh'}{Arh'} - \frac{Wv'}{Arv'},\ \ \frac{Wd'}{Ard'} - \frac{Wx'}{Arx'},\ \ -\frac{Wl'}{Arl'} + \frac{Wr'}{Arr'} \right] \tag{1}$$

where W_i's are powers detected by each antennas and A_{ri}'s are effective areas of each antennas, i indicating polarizations. A Stokes vector [g] is converted to a modified Stokes vector [gm] by: $[gm]=[(g_o+g_1)/2,\ (g_o-g_1)/2,\ g_2,\ g_3]$.

A polarization transformation property of a radar target is completely described by the scattering matrix [S] or the Mueller (or modified Mueller) matrix. When treating partially polarized processes, the modified Mueller matrix [Mm] is adequate because (1) it is a transformation matrix connecting (modified) Stokes vectors and (2) the matrix is additive (can be averaged). The modified Stokes vector of a scattered field [Gm'] is related to that of an incident field [Gm] by $[Gm']=(1/4\pi R^2)[Mm][Gm]$. For backscattering, an average modified Mueller matrix is expressed using the components of the scattering matrix [S] (< > stands for an expectation):

$$[Mm]=\begin{bmatrix} \langle|Sh'h|^2\rangle & \langle|Sv'h|^2\rangle & \langle Re(Sh'hSv'h^*)\rangle & \langle Im(Sh'hSv'h^*)\rangle \\ \langle|Sv'h|^2\rangle & \langle|Sv'v|^2\rangle & \langle Re(Sv'hSv'v^*)\rangle & \langle Im(Sv'hSv'v^*)\rangle \\ \langle 2Re(Sh'hSv'h^*)\rangle & \langle 2Re(Sv'hSv'v^*)\rangle & \langle Re(Sh'hSv'v^*+Sv'hSv'h^*)\rangle & \langle Im(Sh'hSv'v^*)\rangle \\ -\langle 2Im(Sh'hSv'h^*)\rangle & -\langle 2Im(Sv'hSv'v^*)\rangle & -\langle Im(Sh'hSv'v^*)\rangle & \langle Re(Sh'hSv'v^*-Sv'hSv'h^*)\rangle \end{bmatrix}$$

Our method of measuring an average modified Mueller matrix is based on backscattering coefficient measurements. We transmit in five polarizations (H, V, D, L, R; theoretically four are enough), successively, and receive backscatters in six polarizations (see Eq. (1)). We can show that the components of the average modified Mueller matrix are related to measured backscattering coefficients by the following equations ($\sigma_i{}'_j$ stands for a scattering coefficient of j-pol transmit and i-pol receive):

$$\begin{aligned} &\langle|Sh'h|^2\rangle=\langle\sigma h'h\rangle \quad \langle|Sv'h|^2\rangle=\langle\sigma v'h\rangle \quad \langle|Sv'v|^2\rangle=\langle\sigma v'v\rangle \\ &\langle Re(Sh'hSv'h^*)\rangle=(\langle\sigma d'h\rangle-\langle\sigma x'h\rangle)/2 \quad \langle Im(Sh'hSv'h^*)\rangle=-(\langle\sigma l'h\rangle-\langle\sigma r'h\rangle)/2 \\ &\langle Re(Sv'hSv'v^*)\rangle=(\langle\sigma d'v\rangle-\langle\sigma x'v\rangle)/2 \quad \langle Im(Sv'hSv'v^*)\rangle=-(\langle\sigma l'v\rangle-\langle\sigma r'v\rangle)/2 \\ &\langle Re(Sh'hSv'v^*)\rangle=(\langle\sigma r'l\rangle-\langle\sigma x'd\rangle)/2 \quad \langle Im(Sh'hSv'v^*)\rangle=-(\langle\sigma d'l\rangle-\langle\sigma x'l\rangle)/2 \\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad +(\langle\sigma d'r\rangle-\langle\sigma x'r\rangle)/2 \end{aligned} \tag{2}$$

3. Measurement System and Absolute Calibration

We had a C-band scatterometer (4.0 GHz) for indoor-use (Ref. 3). We have modified it such that it can operate for mutliple polarizations necessary for the Mueller matrix measurement. The measurements are made indoors. Targets are placed on a turntable. By rotating the table during backscatter measurements, we can get a large number of independent samples. Typical numbers of the independent samples we get are about 200, under which an uncertainty of σ is less than 1 dB.

Accurate absolute and relative calibrations of antenna-product-gains among a large number of sets of transmit and receive polarization combinations are required in our system. We uses a conducting sphere for calibrations of HH, VV, LR, RL, DD, XX. The remaining polarization combinations have been calibrated by measuring backscatters from an ensamble of randomly-oriented half-wavelength metallic dipoles embedded in a polystyrene block. We embed them sparsely enough such that back- scatters can be assumed to be a sum of single scatterings. We assume that the antenna gains are calibrated in relative with an accuracy of about 0.5 dB.

4. Measurement Results

We have measured polarization transformation properties of the targets: an ensamble of randomly-oriented dielectric rods, J. Pine and J. Cypress. The measurements have indicated that the polarizations of HH, HV, VV, LR, LL, DD, and DX are important; the elements derived from these polarizations are large in an average modified Mueller matrix, while the remaining elements in the matrix are small (The latter implies that a symmetry of targets existed). Let us show an example of the matrix, measured on J. Pine at the incident angle of 20°:

$$\begin{bmatrix} .0860994 & .0427563 & -3.70562E-03 & 4.86167E-04 \\ .0427563 & .107152 & -4.68444E-04 & 5.52551E-03 \\ -7.41123E-03 & -9.36888E-04 & .0787216 & 4.68779E-03 \\ -9.72334E-04 & -.011051 & -4.68779E-03 & -6.79099E-03 \end{bmatrix}$$

The scattering coefficients at the principal polarizations mentioned above mainly characterize the targets. Differences of the targets appear noticeably in depolarization, that is, in changes of ratios of HH/HV, VV/VH, LR/LL, DD/DX and so on.

Randomly-oriented dielectric rods Rods are half-wavelength thin poly - ethyrene tubes, inside of which are filled with water. Over 6000 rods are spread over a volume of 150x150x50 cm^3. Three types of targets with different distributions in the elevation angles (θ) of the rods have been formed: 1) randomly oriented ($0° < \theta < 90°$), 2) horizontally distributed ($0° < \theta < 45°$), 3) vertically distributed ($45° < \theta < 90°$). Figure 1 shows the scattering coefficients. In every cases, the level of LR and LL is equal. The backscattering properties of cases 1) and 2) are similar, though the absolute levels differ. The ratio of linear-like / linear-cross is about 4 dB, which indicates multiple scatterings are taking place. In case 3), VV increases rapidly when an incident angle increases, as exected from the distribution of θ.

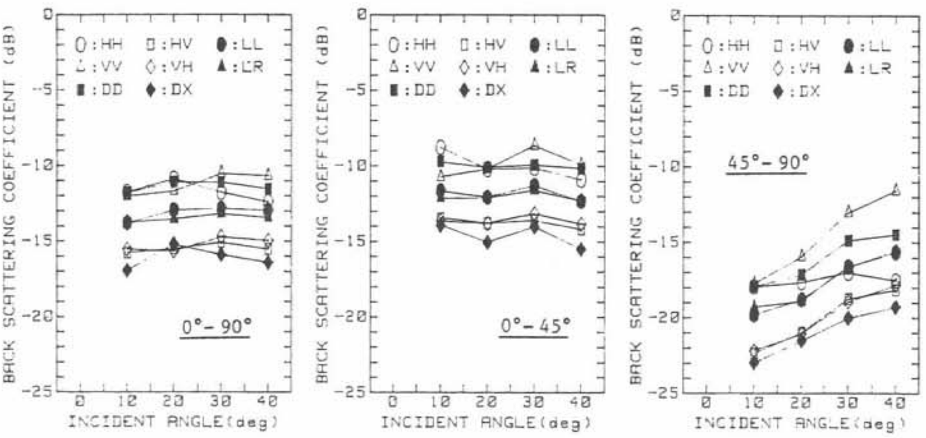

Fig. 1. Scattering coefficients of an ensamble of randomly-oriented half-wavelength dielectric rods. The elevation angles of rods are uniformly-distributed in the range indicated in the figures. The frequency is 4.0 GHz.

Coniferous trees Extended targets of J. Pine and J. Cypress were formed on the turn table. The heights were 70-80 cm. Since the heights were smaller than penetration depths, we covered the underlying surface by microwave absorbers. J. Cypress was measured in two states: with leaves and without leaves. Figure 2 shows the scattering coefficients. Backscatters from J. Pine are typical of needle like scatterers. Significant differences are between the two states of J. Cypress, and J. Cypress without leaves is quite similar to J. Pine. Figure 3 shows polarization signature diagrams (Ref. 4) of the conifers derived from the average modified Mueller Matrices. The higher pedestal level in the diagrams represents greater depolarization; J. Pine deporalizes most and J. Cypress less. Removing leaves form J. Cypress increases the degree of deporalization.

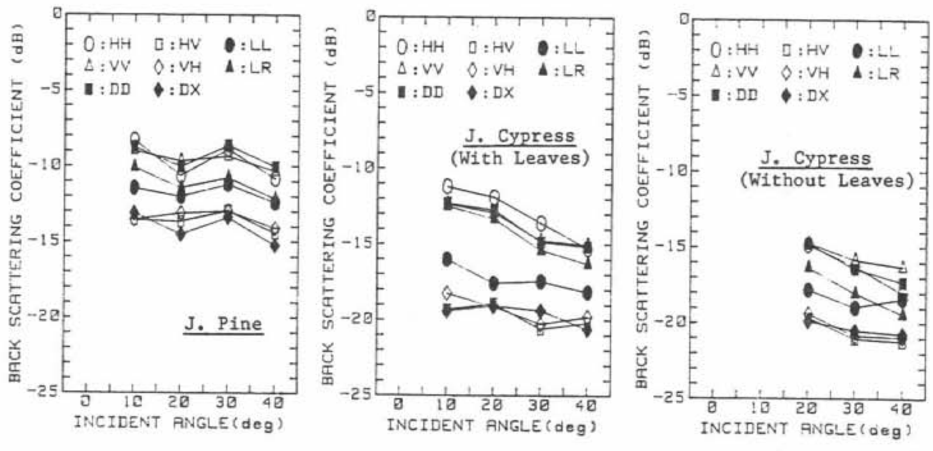

Fig. 2. Scattering coefficients of J. Pine, and J. Cypress with and without leaves. The frequency is 4.0 GHz.

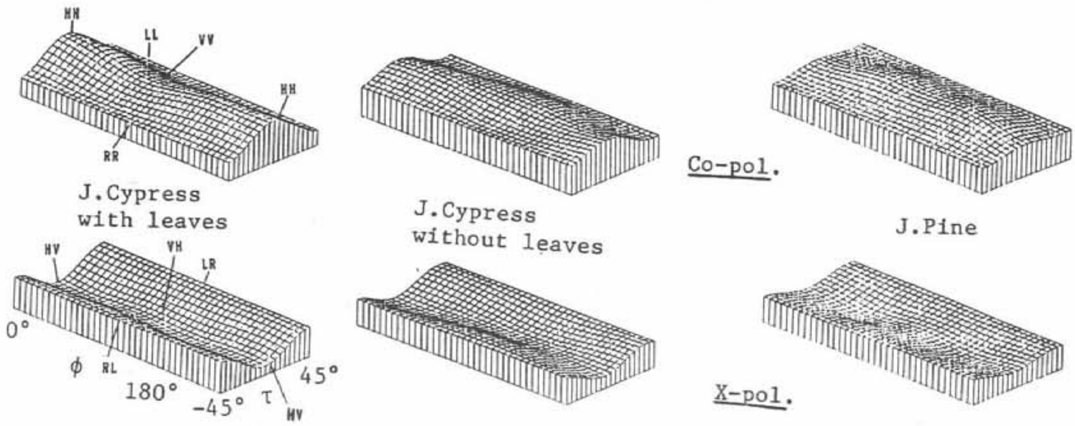

Fig. 3. Polarimetric signature diagrams of J. Cypress with and without leaves, and J. Pine.

5. Conclusions

We have presented a modified Mueller matrix measurement method using a power-measuring scatterometer for ground-based polarimetric signatures studies, and discussed results of some measurements. Following the approach described in this paper, we will further extend studies on radar polarimetric signatures.

References. (1) Proc. IGARSS'87, Ann Arobor, May 1987. (2) Proc. IGARSS'88, Endinburgh, Sep. 1988. (3) H. Hirosawa et.al., Proc. IGARSS'88, Sep. 1988. (4) H. Zebker, et al., J. Geophys. Res., Vol. 92, pp. 683-701, 1987.