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HANDBOOK OF MILLIMETER-WAVE POLARIMETRIC RADAR RESPONSE OF TERRAIN

A JOINT REPORT BY

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HANDBOOK OF MILLIMETER-WAVE POLARIMETRIC RADAR RESPONSE OF TERRAIN

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1 Introduction

In the mid-1980's the Geosciences Division of the U.S. Army Research Office, under the directorship of Dr. Walter Flood, established a program aimed at improving our understanding of the millimeter-wave (MMW) radar response of terrain. The University of Michigan and the University of Massachusetts were selected for carrying out independent, but complementary, efforts to (1) design and construct MMW scatterometer systems, (2) develop accurate calibration techniques, (3) conduct experimental measurements, and (4) develop theoretical models that adequately characterize the radar backscatter from terrain. In the ensuing years, a wealth of data was accumulated and numerous results were achieved, most of which have appeared in print in the form of journal papers and technical reports.

With the advent of polarimetric radar at centimeter wavelengths in the late 1980's, the ARO Millimeter-Wave Terrain program was extended in 1991 to examine aspects of terrain scattering at millimeter-wave frequencies. This necessitated the redesign of the millimeter-wave scatterometers at Michigan and Massachusetts to enhance their measurement capabilities. Accordingly, the systems were modified and new calibration techniques were developed to make it possible to operate them in a polarimetric mode. The systems were then used to measure the polarimetric backscatter for bare soil surfaces, snow cover, and vegetation cover, and other terrain surfaces, under a variety of conditions.

Whereas handbooks of measured multipolarized, but not polarimetric, radar data exist in print for various types of terrain surfaces at both centimeter- and millimeter-wave frequencies, no such handbook exists at present that documents carefully made polarimetric observations of well-characterized media. This report is intended to provide a compilation of polarimetric radar responses for various types of terrain at millimeter-wave frequencies. The polarimetric radar response is characterized by the Mueller matrix, from which the backscattering coefficient can be calculated for any desired combination of transmit and receive antenna polarizations. For each terrain surface and condition considered in this report, the presented data consists of (a) the measured values of the 16 elements of the Mueller matrix, (b) values of certain attributes derivable from the Mueller matrix, such as degree of polarization and depolarization ratio, and (c) a list of the relevant physical parameters of the terrain surface.

The next section provides definitions for the key quantities associated with radar polarimetry, in the context of a general overview of the subject. Sections 3 and 4 provide descriptions of the Michigan and Massachusetts polarimetric scatterometer systems, respectively, including system operation, measurement procedure, and calibration process. These are followed with Section 5, which explains the format used for data presentation in succeeding sections and provides an analysis that shows that the Michigan and Massachusetts systems have a good inter-measurement accuracy. Then, the polarimetric data is presented in Sections 6–8.

Even though this report is intended to be only a data handbook, a collection of reprints of representative articles will be included in the report as appendices. These articles are useful examples of in-depth studies related to the system design, calibration techniques, data analysis, and applicable theoretical models.

2 Polarimetric Radar Terminology

This section presents definitions for the polarimetric radar quantities and terms used in this handbook. For the most part, we have adopted the notation and symbology given in Ulaby and Elachi [1]. A major exception is the use of the overbar symbol, which was used in Ulaby and Elachi [1] to denote that the quantity under consideration is defined according to the backscatter alignment (BSA) convention, so as to differentiate it from the form defined according to the forward scattering alignment (FSA) convention (no overbar is used). In this handbook, all quantities are defined in accordance with the BSA convention. Hence, the overbar is not needed, and its use was deleted for simplicity.

Another simplification adopted in this handbook pertains to the scattering geometry. In Ulaby and Elachi [1], the directions of the propagation and polarization vectors are defined for the general case of bistatic scattering. In this handbook, we consider only the backscattering case and select a convenient coordinate system, thereby simplifying the expressions and rendering them a function of only one variable, the incidence angle θ.

2.1 Wave Polarization

In the (x, y, z) frame of reference shown in Fig. 1, the terrain surface, which lies in the x-y plane, is observed at an incidence angle θ in the direction of the unit vector $\hat{\mathbf{k}}$, which was chosen to lie on the x-z plane for convenience. Such a choice is always valid for azimuthally symmetric terrain surfaces. For periodic surfaces, such as row crops, the incidence direction would have to be specified in terms of both θ and the azimuth angle, ϕ, the latter being defined in the $x - y$ plane relative to a reference direction of the periodic surface. As no millimeter-wave radar observations have been made for such surfaces, they are not considered in this report.

Throughout this handbook, the direction of wave polarization shall be defined in accordance with the backscattering alignment convention, wherein for both the transmit and receive antennas the direction of propagation is defined to point from the antenna towards the surface, as shown in Fig. 1. Thus, for

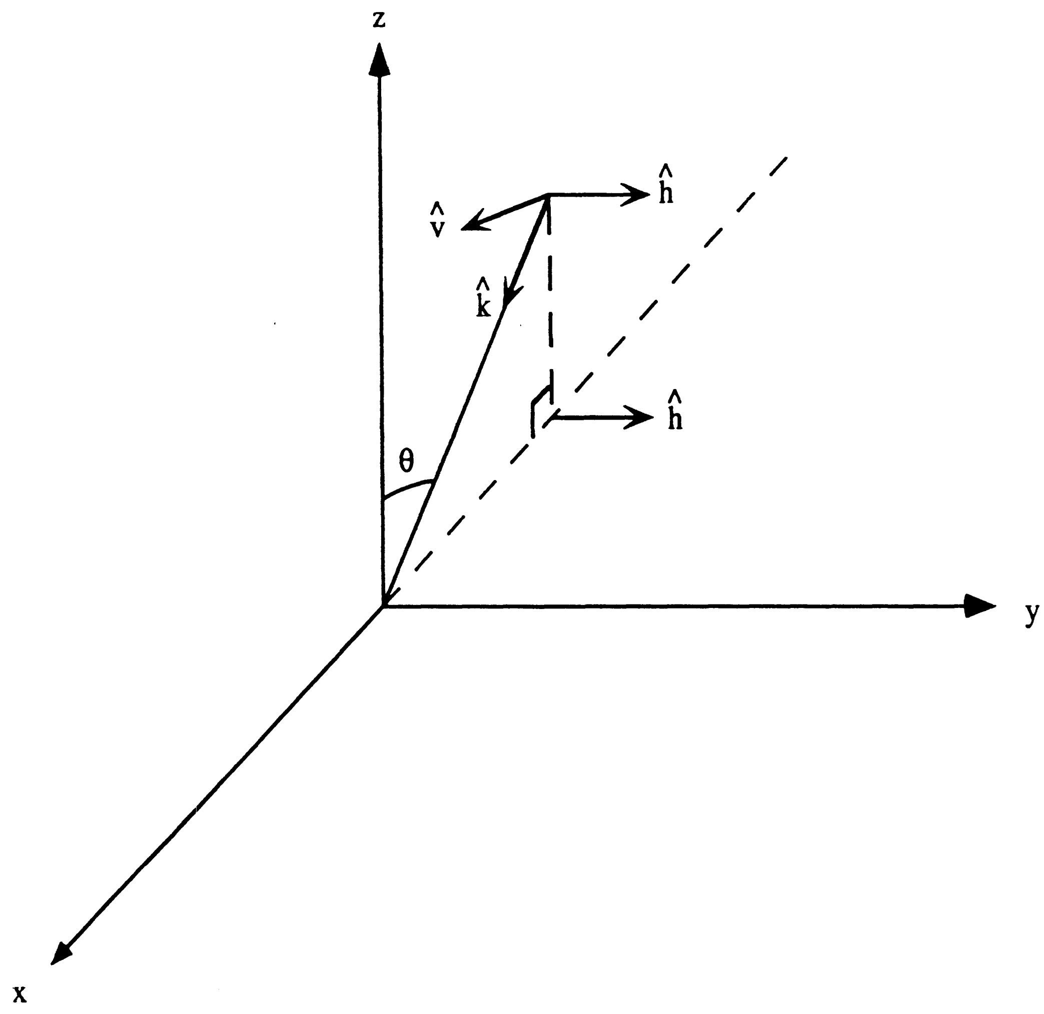


Figure 1. Wave incident upon the x-y plane along direction $\hat{\mathbf{k}}$, with electric field polarization components $\hat{\mathbf{h}} = \hat{\mathbf{y}}$ and $\hat{\mathbf{v}} = \hat{\mathbf{h}} \times \hat{\mathbf{k}}$.

either antenna

$$\hat{\mathbf{k}} = \sin\theta\,\hat{\mathbf{x}} + \cos\theta\,\hat{\mathbf{z}}, \tag{1}$$

and the associated horizontal and vertical polarization unit vectors are given by:

$$\hat{\mathbf{h}} = \frac{\hat{\mathbf{z}} \times \hat{\mathbf{k}}}{|\hat{\mathbf{z}} \times \hat{\mathbf{k}}|} = \hat{\mathbf{y}} \tag{2}$$

$$\hat{\mathbf{v}} = \hat{\mathbf{h}} \times \hat{\mathbf{k}} = \cos\theta\,\hat{\mathbf{x}} - \sin\theta\,\hat{\mathbf{z}} \tag{3}$$

For a plane wave at a distance r from the center of the reference coordinate system, traveling in the direction $\hat{\mathbf{k}}$ as shown in Fig. 1, the electric field vector $\mathbf{E}$ consists, in the general case, of a vertically polarized component, $E_{\mathrm{v}}\hat{\mathbf{v}}$, and a horizontally polarized component, $E_{\mathrm{h}}\hat{\mathbf{h}}$:

$$\mathbf{E} = (E_{\mathrm{v}}\hat{\mathbf{v}} + E_{\mathrm{h}}\hat{\mathbf{h}})e^{ikr} \tag{4}$$

where $k = 2\pi/\lambda$ is the wave number.

The polarization amplitudes E_{v} and E_{h} are in general complex quantities, each consisting of a magnitude and a phase angle:

$$E_{\mathrm{v}} = a_{\mathrm{v}}e^{-i\delta_{\mathrm{v}}} \tag{5}$$

$$E_{\mathrm{h}} = a_{\mathrm{h}}e^{-i\delta_{\mathrm{h}}} \tag{6}$$

The total intensity of the wave is given by:

$$I_0 = a_{\mathrm{v}}^2 + a_{\mathrm{h}}^2, \tag{7}$$

and the polarization state is characterized by the angles δ and α where

$$\delta = \delta_{\mathrm{h}} - \delta_{\mathrm{v}}, \tag{8}$$

$$\tan\alpha = \frac{a_{\mathrm{h}}}{a_{\mathrm{v}}}. \tag{9}$$

In general, in the plane orthogonal to the direction of propagation, the time variation of the tip of the $\mathbf{E}$ vector traces an ellipse as illustrated in Fig. 2. Special cases of the polarization state include:

h-polarized	$a_{\mathrm{v}} = 0$,
v-polarized	$a_{\mathrm{h}} = 0$,
linearly polarized	$\delta = 0$,
right-hand circularly polarized	$a_{\mathrm{v}} = a_{\mathrm{h}}$ and $\delta = -\pi/2$,
left-hand circularly polarized	$a_{\mathrm{v}} = a_{\mathrm{h}}$ and $\delta = \pi/2$.

Alternatively, the polarization state may be described by the rotation angle ψ and the ellipticity angle χ shown in Fig. 2, which are related to α and δ by:

$$\tan 2\psi = (\tan 2\alpha)\cos\delta, \tag{10}$$

$$\sin 2\chi = (\sin 2\alpha)\sin\delta. \tag{11}$$

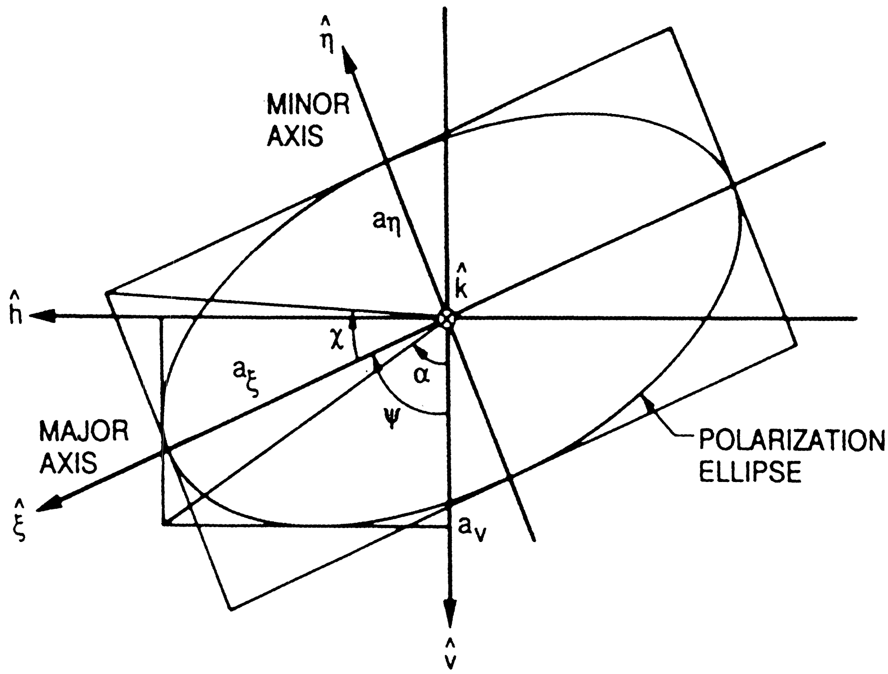


Figure 2: Polarization ellipse in the v–h plane for a wave traveling in the $\hat{k}$ direction.

2.2 Stokes Vector

In radar polarimetry, it is mathematically convenient to characterize wave polarization by an equivalent form known as the Stokes vector which allows the incident and scattered waves to be related in a compact form using matrices. The Stokes vector, which consists of four Stokes parameters of the same physical dimensions, is given by:

$$\mathbf{F} = \begin{bmatrix} I_0 \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_\mathrm{v}|^2 + |E_\mathrm{h}|^2 \\ |E_\mathrm{v}|^2 - |E_\mathrm{h}|^2 \\ 2\,\mathrm{Re}(E_\mathrm{v}E_\mathrm{h}^*) \\ 2\,\mathrm{Im}(E_\mathrm{v}E_\mathrm{h}^*) \end{bmatrix} = \begin{bmatrix} a_\mathrm{v}^2 + a_\mathrm{h}^2 \\ a_\mathrm{v}^2 - a_\mathrm{h}^2 \\ 2a_\mathrm{v}a_\mathrm{h}\cos\delta \\ 2a_\mathrm{v}a_\mathrm{h}\sin\delta \end{bmatrix} = \begin{bmatrix} I_0 \\ I_0\cos 2\psi\cos 2\chi \\ I_0\sin 2\psi\cos 2\chi \\ I_0\sin 2\chi \end{bmatrix} \tag{12}$$

The first Stokes element, I_0, represents the total intensity, which is the sum of the vertically polarized intensity I_v and the horizontally polarized intensity I_h. The second element Q represents the difference between the two intensities, and the ratio of the fourth element to the third element determines the phase difference δ:

$$\frac{V}{U} = \tan\delta. \tag{13}$$

The modified Stokes vector $\mathbf{F}_\mathrm{m}$, a more modern form, is defined in terms of I_v, I_h, U and V as follows:

$$\mathbf{F}_\mathrm{m} = \begin{bmatrix} I_\mathrm{v} \\ I_\mathrm{h} \\ U \\ V \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(1+\cos 2\psi\cos 2\chi) \\ \frac{1}{2}(1-\cos 2\psi\cos 2\chi) \\ \sin 2\psi\cos 2\chi \\ \sin 2\chi \end{bmatrix} I_0 \tag{14}$$

where

$$I_\mathrm{v} = |E_\mathrm{v}|^2 = a_\mathrm{v}^2, \tag{15}$$
$$I_\mathrm{h} = |E_\mathrm{h}|^2 = a_\mathrm{h}^2. \tag{16}$$

2.3 Scattering Matrix

The diagram in Fig. 3 depicts the geometry for the general case of bistatic scattering from a target located at the origin. In the backscattering case where the transmit and receiver antennas are co-located, and upon choosing $\theta_\mathrm{i} = \theta_\mathrm{s} = 0$ for convenience, $\hat{\mathbf{k}}_\mathrm{t} = \hat{\mathbf{k}}_\mathrm{r} = \hat{\mathbf{k}}$ and $\hat{\mathbf{k}}$ is given by (1). This definition, in which both $\hat{\mathbf{k}}_\mathrm{t}$ and $\hat{\mathbf{k}}_\mathrm{r}$ point from the antenna towards the target, is known as the backscatter alignment (BSA) convention. For the backscattering case in the BSA convention, $\hat{\mathbf{h}}_\mathrm{t} = \hat{\mathbf{h}}_\mathrm{r} = \hat{\mathbf{h}}$, $\hat{\mathbf{v}}_\mathrm{t} = \hat{\mathbf{v}}_\mathrm{r} = \hat{\mathbf{v}}$, and $\hat{\mathbf{h}}$ and $\hat{\mathbf{v}}$ are given by (2) and (3), respectively.

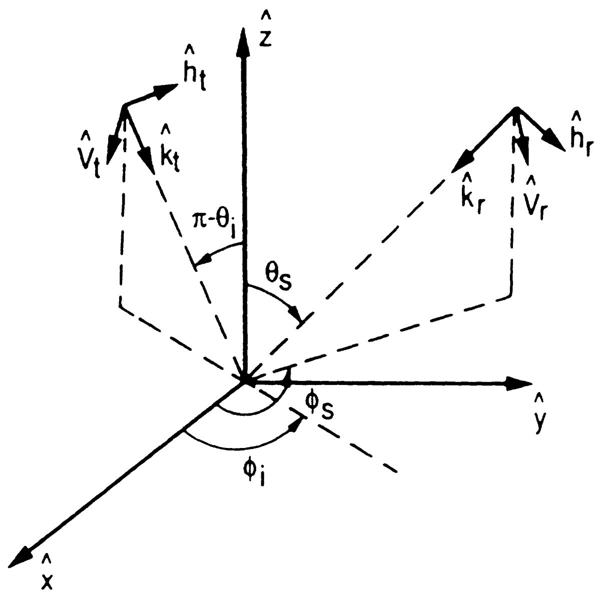


Figure 3: Coordinate systems and scattering geometry for the backscatter alignment (BSA) convention.

The scattering matrix $\mathbf{S}$ of the target under observation relates the electric field $\mathbf{E}^{\mathrm{r}}$ received by the radar to the transmitted electric field $\mathbf{E}^{\mathrm{t}}$ illuminating the target. $\mathbf{E}^{\mathrm{t}}$ is given by:

$$\mathbf{E}^{\mathrm{t}} = E_{\mathrm{v}}^{\mathrm{t}}\hat{\mathbf{v}} + E_{\mathrm{h}}^{\mathrm{t}}\hat{\mathbf{h}} \tag{17}$$

and the electric field received by the radar at a distance r from the target is given by:

$$\mathbf{E}^{\mathrm{r}} = E_{\mathrm{v}}^{\mathrm{r}}\hat{\mathbf{v}} + E_{\mathrm{h}}^{\mathrm{r}}\hat{\mathbf{h}}. \tag{18}$$

Using the vector notation:

$$\mathbf{E} = \begin{pmatrix} E_{\mathrm{v}} \\ E_{\mathrm{h}} \end{pmatrix}, \tag{19}$$

the two fields can be related by the scattering matrix $\mathbf{S}$:

$$\begin{pmatrix} E_{\mathrm{v}}^{\mathrm{r}} \\ E_{\mathrm{h}}^{\mathrm{r}} \end{pmatrix} = \frac{e^{ikr}}{r}\begin{pmatrix} S_{\mathrm{vv}} & S_{\mathrm{vh}} \\ S_{\mathrm{hv}} & S_{\mathrm{hh}} \end{pmatrix}\begin{pmatrix} E_{\mathrm{v}}^{\mathrm{t}} \\ E_{\mathrm{h}}^{\mathrm{t}} \end{pmatrix}, \tag{20}$$

or

$$\mathbf{E}^{\mathrm{r}} = \frac{e^{ikr}}{r}\mathbf{S}\mathbf{E}^{\mathrm{t}}. \tag{21}$$

For the backscattering case in the BSA convention, the cross-polarized components of $\mathbf{S}$ are equal:

$$S_{\mathrm{hv}} = S_{\mathrm{vh}}. \tag{22}$$

2.4 Mueller Matrix

In the relationship given by (21), all the elements of $\mathbf{E}^{\mathrm{r}}$, $\mathbf{E}^{\mathrm{t}}$ and $\mathbf{S}$ are in general complex quantities. Using the modified Stokes vector representation given by (14), $\mathbf{E}^{\mathrm{r}}$ and $\mathbf{E}^{\mathrm{t}}$ can be represented by modified Stokes vectors $\mathbf{F}_{\mathrm{m}}^{\mathrm{r}}$ and $\mathbf{F}_{\mathrm{m}}^{\mathrm{t}}$, whose elements are all real quantities. These two Stokes vectors are related to one another by the modified Mueller matrix $\mathbf{L}_{\mathrm{m}}$, which has real elements that are functions of the elements of the scattering matrix $\mathbf{S}$. Thus,

$$\mathbf{F}_{\mathrm{m}}^{\mathrm{r}} = \frac{1}{r^2}\mathbf{L}_{\mathrm{m}}\mathbf{F}_{\mathrm{m}}^{\mathrm{t}} \tag{23}$$

with

$$\mathbf{L}_{\mathrm{m}} = \begin{bmatrix} |S_{\mathrm{vv}}|^2 & |S_{\mathrm{vh}}|^2 & \mathrm{Re}(S_{\mathrm{vh}}^{*}S_{\mathrm{vv}}) & -\mathrm{Im}(S_{\mathrm{vh}}^{*}S_{\mathrm{vv}}) \\ |S_{\mathrm{hv}}|^2 & |S_{\mathrm{hh}}|^2 & \mathrm{Re}(S_{\mathrm{hh}}^{*}S_{\mathrm{hv}}) & -\mathrm{Im}(S_{\mathrm{hv}}S_{\mathrm{hh}}^{*}) \\ 2\,\mathrm{Re}(S_{\mathrm{vv}}S_{\mathrm{hv}}^{*}) & 2\,\mathrm{Re}(S_{\mathrm{vh}}S_{\mathrm{hh}}^{*}) & \mathrm{Re}(S_{\mathrm{vv}}S_{\mathrm{hh}}^{*} + S_{\mathrm{vh}}S_{\mathrm{hv}}^{*}) & -\mathrm{Im}(S_{\mathrm{vv}}S_{\mathrm{hh}}^{*} - S_{\mathrm{vh}}S_{\mathrm{hv}}^{*}) \\ 2\,\mathrm{Im}(S_{\mathrm{vv}}S_{\mathrm{hv}}^{*}) & 2\,\mathrm{Im}(S_{\mathrm{vh}}S_{\mathrm{hh}}^{*}) & \mathrm{Im}(S_{\mathrm{vv}}S_{\mathrm{hh}}^{*} + S_{\mathrm{vh}}S_{\mathrm{hv}}^{*}) & \mathrm{Re}(S_{\mathrm{vv}}S_{\mathrm{hh}}^{*} - S_{\mathrm{vh}}S_{\mathrm{hv}}^{*}) \end{bmatrix} \tag{24}$$

2.5 Polarization Synthesis

The polarimetric scattering response of a point target may be characterized by either its scattering matrix $\mathbf{S}$ or its modified Mueller matrix $\mathbf{L}_{\mathrm{m}}$. In the case of distributed random targets, such as terrain surfaces, it is necessary to perform an ensemble average over the backscattered power. This can be accomplished by measuring $\mathbf{L}_{\mathrm{m}}$ (either directly or by first measuring $\mathbf{S}$ and then using (23) to obtain $\mathbf{L}_{\mathrm{m}}$) for many statistically independent observations (or spatial locations) of the surface under consideration and then performing an average for each element of $\mathbf{L}_{\mathrm{m}}$.

Additionally, if each averaged element is divided by the illuminated area A_{i}, the process leads to the differential modified Mueller matrix,

$$\mathbf{L}_{\mathrm{m}}^{\circ} = \frac{1}{A_{\mathrm{i}}}\langle \mathbf{L}_{\mathrm{m}} \rangle, \tag{25}$$

which can be used to compute the backscattering coefficient $\sigma^{\circ}(\psi_{\mathrm{r}}, \chi_{\mathrm{r}}; \psi_{\mathrm{t}}, \chi_{\mathrm{t}})$ of the distributed target for any desired combination of transmit and receive polarization states. For a given transmit polarization state specified by the rotation angle ψ_{t} and ellipticity angle χ_{t}, the antenna modified Stokes vector $\mathbf{A}_{\mathrm{m}}^{\mathrm{t}}$ is given by $\mathbf{F}_{\mathrm{m}}^{\mathrm{t}}$, as defined by (14), normalized to the total intensity I_0:

$$\mathbf{A}_{\mathrm{m}}^{\mathrm{t}} = \frac{\mathbf{F}_{\mathrm{m}}^{\mathrm{t}}}{I_0} = \begin{bmatrix} I_{\mathrm{v}}' \\ I_{\mathrm{h}}' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(1 + \cos 2\psi_{\mathrm{t}} \cos 2\chi_{\mathrm{t}}) \\ \frac{1}{2}(1 - \cos 2\psi_{\mathrm{t}} \cos 2\chi_{\mathrm{t}}) \\ \sin 2\psi_{\mathrm{t}} \cos 2\chi_{\mathrm{t}} \\ \sin 2\chi_{\mathrm{t}} \end{bmatrix}. \tag{26}$$

A similar definition applies to $\mathbf{A}_{\mathrm{m}}^{\mathrm{r}}$ for the receive antenna, and in terms of the two vectors, the polarization synthesis equation is given by:

$$\sigma^{\circ}(\psi_{\mathrm{r}}, \chi_{\mathrm{r}}; \psi_{\mathrm{t}}, \chi_{\mathrm{t}}) = 4\pi \mathbf{A}_{\mathrm{m}}^{\mathrm{r}} \cdot \mathbf{T}\mathbf{L}_{\mathrm{m}}^{\circ}\mathbf{A}_{\mathrm{m}}^{\mathrm{t}} \tag{27}$$

where $\mathbf{T}$ is a transformation matrix given by:

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & -1/2 \end{bmatrix}. \tag{28}$$

For the principal linear polarization combinations, (27) reduces to simple forms:

$$\sigma_{\mathrm{vv}}^{\circ} = 4\pi L_{11} \tag{29}$$

$$\sigma_{\mathrm{hh}}^{\circ} = 4\pi L_{22} \tag{30}$$

$$\sigma_{\mathrm{vh}}^{\circ} = \sigma_{\mathrm{hv}}^{\circ} = 4\pi L_{12} = 4\pi L_{21} \tag{31}$$

where L_{ij} is the element of $\mathbf{L}_{\mathrm{m}}^{\circ}$ in row i and column j.

2.6 Polarization Response

For a given $\mathbf{L}_{\mathrm{m}}^{\circ}$ whose elements had been measured experimentally or calculated using a theoretical model, it is possible to apply (27) to compute σ° for a large number of combinations of the four angles ψ_{r}, χ_{r}, ψ_{t} and χ_{t} within the applicable limits of $-\pi/2$ to $\pi/2$ for ψ_{r} and ψ_{t} and $-\pi/4$ to $\pi/4$ for χ_{r} and χ_{t}. A convenient and physically meaningful set of planes in the transmit/ receive polarization space are the co-polarized and cross-polarized responses. In the case of the co-polarized response, the transmit and receive antennas have the same polarization, whereas with the cross-polarized response the receive antenna is polarized orthogonal to the transmit antenna. Mathematically, these conditions are:

$$\begin{array}{ll} \text{Co-Polarized Response} & \psi_{\mathrm{r}} = \psi_{\mathrm{t}}, \;\; \chi_{\mathrm{r}} = \chi_{\mathrm{t}} \\ \text{Cross-Polarized Response} & \psi_{\mathrm{r}} = \psi_{\mathrm{t}} + \pi/2, \;\; \chi_{\mathrm{r}} = -\chi_{\mathrm{t}} \end{array}$$

Figure 4(a) shows the polarization responses for a large conducting sphere with a scattering matrix given by:

$$\mathbf{S} = \frac{a}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{32}$$

where a is the radius of the sphere. Indicated on the plots are the $(\psi_{\mathrm{t}}, \chi_{\mathrm{t}})$ locations corresponding to the principal linear and circular polarization states (with L denoting left-hand circular and R denoting right-hand circular). The vertical axis represents the radar cross section normalized with respect to its maximum value over the indicated ranges of χ_{t} and ψ_{t}. A similar set of polarization responses are displayed in Fig. 4(b) for a soil surface; in this case, the vertical axis represents the backscattering coefficient σ°, again normalized to the maximum value.

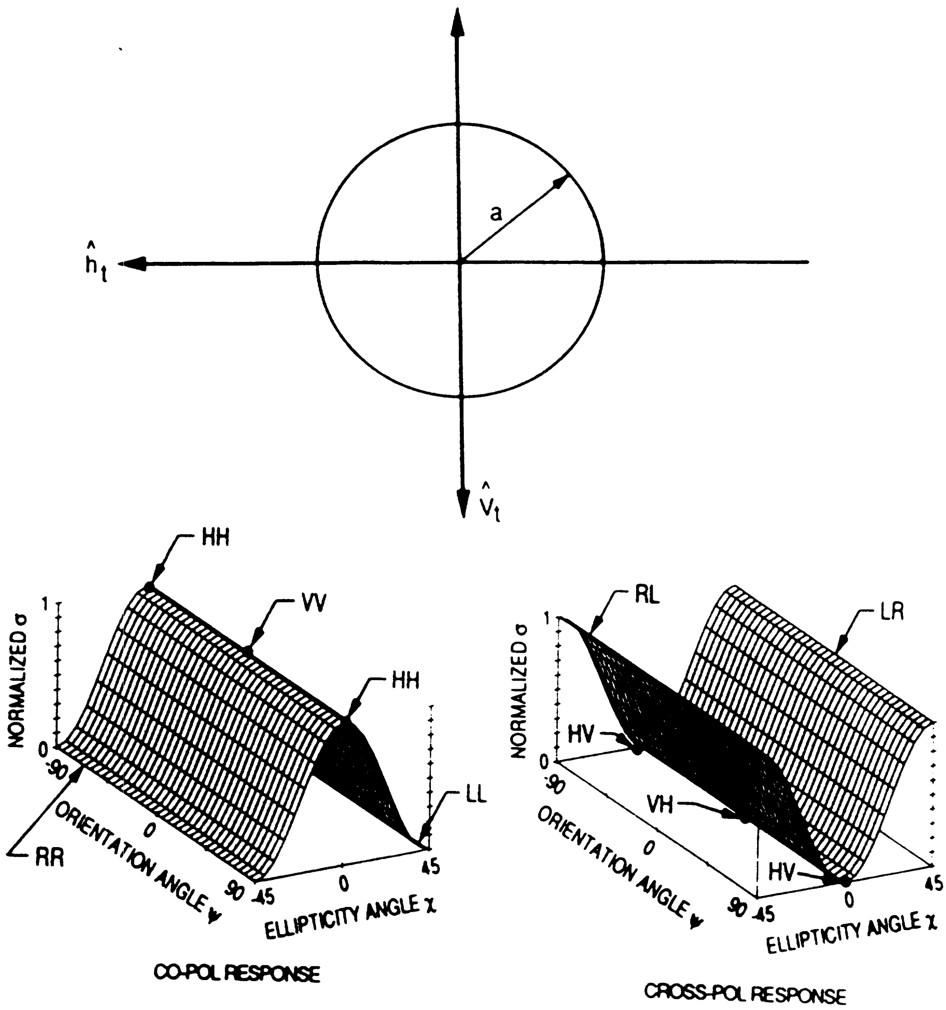
2.7 Degree of Polarization

According to (23), the receive modified Stokes vector $\mathbf{F}_{\mathrm{m}}^{\mathrm{r}}$ is related to the transmit modified Stokes vector $\mathbf{F}_{\mathrm{m}}^{\mathrm{t}}$ by:

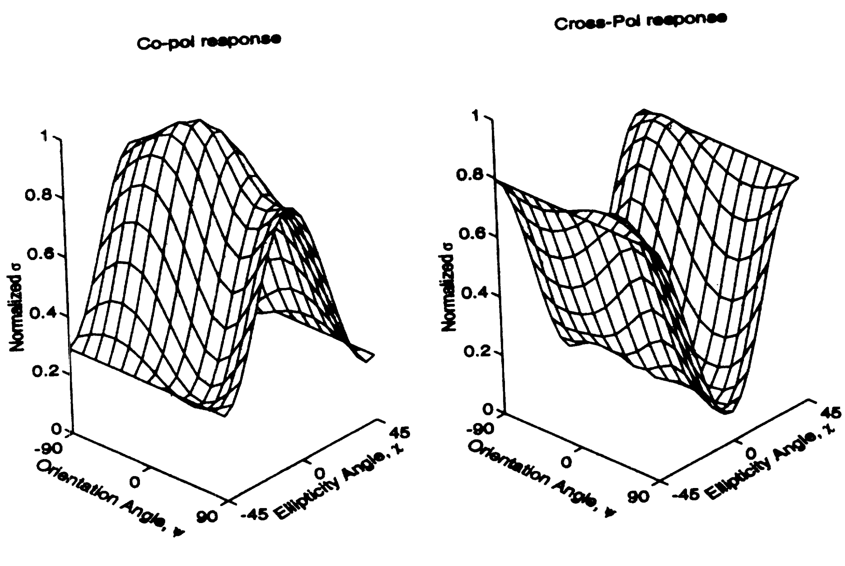
$$\mathbf{F}_{\mathrm{m}}^{\mathrm{r}} = \begin{bmatrix} I_{\mathrm{v}}^{\mathrm{r}} \\ I_{\mathrm{h}}^{\mathrm{r}} \\ U^{\mathrm{r}} \\ V^{\mathrm{r}} \end{bmatrix} = \frac{1}{r^2}\mathbf{L}_{\mathrm{m}}\mathbf{F}_{\mathrm{m}}^{\mathrm{t}} \tag{33}$$

For a specified transmit polarization, $\mathbf{F}_{\mathrm{m}}^{\mathrm{t}}$, and a given $\mathbf{L}_{\mathrm{m}}$, (33) leads to specific values for the elements of $\mathbf{F}_{\mathrm{m}}^{\mathrm{r}}$. The degree of polarization m is defined as:

$$m = \frac{[(I_{\mathrm{v}}^{\mathrm{r}} - I_{\mathrm{h}}^{\mathrm{r}})^2 + (U^{\mathrm{r}})^2 + (V^{\mathrm{r}})^2]^{1/2}}{I_{\mathrm{v}}^{\mathrm{r}} + I_{\mathrm{h}}^{\mathrm{r}}}. \tag{34}$$



(a) Sphere



(b) Soil Surface

Figure 4: Polarization responses of (a) a large conducting sphere, and (b) for a soil surface at 94 GHz.

For a completely polarized scattered wave, $m = 1$; for a completely unpolarized scattered wave, $m = 0$; and for a partially polarized wave, $0 < m < 1$.

For a distributed target with $\mathbf{L}_\mathrm{m}^\circ$ defined as:

$$\mathbf{L}_\mathrm{m}^\circ = \begin{bmatrix} L_{11} & L_{12} & L_{13} & L_{14} \\ L_{21} & L_{22} & L_{23} & L_{24} \\ L_{31} & L_{32} & L_{33} & L_{34} \\ L_{41} & L_{42} & L_{43} & L_{44} \end{bmatrix}, \tag{35}$$

experimental observations have shown that the four elements in the top right quadrant (L_{13}, L_{14}, L_{23}, and L_{24}) and the elements in the bottom left quadrant (L_{31}, L_{32}, L_{41}, and L_{42}) are much smaller in magnitude than those in the other two quadrants which is consistent with theoretical expectations for azimuthally symmetric media. Upon setting them equal to zero, application of (33) and (34) leads to the following expressions for the following special cases.

2.7.1 Vertically Polarized Transmit Polarization

$$\mathbf{F}_\mathrm{v}^\mathrm{t} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{36}$$

$$m_\mathrm{v} = \frac{L_{11} - L_{21}}{L_{11} + L_{21}} = \frac{\sigma_\mathrm{vv}^\circ - \sigma_\mathrm{vh}^\circ}{\sigma_\mathrm{vv}^\circ + \sigma_\mathrm{vh}^\circ} \tag{37}$$

2.7.2 Horizontally Polarized Transmit Polarization

$$\mathbf{F}_\mathrm{h}^\mathrm{t} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \tag{38}$$

$$m_\mathrm{h} = \frac{L_{22} - L_{12}}{L_{22} + L_{12}} = \frac{\sigma_\mathrm{hh}^\circ - \sigma_\mathrm{hv}^\circ}{\sigma_\mathrm{hh}^\circ + \sigma_\mathrm{hv}^\circ} \tag{39}$$

2.7.3 Other Transmit Polarizations

By introducing the intermediate coefficients a_1 through a_6 defined by:

$$a_1 = (L_{11} - L_{21})^2, \tag{40}$$

$$a_2 = (L_{22} - L_{12})^2, \tag{41}$$

$$a_3 = L_{33}^2 + L_{43}^2, \tag{42}$$

$$
\begin{aligned}
a_4 &= L_{34}^2 + L_{44}^2, && (43)\\
a_5 &= 2(L_{11} - L_{21})(L_{21} - L_{22}), && (44)\\
a_6 &= (L_{11} + L_{22} + L_{12} + L_{21})^2, && (45)
\end{aligned}
$$

we can provide simple expressions for the following four configurations of the transmit polarization state.

<u>**45° and 135° Linear Polarization**</u>

$$
\mathbf{F}_{45}^{\mathrm{t}} = \begin{bmatrix} 1/2 \\ 1/2 \\ 1 \\ 0 \end{bmatrix} \tag{46}
$$

$$
\mathbf{F}_{135}^{\mathrm{t}} = \begin{bmatrix} 1/2 \\ 1/2 \\ -1 \\ 0 \end{bmatrix} \tag{47}
$$

$$
m_{45} = m_{135} = \left[\frac{a_1 + a_2 + a_5 + 4a_3}{a_6}\right]^{1/2} \tag{48}
$$

<u>**Circular Polarization**</u>

$$
\mathbf{F}_{\mathrm{RHC}}^{\mathrm{t}} = \begin{bmatrix} 1/2 \\ 1/2 \\ 0 \\ -1 \end{bmatrix} \tag{49}
$$

$$
\mathbf{F}_{\mathrm{LHC}}^{\mathrm{t}} = \begin{bmatrix} 1/2 \\ 1/2 \\ 0 \\ 1 \end{bmatrix} \tag{50}
$$

$$
m_{\mathrm{lhc}} = m_{\mathrm{rhc}} = \left[\frac{a_1 + a_2 + a_5 + 4a_4}{a_6}\right]^{1/2} \tag{51}
$$

2.8 Depolarization Ratio

The depolarization ratio, which is the ratio of depolarized power to polarized power, is defined as:

$$
\chi_d = \frac{L_{12} + L_{21}}{L_{11} + L_{22}} = \frac{2\sigma_{\mathrm{hv}}^{\circ}}{\sigma_{\mathrm{vv}}^{\circ} + \sigma_{\mathrm{hh}}^{\circ}}, \tag{52}
$$

where we used the fact that $L_{12} = L_{21}$.

For azimuthally symmetric media (defined as media in which the scattering particles are randomly oriented in the plane orthogonal to the direction of propagation) containing particles with isotropic scattering properties in the polarization plane, the differential modified Mueller matrix $\mathbf{L}_{\mathrm{m}}^{\circ}$ assumes the simple form:

$$\mathbf{L}_{\mathrm{m}}^{\circ} = L_{11} \begin{bmatrix} 1 & \chi_{\mathrm{d}} & 0 & 0 \\ \chi_{\mathrm{d}} & 1 & 0 & 0 \\ 0 & 0 & 1-\chi_{\mathrm{d}} & 0 \\ 0 & 0 & 0 & 1-3\chi_{\mathrm{d}} \end{bmatrix}, \tag{53}$$

thereby reducing $\mathbf{L}_{\mathrm{m}}^{\circ}$ to two parameters, L_{11} and χ_{d}.

2.9 Co-Polarized Phase Parameters

The scattering elements of the scattering matrix $\mathbf{S}$ are, in general, complex quantities. Thus,

$$S_{\mathrm{vv}} = |S_{\mathrm{vv}}|e^{i\phi_{\mathrm{vv}}} \tag{54}$$

$$S_{\mathrm{hh}} = |S_{\mathrm{hh}}|e^{i\phi_{\mathrm{hh}}} \tag{55}$$

$$S_{\mathrm{hv}} = |S_{\mathrm{hv}}|e^{i\phi_{\mathrm{hv}}} \tag{56}$$

The co-polarized phase difference is defined as:

$$\phi = \phi_{\mathrm{hh}} - \phi_{\mathrm{vv}}. \tag{57}$$

For a distributed random target, ϕ is characterized by a probability density function $p(\phi)$, for which an exact expression has been derived [2]:

$$p(\phi) = \frac{1-\alpha^2}{2\pi(1-D^2)} \left\{ 1 + \frac{D}{\sqrt{1-D^2}} \left[\frac{\pi}{2} + \tan^{-1} \frac{D}{\sqrt{1-D^2}} \right] \right\} \tag{58}$$

where

$$D = \alpha \cos(\phi - \zeta) \tag{59}$$

$$\alpha = \frac{1}{2} \left[\frac{(L_{33}+L_{44})^2 + (L_{34}-L_{43})^2}{L_{11}L_{22}} \right]^{1/2} \tag{60}$$

$$\zeta = \tan^{-1} \left(\frac{L_{34}-L_{43}}{L_{33}+L_{44}} \right) \tag{61}$$

Thus, $p(\phi)$ is specified in terms of two intermediate parameters, α and ζ, both of which are given in terms of the elements of $\mathbf{L}_{\mathrm{m}}^{\circ}$. The parameter α is called the degree of correlation and ζ is the value of ϕ at which $p(\phi)$ is maximum. Fig. 5 shows plots for $p(\phi)$ for various values of α at a fixed value of $\zeta = 45°$.

Although a similar probability density function can be defined for the cross-polarized phase difference $\phi_x = \phi_{\mathrm{hv}} - \phi_{\mathrm{vv}}$, $p(\phi_x)$ has been found to be approximately uniformly distributed over $[0, 2\pi]$ for terrain surfaces, and therefore contains no surface-specific information. This is consistent with theoretical expectations for azimuthally symmetric media.

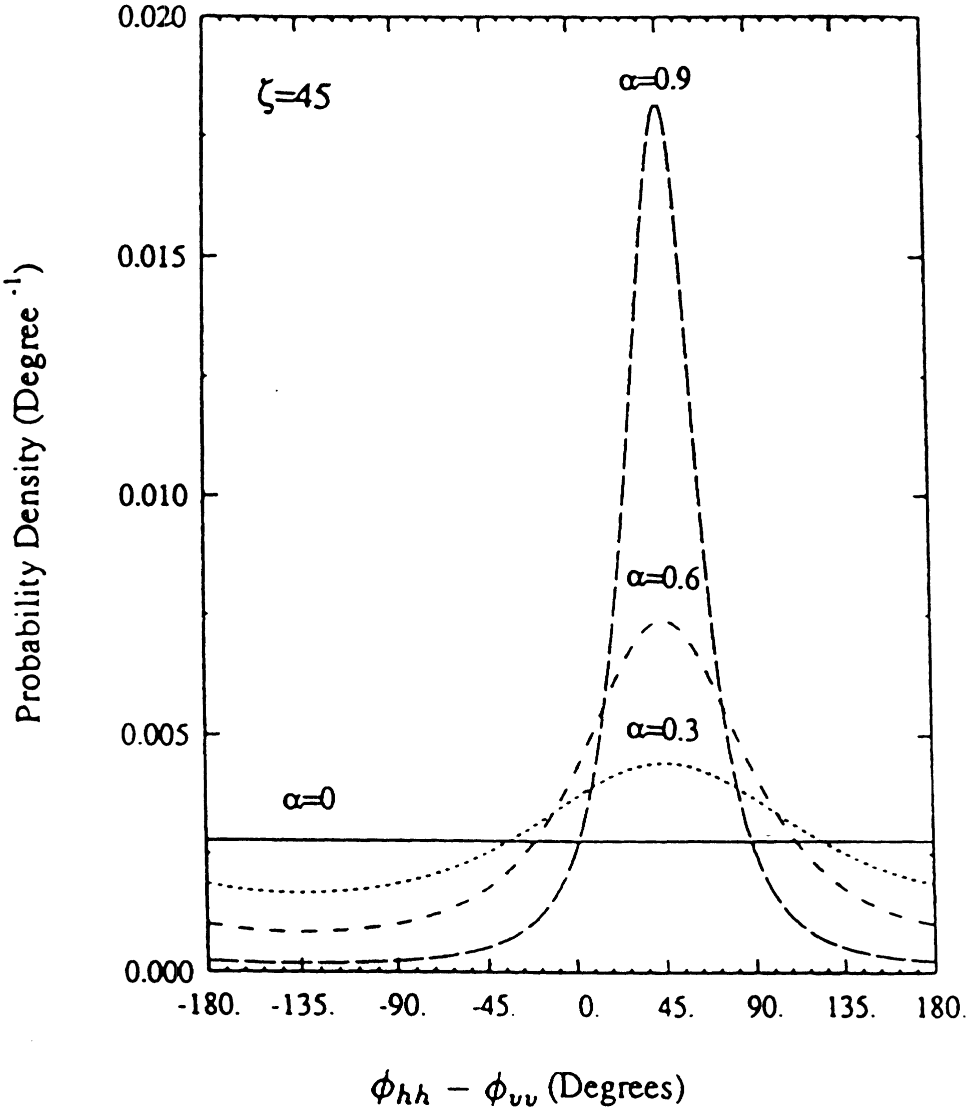


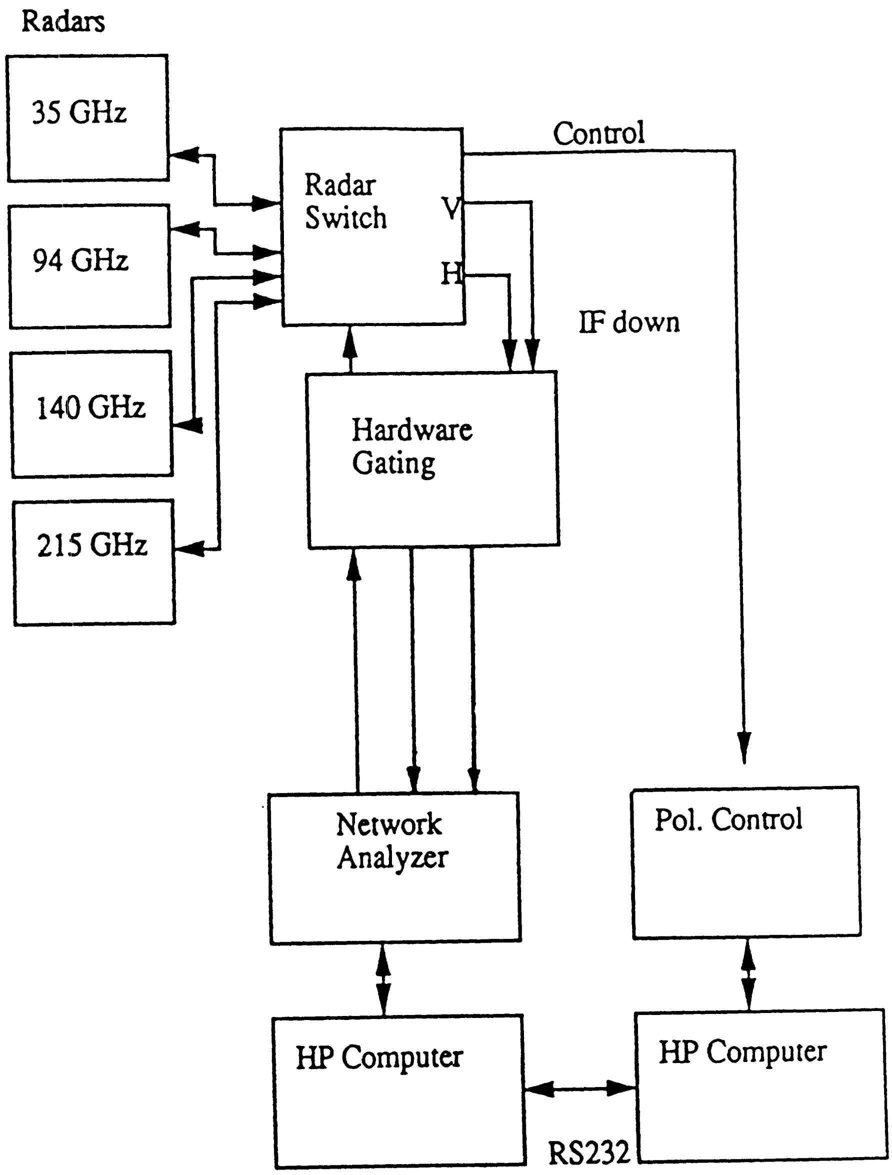
Figure 5: The probability density function $p(\phi)$ for a fixed value of ζ and four values of the degree of correlation α.

3 U-M Measurement System

This section provides a summary of the capabilities and characteristics of the University of Michigan's millimeter wave (MMW) scatterometer systems. Currently, three of the four scatterometers, with operating frequencies of 35, 94, and 140 GHz, are fully polarimetric, and the fourth one which operates at 215 GHz is only capable of measuring the magnitudes of the scattering matrix elements. Fig. 6 shows a simplified block diagram of the University of Michigan's MMW polarimetric radar system. The core of this system is the vector network analyzer where most of the signal processing takes place. An HP 8753C network analyzer is used, which includes a microwave synthesizer that covers the range from 0.3–3 GHz. The network analyzer serves as the base transmit and receive unit, with frequency up- and down-conversion used to provide the desired center frequencies.

The antennas and other RF equipment are mounted on a platform atop an articulating boom, and the control and processing equipment are housed in a control room on the truck bed. The scatterometers operate in high-PRF chirped pulse mode to permit rejection of short range returns using the hardware gating unit. The PRF is chosen to be larger than the network analyzer receiver's bandwidth and therefore the network analyzer operation is not affected by the pulsing of the chirped signal [3]. An HP 3488 Switch/Control System with HP-Basic Language Processor was purchased and integrated with the radar system to provide control and feedback for many parts of the four-frequency radar system, including polarization control and antenna pointing. The HP-Basic Language Processor provides control for numerous HP-IB instruments in an IBM compatible computer. The truck is a Ford F-800, and the boom can lift the antenna platform to a height of 56 feet.

Each of the radar units in the MMW Scatterometer System can be operated in a number of measurement modes as indicated in Table 1. In this table the term "power only" means that the radar unit is capable of measuring the magnitude square of the scattering matrix elements. The term "coherent" indicates that the radar unit can measure the scattering matrix using either single- or dual-antenna mode. Coherent-on-receive mode is a radar polarimetric measurement configuration where instead of measuring the scattering matrix, the modified Mueller matrix of the target is measured directly. This mode of operation is necessary in measurement of targets under field conditions when the fluctuation of the radar platform or the target does not permit phase-coherent measurement of all the scattering matrix elements. The coherent-on-receive measurement technique is explained in Section 3.2. In bistatic mode, the radar unit operates in a dual-antenna mode and depending on the capability of the radar unit, the measurement can be performed in coherent, coherent-on-receive, or both modes.



MMW POLARIMETRIC RADAR SYSTEM

Figure 6: The probability density function $p(\phi)$ for a fixed value of ζ and four values of the degree of correlation α.

GHz	Power Only	Coherent		Coherent-on-Receive	Bistatic
		1-Antenna	2-Antenna		
35	√	√	√	√	√
94	√	√	√	√	√
140	√			√	√
215	√				

Table 1: MMW Scatterometer System modes of operation for each frequency.

3.1 Description of the Radar Units

This section describes the performance and characteristics of each radar unit. As mentioned earlier, all the radar units use the network analyzer as the base transmitter/receiver and an RF unit simply acts as an up-/down-converter. All the RF units can operate with a bandwidth of at least 2 GHz, which corresponds to a range resolution of about 7.5 cm. The transmit polarization of the radar units in coherent-on-receive mode is facilitated by two cascaded polarization switches. Each polarization switch is basically a waveguide polarizer which includes a rotatable dielectric card in a circular waveguide. In this type of polarizer, the component of the electric field parallel to the dielectric card propagates slower than the perpendicular component, thereby a phase shift between the two components is created. The magnitude of each component of the electric field can be adjusted by rotating the dielectric card with respect to the direction of the incoming wave. If only one polarization switch is used, only certain polarization states can be generated. In order to generate any desired polarization, two polarization switches must be cascaded. The dielectric cards are rotated to a desired orientation to within a fraction of a tenth of a degree using a DC motor in conjunction with an optical encoder.

The design of the 35 and 94 GHz radar units are very similar and their simplified block diagrams are shown in Figs. 7 and 8 comprised of three major modules: (1) transmitter module, (2) transceiver module, and (3) bistatic transmit antenna module. The transmitter module includes a stabilized local oscillator, an up-converter mixer, and a power amplifier. To maintain phase coherence between the up- and down-converter in bistatic mode, an X-band oscillator is used as the fundamental source whose frequency is an integral fraction of the desired frequency for the local oscillator. The X-band source feeds the multiplier, which in turn is connected to an injection-locked Gunn oscillator and therefore the Gunn is phase-locked to the X-band source. The chirped output of the network analyzer (IF up) is up-converted and then amplified to form the desired transmitting signal. The RF output power of the 35 and 94 GHz units are, respectively, 25 dBm and 10 dBm. For the bistatic

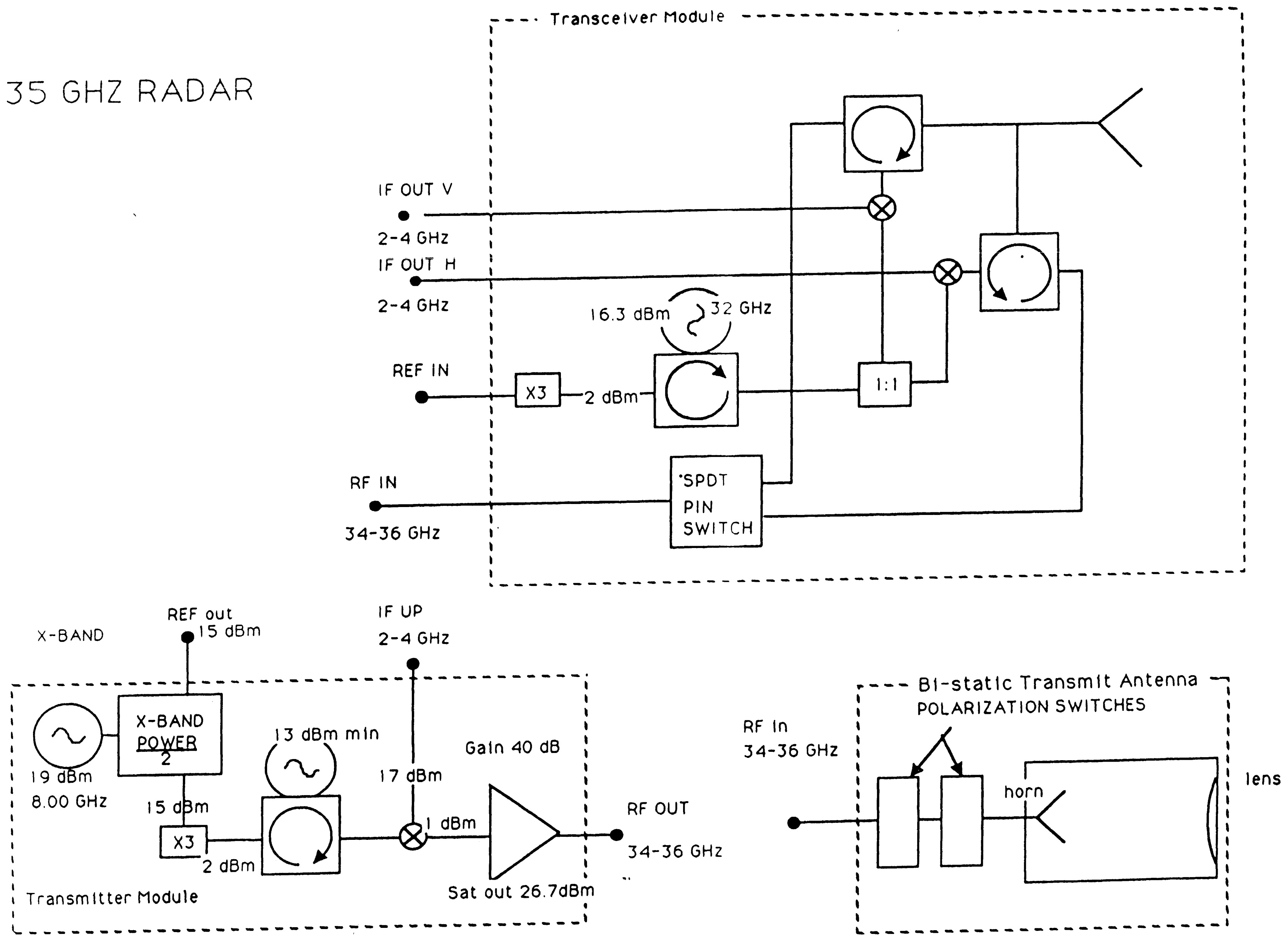


Figure 7: Block diagram of University of Michigan MMW polarimetric scatterometer system.

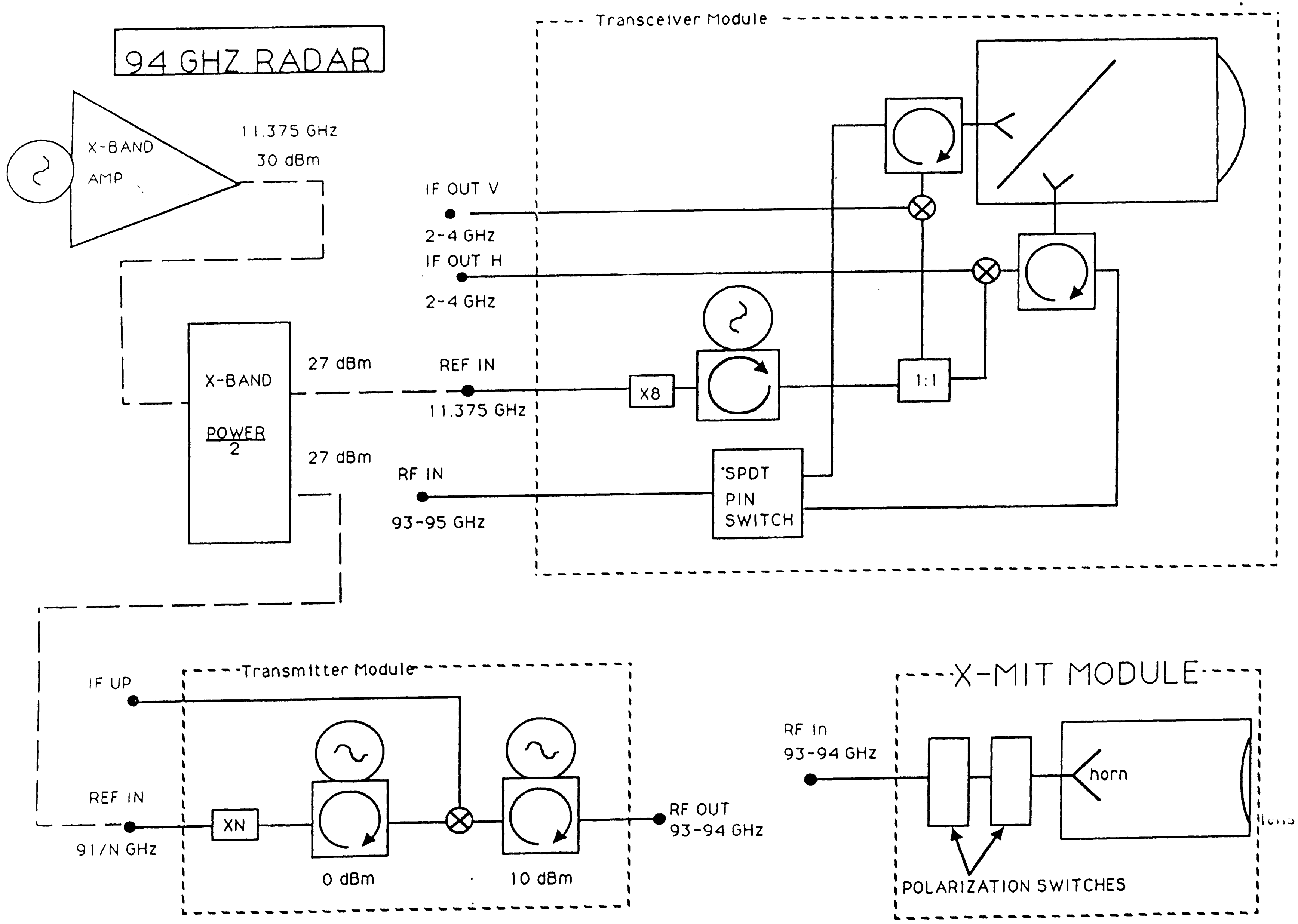


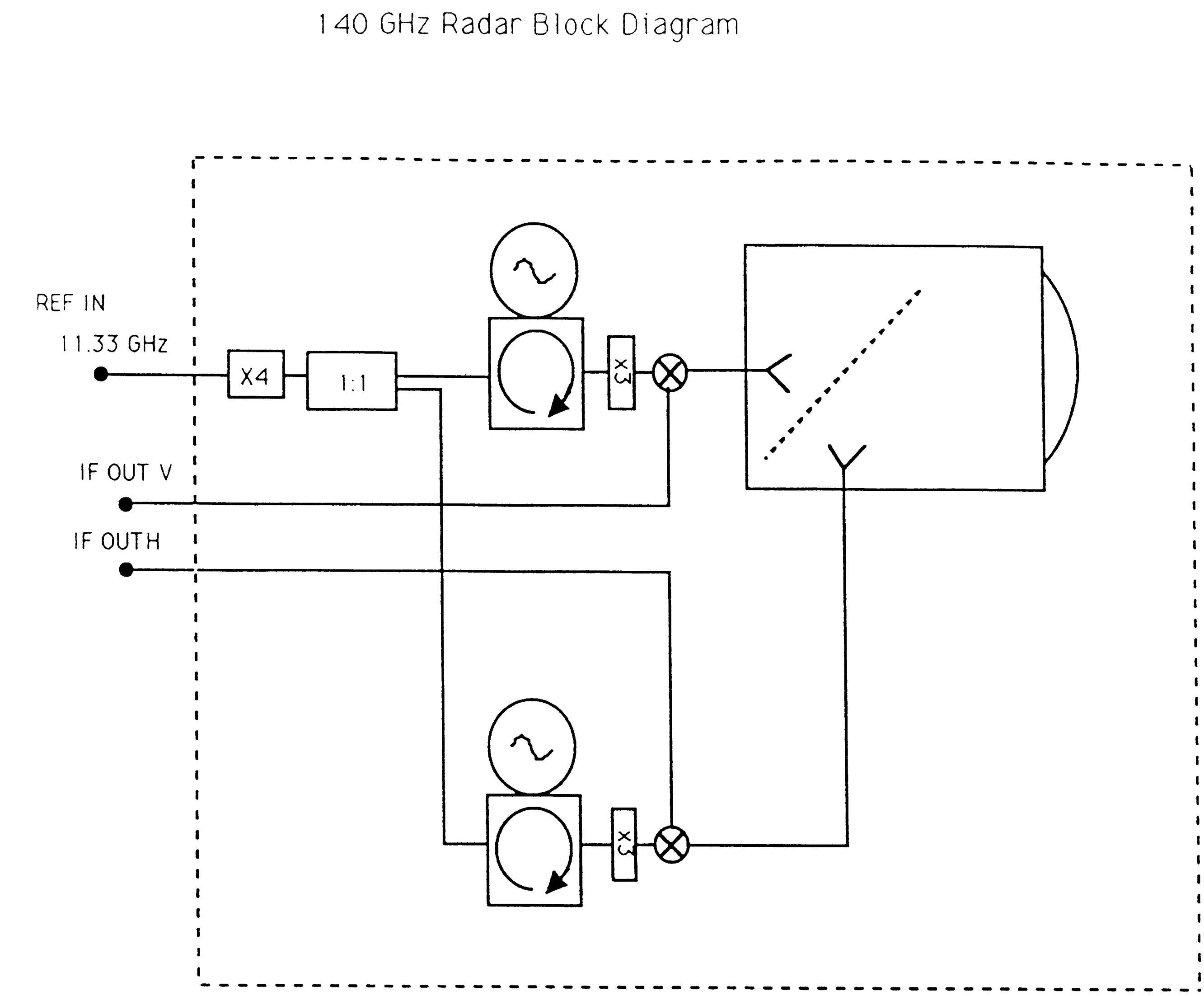
Figure 8: Schematic diagram of the 35 GHz radar unit.

and coherent-on-receive modes, the RF output of the transmit module is connected to the bistatic transmit antenna module and for the monostatic mode the output is connected to the transceiver module.

The transceiver module is comprised of a dual-polarized antenna, a pair of circulators for the monostatic mode, a multiplier and injection locking Gunn oscillator, and a PIN diode switch. For the 35 GHz unit the antenna is a lens-corrected corrugated horn connected to an orthogonal mode transducer. The antenna of the 94-GHz transceiver uses two separated corrugated horns and a polarization wire grid between the horns and the lens, as shown in Fig. 8. In the monostatic mode the RF output of the transmitter module is connected to the RF input of the transceiver module via a waveguide. Using the PIN diode switch, the desired transmit polarization (V or H) is selected. The receiver local oscillator, similar to the transmitter LO, is phase locked by the reference X-band source. Using two balanced mixers, the received signal in both V and H channels are down-converted to the network analyzer frequency. In the bistatic mode, a long coaxial cable is used to connect the reference signal to the LO of the transceiver and the RF output of the transmitter module is connected to the bistatic transmit antenna module. For coherent operation, the polarization switches generate only V- and H-polarized waves while for the coherent-on-receive mode, six different polarizations (V, H, 45, 135, RHC, LHC) are generated. The minimum backscattering coefficient that can be measured (noise equivalent backscattering coefficient) with the 35 and 94 GHz units at a range of 10 m is about -65 dB.

The 140 GHz radar unit is slightly different from the 35 and 94 GHz in that it cannot operate in single antenna mode. Again the transmit and receive modules are phase-locked using a reference stable X-band source (Fig. 9). The injection locking oscillators, which operate at around 45.3 GHz, are connected to triplers in order to generate the desired 136 GHz signal. The output power of this unit is about 0 dBm and its noise equivalent backscattering coefficient at a range of 10 m is approximately -55 dB. The receiver and transmitter antennas are similar to the 94-GHz radar and their radiation characteristics are given in Table 2.

The 215 GHz unit can only measure the magnitude of the scattering matrix elements and its block diagram is shown in Fig. 10. In this unit, a single local oscillator at half the desired frequency (106 GHz) is used for up- and down-conversion. The up-converter also acts as a doubler and has an overall conversion loss of about 10 dB. The receiving branch of the radar uses a fundamental mixer. Generation of the transmit and receive polarizations is facilitated by rotatable corrugated dielectric plates. The transmitted power for this system is about -10 dBm and the noise equivalent backscattering coefficient of the unit at a range of 10 m is approximately -25 dB.



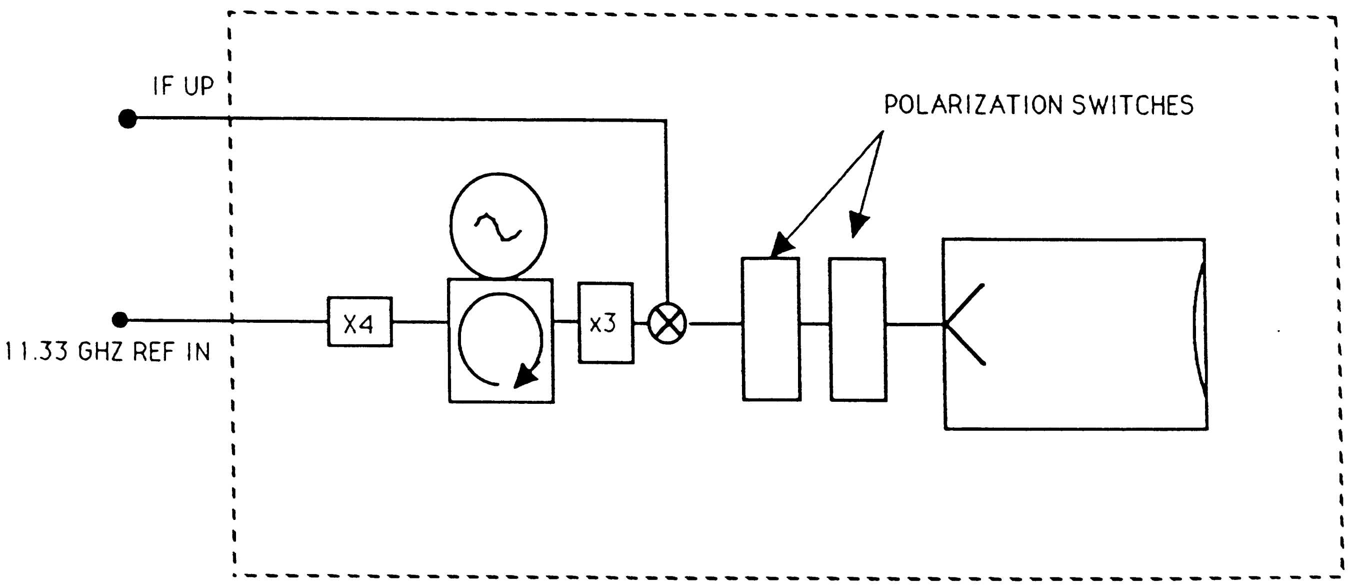


Figure 9: Schematic diagram of the 94 GHz radar unit.

215 GHz Radar (Power Only)

Transmitter

IF bandwidth	2 GHz
Power	-10 dB
Antenna	beamwidth = 3°
	Sidelobe level < 25
Polarization	V and H (mechanically)
	Polarization isolation > 25

Receiver

Single channel	V and H (mechanically)
Mixer	Fundamental mixing
Antenna	Beamwidth = 1.5°
	Polarization isolation > 25

Polarimetric data

$\sigma_{vv}, \sigma_{hh}, \sigma_{hv}, \sigma_{vh}$

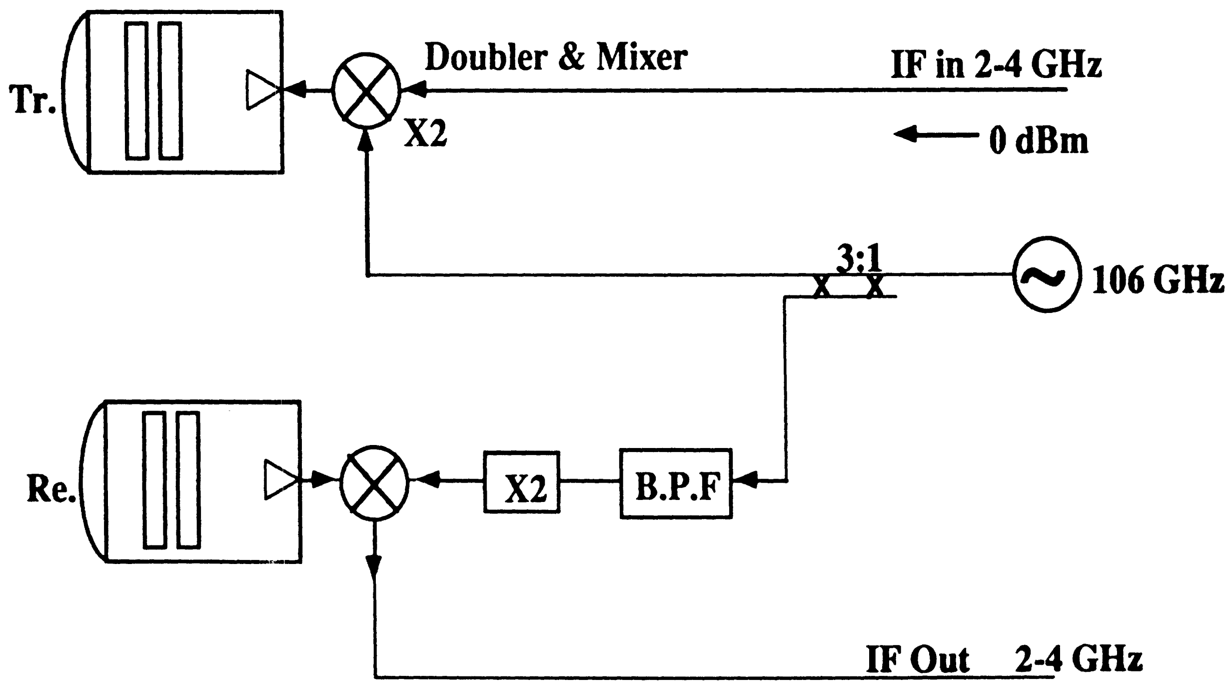


Figure 10: Schematic diagram of the 140 GHz radar unit.

GHz	35	94	140	215
RECEIVER				
Beamwidth	4.2°	1.4°	1.0°	1.5°
Sidelobe Level	< -20 dB	< -25 dB	< -25 dB	< -25 dB
Pol. Isolation	> 25 dB	> 25 dB	> 25 dB	> 25 dB
TRANSMITTER				
Beamwidth	4.2°	2.8°	2.0°	3.0°
Sidelobe Level	< -20 dB	< -25 dB	< -25 dB	< -25 dB
Pol. Isolation	> 25 dB	> 25 dB	> 25 dB	> 25 dB

Table 2: Radiation characteristics of the transmit and receive antennas used in the MMW scatterometer system.

3.2 Coherent-on-Receive Measurement Technique

The main advantage offered by the coherent-on-receive radars in polarimetric measurements is when the target is fluctuating or when the radar platform is not stable. In this section we briefly introduce the basic concepts of this approach.

By defining a set of orthogonal directions $(\hat{v}, \hat{h})$ in a plane perpendicular to the direction of propagation, the components of the scattered field $\mathbf{E}^{\mathrm{s}}$ from a given target can be related to the components of the incident wave $\mathbf{E}^{\mathrm{i}}$ through the scattering matrix of the target, i.e.,

$$\mathbf{E}^{\mathrm{s}} = \frac{e^{ik_0 r}}{r} \begin{bmatrix} S_{\mathrm{vv}} & S_{\mathrm{vh}} \\ S_{\mathrm{hv}} & S_{\mathrm{hh}} \end{bmatrix} \mathbf{E}^{\mathrm{i}} \tag{62}$$

where k_0 is the propagation constant and r is the range from the target to the receive antenna. In general, the polarization state of the transmitted wave can be any arbitrary elliptical polarization. An elliptically polarized wave can be characterized by two angles known as the rotation angle (ψ) and ellipticity angle (χ) as mentioned in Chapter 2. It was also shown that the modified Stokes vector $\mathbf{F}_{\mathrm{m}}(\psi, \chi)$ provides an alternate but equivalent representation of wave polarization and that the scattered (received) modified Stokes vector $\mathbf{F}^{\mathrm{r}}_{\mathrm{m}}$ can be related to the incident (transmitted) Stokes vector via the modified Mueller matrix given by (24).

When dealing with natural targets, such as soil surfaces and vegetation canopies, the quantity of interest is $\langle \mathbf{L}_{\mathrm{m}} \rangle$, the ensemble average of $\mathbf{L}_{\mathrm{m}}$. Given $\langle \mathbf{L}_{\mathrm{m}} \rangle$, the technique of polarization synthesis can be used to compute the polarization response of the target under consideration. With a coherent polarimetric radar, the process starts by measuring the scattering matrix for many statistically independent samples of the target. Each scattering matrix is converted to its corresponding modified Mueller matrix $\mathbf{L}_{\mathrm{m}}$, and then all the

$\mathbf{L}_{\mathrm{m}}$ matrices are averaged together. With incoherent and coherent-on-receive polarimetric radars, $\langle \mathbf{L}_{\mathrm{m}} \rangle$ is measured directly. To examine how the coherent-on-receive radar functions, consider the 35 GHz system shown in Fig. 7. The output of the transmitter module is a rectangular waveguide which is connected to a circular waveguide through a transition, followed by the two waveguide polarizers. The position of the dielectric card with respect to the polarization of the incoming wave determines the polarization of the outgoing wave from the waveguide polarizer. The dielectric cards are designed such that the phase difference between two outgoing waves corresponding to two incoming waves whose electric fields are parallel and perpendicular to the card is 90°. This feature allows the generation of any polarization configuration of interest, including vertical (V), 45° linear (45), left-hand circular (LHC), and right-hand circular (RHC), which together are used to obtain the elements of the modified Mueller matrix. The receiver part of the radar is capable of receiving the vertical and horizontal polarization components of the scattered wave simultaneously. After down-converting the frequency of the received signals, the two IF signals are measured in both magnitude and phase.

To measure the modified Mueller matrix with 16 unknowns, we are required to perform at least four measurements. The entries of the modified Mueller matrix can easily be obtained by transmitting four different polarizations; namely, vertical, 45° linear, right-hand circular, and left-hand circular, whose Stokes vectors are given by

$$\mathbf{F}_{\mathrm{V}}^{\mathrm{t}} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{F}_{45}^{\mathrm{t}} = \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \\ 1 \\ 0 \end{bmatrix}, \quad \mathbf{F}_{\mathrm{LHC}}^{\mathrm{t}} = \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \\ 0 \\ 1 \end{bmatrix}, \quad \mathbf{F}_{\mathrm{RHC}}^{\mathrm{t}} = \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \\ 0 \\ -1 \end{bmatrix} \tag{63}$$

The received Stokes vectors can be computed using the measured $E_{\mathrm{v}}^{\mathrm{r}}$ and $E_{\mathrm{h}}^{\mathrm{r}}$. By denoting the ith column of the modified Mueller matrix by $\mathbf{L}_{\mathrm{m}}^{i}$ it is a straightforward matter to show that

$$\begin{aligned}
\mathbf{L}_{\mathrm{m}}^{1} &= \frac{1}{r^2}\mathbf{F}_{\mathrm{V}}^{\mathrm{r}} \\
\mathbf{L}_{\mathrm{m}}^{2} &= \frac{1}{r^2}\left[\mathbf{F}_{\mathrm{LHC}}^{\mathrm{r}} + \mathbf{F}_{\mathrm{RHC}}^{\mathrm{r}} - \mathbf{F}_{\mathrm{V}}^{\mathrm{r}}\right] \\
\mathbf{L}_{\mathrm{m}}^{3} &= \frac{1}{r^2}\left[\mathbf{F}_{45}^{\mathrm{r}} - \tfrac{1}{2}\left(\mathbf{F}_{\mathrm{LHC}}^{\mathrm{r}} + \mathbf{F}_{\mathrm{RHC}}^{\mathrm{r}}\right)\right] \\
\mathbf{L}_{\mathrm{m}}^{4} &= \frac{1}{r^2}\left[\tfrac{1}{2}\left(\mathbf{F}_{\mathrm{LHC}}^{\mathrm{r}} - \mathbf{F}_{\mathrm{RHC}}^{\mathrm{r}}\right)\right]
\end{aligned} \tag{64}$$

where $\mathbf{F}_{p}^{\mathrm{r}}$ represents the received Stokes vector corresponding to the transmit polarization p.

In case of distributed targets, measurements of $\mathbf{F}_{p}^{\mathrm{r}}$ are repeated many times to estimate the expected value $\langle \mathbf{F}_{p}^{\mathrm{r}} \rangle$. Then, $\langle \mathbf{L}_{\mathrm{m}} \rangle$ can be determined from $\langle \mathbf{F}_{p}^{\mathrm{r}} \rangle$

following the procedure outlined in (64), from which the radar cross section can be computed for any desired combination of transmit and receive antenna polarizations using the polarization synthesis technique [1].

4 U-Mass Measurement System

The three UMass radar systems operate at 35, 95 and 225 GHz. The 95 and 225 GHz radars are configured to measure the target modified Mueller matrix. Prior to Jan. 1994, the 35 GHz radar was only capable of co-polarized and cross-polarized radar cross-section measurements. This radar was subsequently modified to make modified Mueller matrix measurements using the noncoherent technique described below. Table 3 summarizes the radar system specifications. Fig. 11 shows the three radar systems mounted on an azimuth-over-elevation positioner. A Hewlett-Packard series 382 computer controlled the radar operational states, positioner pointing angle, and data acquisition systems. An off-the-shelf, 12-bit analog to digital converter (ADC) card was used to sample the 35 GHz radar return, while the other millimeter-wave radars required custom built 12-bit ADCs systems for the more demanding requirements of the polarimetric radars.

4.1 35 GHz Stepped Frequency Radar Description

The 35 GHz radar is a stepped frequency CW system with separate transmit and receive cassegrain reflector antennas. Each frequency sweep of 300 MHz consists of 256 frequency steps with an average output power of 1 mW. The transmit polarization is switched between vertical and horizontal polarizations with a mechanical rotary joint, while changing receiver polarization requires rotation of the entire radar by 90°. The in-phase and quadrature components of the received signal are stored and later transformed to provide power versus range profiles. A block diagram of the system is shown in Fig. 12.

The 35 GHz radar was modified in late 1993 to measure the target modified Mueller matrix noncoherently. This required replacing the fixed-polarization receiver antenna with a 30 cm diameter lens antenna which is rapidly switched between vertical and horizontal polarization on alternate frequency sweeps. The transmit antenna was modified to rotate between any one of six linear polarization states. To measure both receiver polarizations in less than the signal decorrelation time, the frequency sweep was reduced from 300 MHz to 75 MHz, increasing the range resolution from .5 to 2 m. The number of frequency steps was reduced to 64, each with a dwell time of 40 μs, thus, the sampling time was 2.56 ms per polarization, or 5.12 ms per polarization pair. This process is repeated until enough independent samples are obtained to generate a Stokes vector for the particular transmit polarization in use. The

Table 3: 35, 95 and 225 GHz radar specifications

Radar specifications			
Parameter	35 GHz	95 GHz	225 GHz
Transmitter:			
Frequency	34.82–35.12 GHz	94.92 GHz	225.63 GHz
Transmitter	Gunn Osc.	Klystron Amp.	Klystron Osc.
Peak Power	1 mW	1.5 kW	60 W
Modulation	stepped freq.	Pulse	Pulse
Range Resolution	.5 m	30 m	30 m
Maximum PRF	n/a	80 KHz	20 KHz
Receiver:			
Front-End Mixer(s)	Balanced	Balanced	2nd harmonic
SSB Noise Figure	4.5 dB	9 dB	15 dB
Dynamic Range	60 dB	75 dB	70 dB
Antennas:			
Type	Dual Cassegrain	Rexolite lens	dual TPX lenses
Diameter	30 cm	30 cm	15 cm
3 dB beamwidth	1.8°	0.7°	0.6°
Transmit polarization	mechanically rotated, v and h	ferrite switch v and h	motor-controlled v, h, ±45° RHCP, LHCP
Receiver polarization	mechanically rotated, v and h	dual v and h	dual v and h

Figure 11: The 35, 95 and 225 GHz radars mounted on a computer controlled positioner.

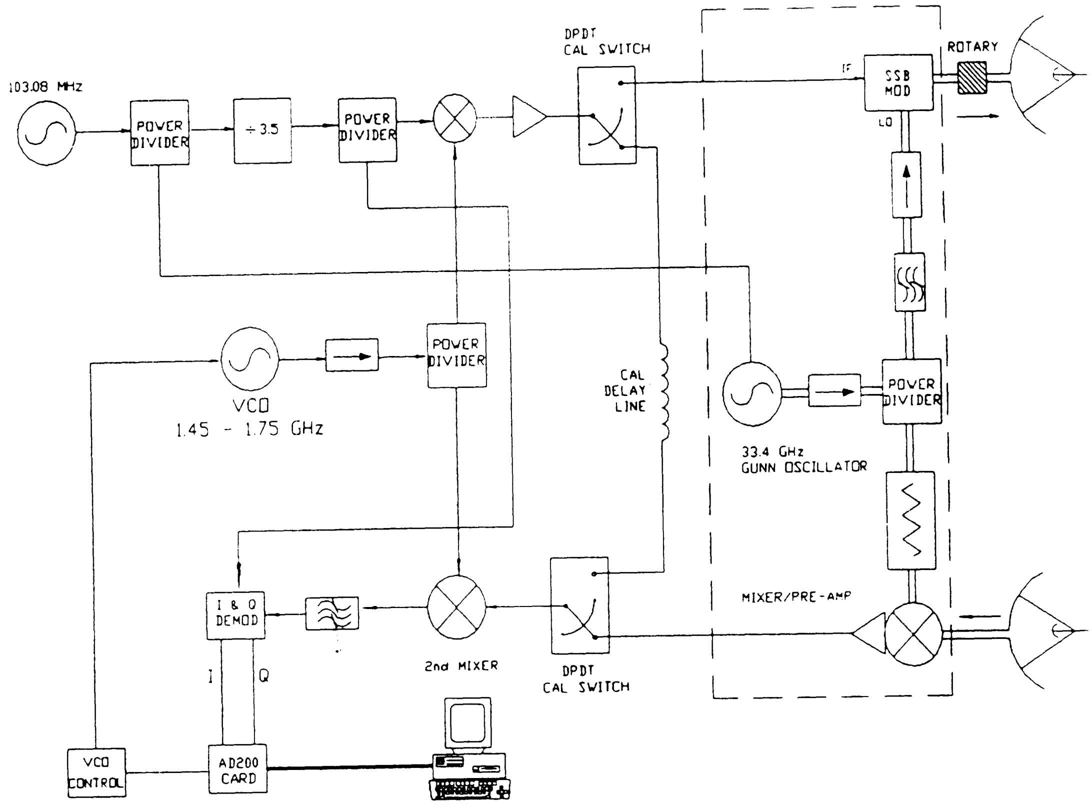


Figure 12: Block diagram of the dual-polarization 35 GHz radar.

process is then repeated for up to five more linear polarizations. The modified Mueller matrix is then computed using the Kalman filter technique described below.

4.2 95 GHz Polarimeter Description

The 95 GHz polarimetric radar system consists of a pulsed, dual-polarization radar, a Polarimetric Radar Control and Data Acquisition system (PRACDA), and a data logging/display computer. A block diagram of the 95 GHz polarimetric radar is shown in Fig. 13. The system utilizes a low-noise reference oscillator at 15.62 GHz which is multiplied six times to 93.72 GHz. This signal acts as both receiver local oscillator and driver for the transmitter amplifier chain. The transmitter amplifier consists of a solid-state injection-locked amplifier, followed by an Extended Interaction klystron Amplifier (EIA). Alternate transmission of vertically and horizontally polarized 95 GHz pulses is achieved by a latching circulator which alternately selects the vertical and horizontal ports of an orthomode transducer (OMT). A single 30 cm diameter dielectric lens antenna is used for both transmission and reception. The lens is illuminated by a dual-polarization scalar feed horn, providing an axially symmetric radiation pattern. The combination of the scalar feed and lens antenna yields excellent polarization isolation, with the cross-polarized power integrated over the antenna pattern approximately 30 dB below the copolarized level. Upon reception, the OMT separates the signal into its vertical and horizontal components, which are downconverted to 1.2 GHz using a single balanced mixer. After amplification, the signal is again downconverted to 120 MHz where separate magnitude and phase detection are performed. A log amplifier/detector is employed in the amplitude channels, providing a dynamic range of 80 dB. The phase detector is preceded by a constant phase limiter, which maintains nearly constant phase over a dynamic range of 70 dB.

4.3 225 GHz Polarimeter

The 225 GHz polarimeter consists of a multiple polarization transmitter, a dual polarization receiver, the Polarimetric RAdar Control and Data Acquisition (PRACDA) subsystem and a data logging computer [4]. A block diagram of the system is shown in Fig. 14. Scalar feed lens antennas were selected for both the transmitter and receiver to minimize sidelobe levels and to provide low cross-polarization across the main beam. During polarimetric measurements, the transmitter's multiple-polarization lens antenna is sequentially switched between the six polarization states given in Table 3. The magnitude of the vertical and horizontal components of the scattered wave along with the phase difference between these components is measured using a dual-polarization receiver for each transmit state. This provides sufficient information to deter-

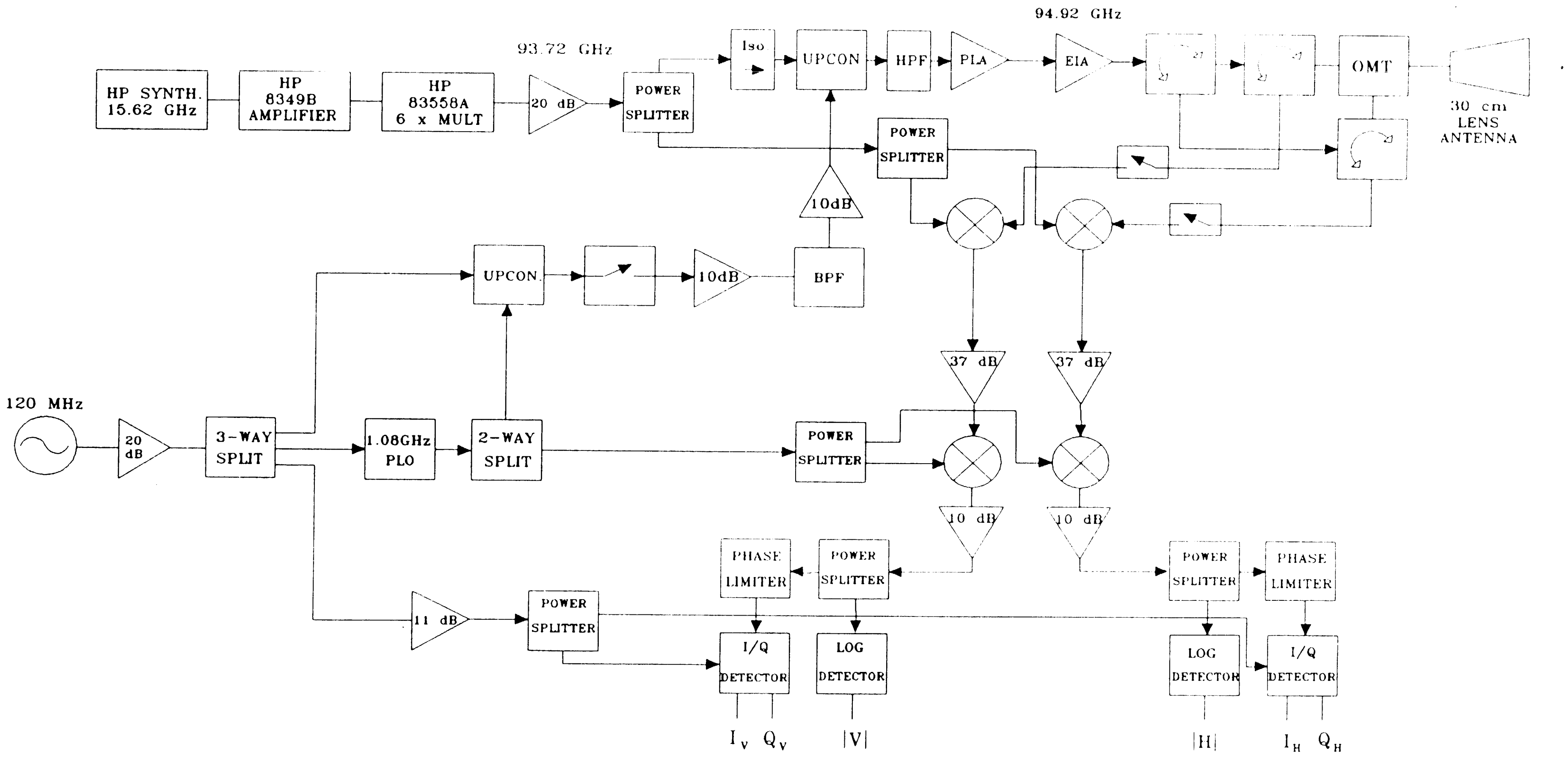


Figure 13: Block diagram of the 95 GHz polarimetric radar.

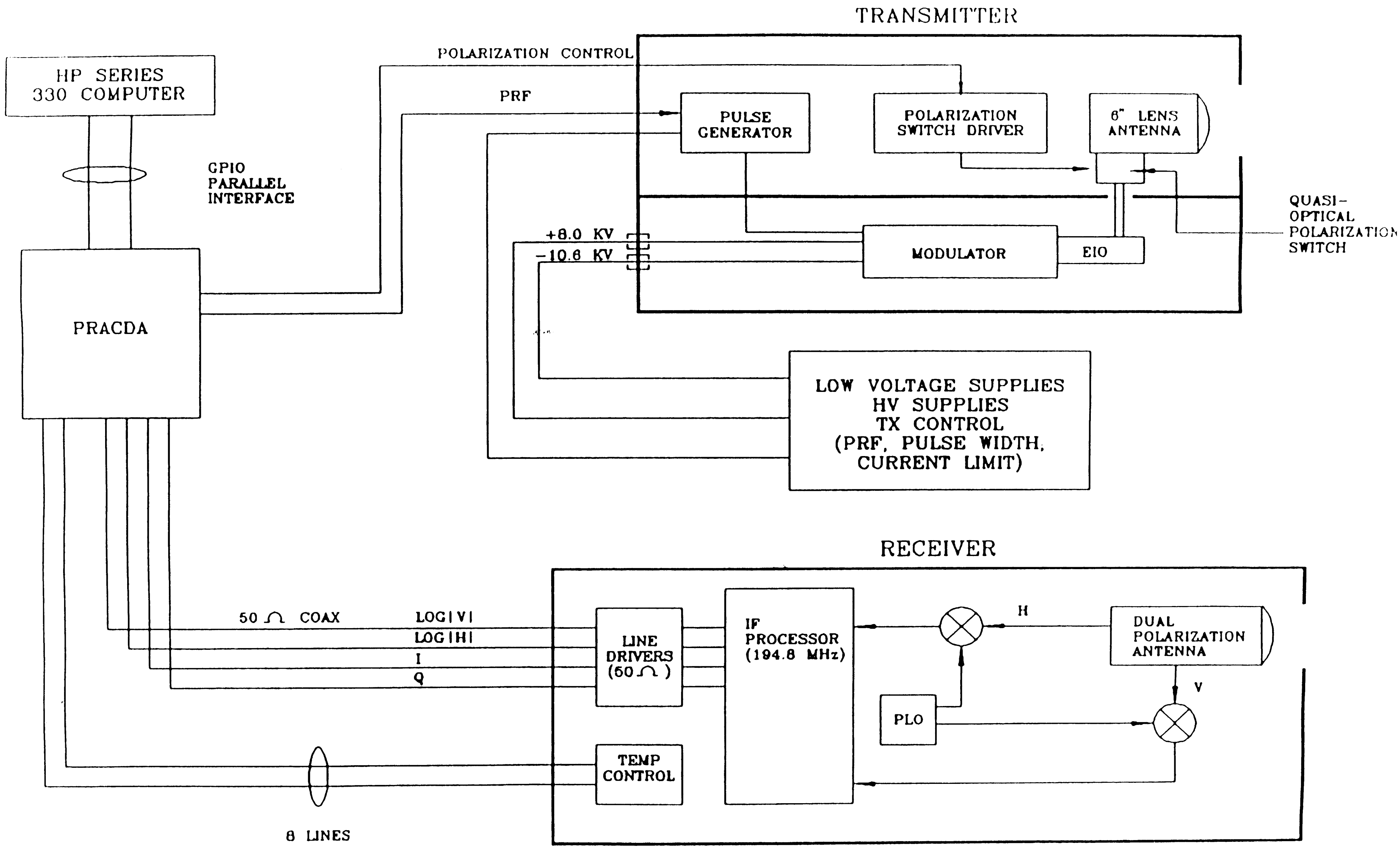


Figure 14: Block diagram of the 225 GHz polarimetric radar.

mine the received Stokes vector. A set of six Stokes vectors, associated with six different transmit polarization states, is used to compute the modified Mueller matrix as described below.

4.4 Coherent Measurement Technique (UMass 95 GHz Polarimeter)

Measurement of the complex scattering matrix, **S**, is achieved by alternately transmitting horizontally and vertically polarized waves in rapid succession. Elements of the first column of the scattering matrix S_{vv} and S_{hv} are measured during the first pulse period (vertical transmit) while S_{vh} and S_{hh} are measured during the second (horizontal transmit). The modified Mueller matrix is then computed from the individual scattering matrix quantities as described in Section 2.4.

4.5 Noncoherent Measurement Technique (UMass 35 and 225 GHz Polarimeters)

Noncoherent techniques are often preferable for millimeter wave measurements, where generating coherent, low-phase noise signals is expensive. Furthermore, the noncoherent technique is not adversely affected by rapid decorrelation of the scattered signal. One method for making noncoherent measurement of the modified Mueller matrix is to measure the scattered Stokes vectors associated with at least four transmit polarizations. The Mueller matrix may be expressed in terms of the scattered Stokes vectors associated with transmission of six polarization states using a minimum mean-squared error approach [5]:

$$\mathbf{L} = \begin{bmatrix} I_{\mathrm{v}} + I_{\mathrm{h}} + I_{\mathrm{p}} + I_{\mathrm{m}} + I_{\mathrm{l}} + I_{\mathrm{r}} & 3(I_{\mathrm{h}} - I_{\mathrm{v}}) & 3(I_{\mathrm{p}} - I_{\mathrm{m}}) & 3(I_{\mathrm{r}} - I_{\mathrm{l}}) \\ Q_{\mathrm{v}} + Q_{\mathrm{h}} + Q_{\mathrm{p}} + Q_{\mathrm{m}} + Q_{\mathrm{l}} + Q_{\mathrm{r}} & 3(Q_{\mathrm{h}} - Q_{\mathrm{v}}) & 3(Q_{\mathrm{p}} - Q_{\mathrm{m}}) & 3(Q_{\mathrm{r}} - Q_{\mathrm{l}}) \\ U_{\mathrm{v}} + U_{\mathrm{h}} + U_{\mathrm{p}} + U_{\mathrm{m}} + U_{\mathrm{l}} + U_{\mathrm{r}} & 3(U_{\mathrm{h}} - U_{\mathrm{v}}) & 3(U_{\mathrm{p}} - U_{\mathrm{m}}) & 3(U_{\mathrm{r}} - U_{\mathrm{l}}) \\ V_{\mathrm{v}} + V_{\mathrm{h}} + V_{\mathrm{p}} + V_{\mathrm{m}} + V_{\mathrm{l}} + V_{\mathrm{r}} & 3(V_{\mathrm{h}} - V_{\mathrm{v}}) & 3(V_{\mathrm{p}} - V_{\mathrm{m}}) & 3(V_{\mathrm{r}} - V_{\mathrm{l}}) \end{bmatrix}$$

where $[I_i, Q_i, U_i, V_i]$ is the scattered Stokes vector associated with the ith transmit polarization. If these six Stokes vectors are measured sequentially, the scattered field must remain stationary in the mean during the measurement process. The Mueller matrix, **L**, can be converted into the modified Mueller matrix, $\mathbf{L}_m$, through a simple matrix transformation [Ulaby and Elachi, 1990].

A Kalman filter technique has also been developed to process noncoherent data sets [6]. This technique is very similar to the minimum mean squared error approach described above, but it also takes into account the properties of reciprocal media which forces the modified Mueller matrix to be symmetric (except for a minus sign along the last row) and forces $\langle |S_{\mathrm{vh}}|^2 \rangle = \langle |S_{\mathrm{hv}}|^2 \rangle$.

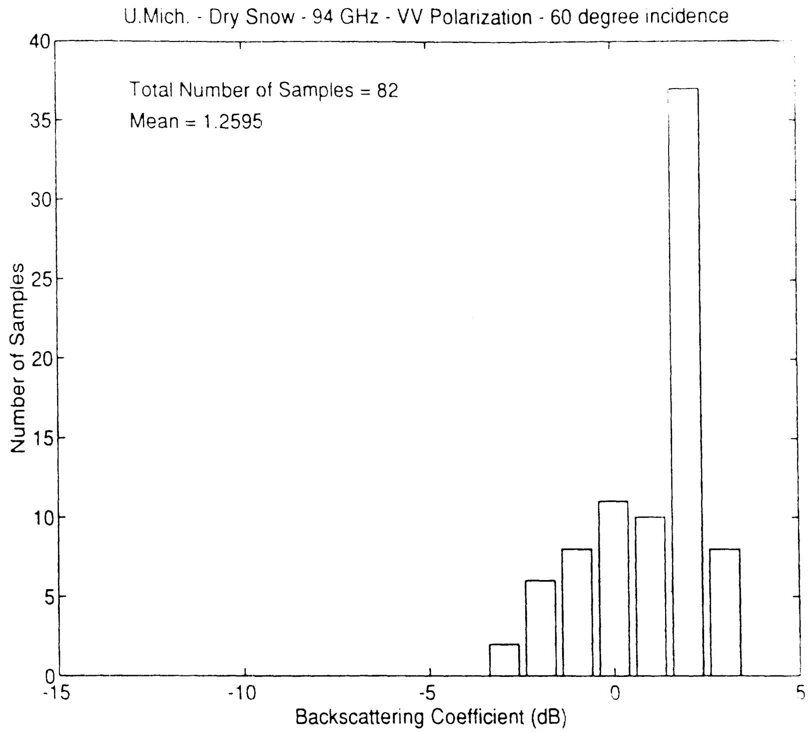
5 Data Presentation Format

5.1 Inter-Calibration of U-M and U-Mass Systems

Two different polarimetric radar systems—the University of Michigan's and the University of Massachusetts'—are responsible for the radar observations catalogued in this handbook. The two systems are different in design and employ somewhat different calibration techniques. This brings out the question: "When using the data reported in this handbook, is it reasonable to treat the data as if it were system-independent and free of calibration biases (between the two systems)?". In order to obtain an exact and complete answer to this question, it would be necessary to conduct a cross-calibration experiment in which both systems are made to measure the backscattering Mueller matrix for the same distributed target. This poses two problems. First, both systems have 35 and 95 GHz channels (so it is possible to compare the performance of the 35 GHz channels of the two systems to one another, and the same can be done for the 95 GHz channels), but the third channel of the U-M scatterometer operates at 140 GHz and the third channel of the U-Mass system operates at 225 GHz, and hence it would not be meaningful to compare those two channels. Second, to conduct such a cross-calibration experiment would entail considerable cost and time for transporting one of the systems to the site of the other.

Although less desirable and not as exact, an alternative approach to conducting a cross-calibration experiment is to perform a statistical comparison using data measured by the two systems for the same type of target. Among the various combinations of target types, frequency channels, and incidence angles, it was determined that both systems have made numerous observations of snow-covered ground, mostly by the 94/95 GHz channels (U-M at 94 GHz and U-Mass at 95 GHz) at 60° incidence relative to nadir. Fig. 15 presents histograms of the vv-polarized backscattering coefficient, as measured by the U-M and U-Mass systems, for dry snow. In each case, the data covers a wide range of snow depths and crystal sizes, but it is noteworthy to mention that the crystal sizes of the snow covers observed by the U-Mass system covered the range between 0.2 mm and 1.0 mm, compared to the range 0.6 mm–2.7 mm for the snow conditions observed by the U-M system. Hence, it is not surprising that the average value of the backscattering coefficient of the U-M data (+1.3 dB) is higher than the average value of the U-Mass data (−1.6 dB) by 2.9 dB.

Distributions similar to those shown in Fig. 15 for dry snow were generated for vh polarization, as well as for both vv and vh polarizations for wet snow. A summary of the mean values is given in Table 4. In all cases, the mean value of the U-M data is higher than the corresponding mean value of the U-Mass data. The average difference is about 2.5 dB. This can be viewed as a measure of



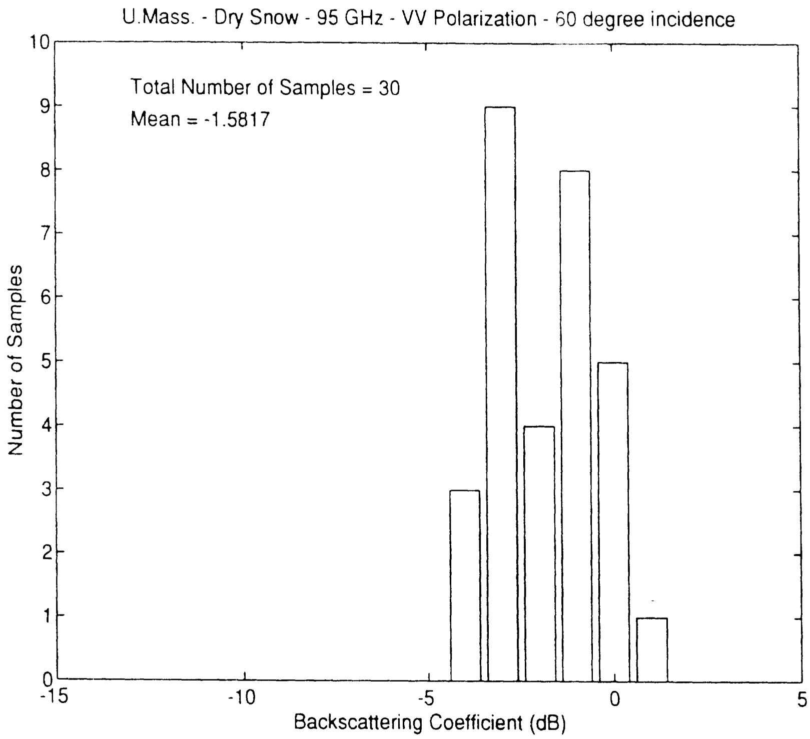


Figure 15. Histograms of measured vv-polarized backscattering coefficient for dry snow.

	U-M	U-Mass	Difference
Polarization/Snow Condition			
VV Dry	+1.3 dB	−1.6 dB	2.9 dB
VH Dry	−2.7 dB	−5.4 dB	2.7 dB
VV Wet	−3.1 dB	−4.8 dB	1.7 dB
VH Wet	−7.5 dB	−10.0 dB	2.5 dB

Table 4: Mean values of the backscattering coefficient measured by the U-M 94-GHz scatterometer and U-Mass 95-GHz scatterometer, both at an incidence angle of 60°.

the calibration bias that might exist between the two systems. Because of the strong dependence of σ° on snow crystal size, however, the authors attribute most, if not all, of the observed difference in σ° to differences in crystal-size, as noted earlier.

5.2 Data Organization

The data reported in this handbook is organized in the form of chapters by target type, and subdivided according to target condition. For example, Chapter 6 deals with soil surfaces, with individual sections devoted to specific surface roughness/moisture content conditions. Typically, such a section may include data at several incidence angles (or different time of day for some of the diurnal data sets) and multiple radar frequencies. The first page of the section provides information about the target and its condition. This is then followed with listings of the elements of the differential modified Mueller matrix $\mathbf{L}_{\mathrm{m}}^\circ$ (see (25) and (35)), written in a form in which L_{11} has been factored out of the matrix, as indicated in the typical example shown in Figure 16. For convenience to the user, additional quantities are given also, all derivable from $\mathbf{L}_{\mathrm{m}}^\circ$, including the principal linear backscattering coefficients (as defined by (29) through (31)), the depolarization ratio given by (52), the co-polarization phase parameters given by (60) and (61), and the degree of polarization for various transmit polarization states. In addition, plots of the normalized co-polarized and cross-polarized responses are also provided.

Target: S1-dry

System/Frequency: UM - 94 GHz.

Incidence Angle: 70^o

Normalized Mueller Matrix:

$$L_m^o = 0.0013 \begin{bmatrix} 1.0000 & 0.1170 & -0.0192 & 0.0150 \\ 0.1170 & 0.5317 & -0.0087 & -0.0115 \\ -0.0384 & -0.0174 & 0.5603 & 0.0644 \\ -0.0300 & 0.0230 & -0.0644 & 0.3261 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -17.77\ dB & \sigma_{hh} &= -20.51\ dB \\ \sigma_{vh} &= -27.09\ dB & & \\ \chi_d &= -8.16\ dB & & \\ \alpha &= 0.61 & \zeta &= 8.26^o \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.79 & m_h &= 0.64 \\ m_{45} &= 0.68 & m_{135} &= 0.70 \\ m_{lhc} &= 0.47 & m_{rhc} &= 0.46 \end{aligned}$$

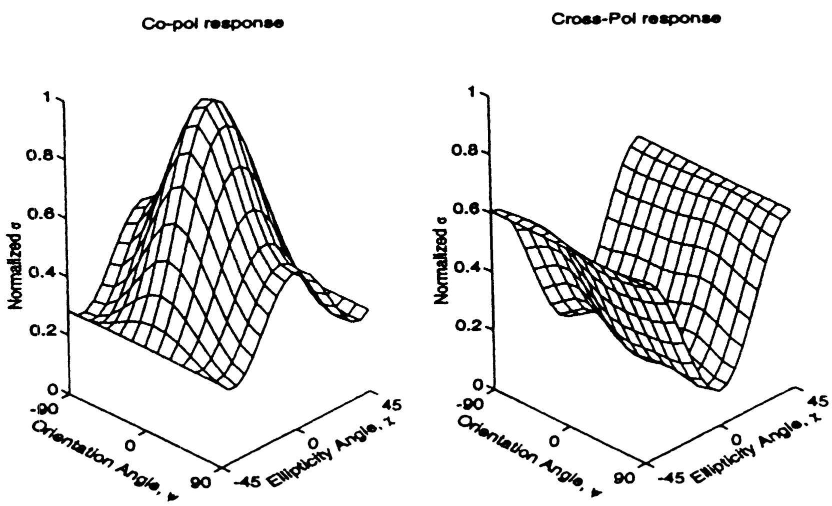


Figure 16. Typical example of the data format used in the presentation of data in succeeding chapters.

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Notes for Data Sets

Some of the data sets required additional information about particular measurements. On each page of the data sets there may appear a short note with one of the following symbols. These are explained here in further detail to assist the user in making the best use of the published measurements.

*** magnitude relative to σ_{vv}**

Indicates that the calibration performed is relative to σ_{vv}. Thus only the ratios σ_{hh}/σ_{vv} and σ_{hh}/σ_{vv} are meaningful.

† value may be inaccurate

Indicates that the value for ζ for this data set may be inaccurate due to uncertainties in the phase calibration. These uncertainties can best be seen at near normal angles of incidence where it is expected that values for ζ would be close to zero.

‡ value may be underestimated

35 GHz tree data may be affected by decorrelation of the target during the time which elapses between the measurement of the v and h received power. This problem manifests itself as dips in the signature at an orientation angle of $\pm 45°$ and ellipticity of $0°$.

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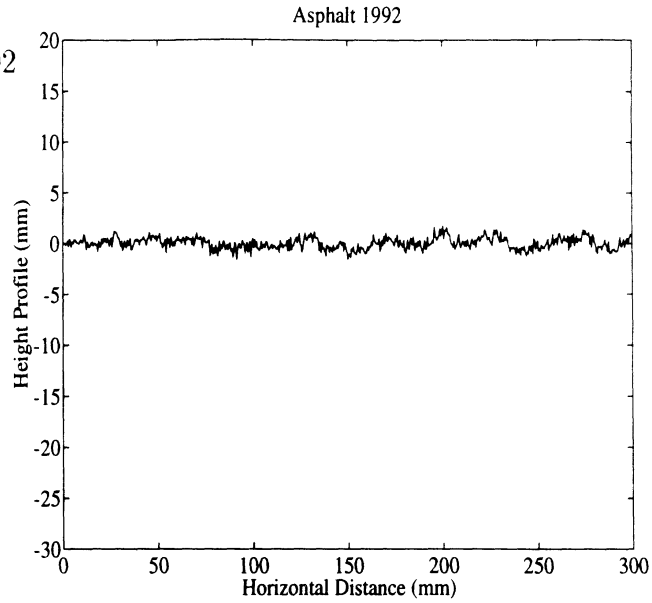
Target Name: Aged Asphalt 1992
System: UM



Target Description: Middle aged asphalt (grayed and weathered yet still in fair condition). Measurement was made of both dry and wet asphalt. To obtain the wet surface, a sufficient amount of water was added to make the surface of the asphalt almost shiny.

Ground Truth:
rms height = 0.60 mm
correlation length = 8.54 mm

frequency	ks	kl
35 GHz	0.44	6.26
94 GHz	1.18	16.8

References:
None

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	asph.1.1	47
45	35	dry	asph.1.2	48
70	35	dry	asph.1.3	49
20	35	wet	asph.1.4	50
45	35	wet	asph.1.5	51
70	35	wet	asph.1.6	52
20	94	dry	asph.1.7	53
45	94	dry	asph.1.8	54
70	94	dry	asph.1.9	55
20	94	wet	asph.1.10	56
45	94	wet	asph.1.11	57
70	94	wet	asph.1.12	58

Target: Dry Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

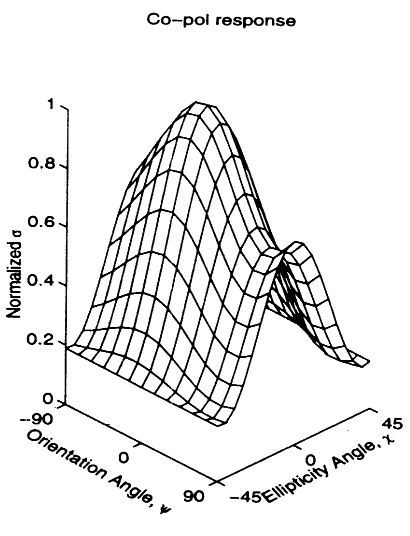
Normalized Mueller Matrix:

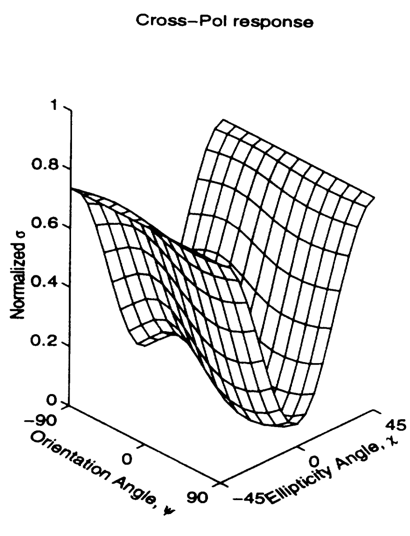
$$\mathbf{L}_m^\circ = 0.0181 \begin{bmatrix} 1.0000 & 0.0796 & -0.0517 & 0.0029 \\ 0.0796 & 0.7189 & -0.0572 & 0.0099 \\ -0.1034 & -0.1144 & 0.7360 & 0.0284 \\ -0.0057 & -0.0198 & -0.0284 & 0.5767 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.44 \text{ dB} & \sigma_{hh} &= -7.88 \text{ dB} \\ \sigma_{vh} &= -17.43 \text{ dB} & & \\ \chi_d &= -10.33 \text{ dB} & & \\ \alpha &= 0.77 & \zeta &= 2.48° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.86 & m_h &= 0.81 \\ m_{45} &= 0.78 & m_{135} &= 0.82 \\ m_{lhc} &= 0.61 & m_{rhc} &= 0.67 \end{aligned}$$





Target: Dry Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

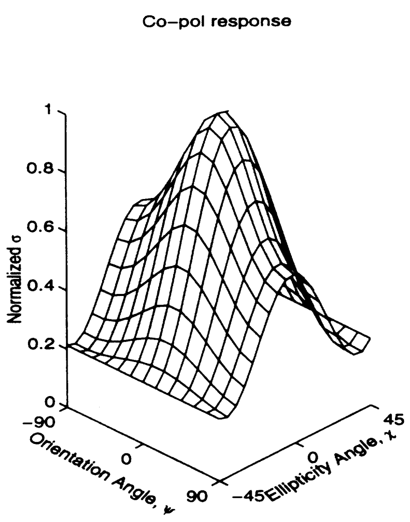
Normalized Mueller Matrix:

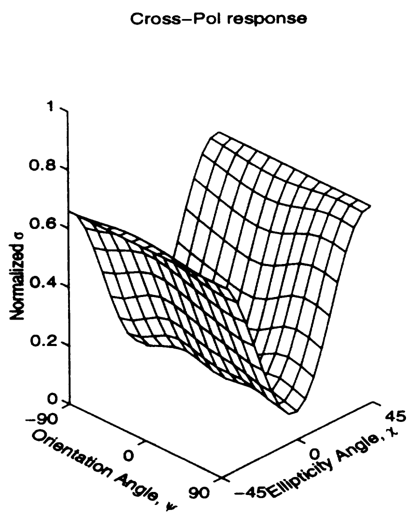
$$\mathbf{L}_m^\circ = 0.0069 \begin{bmatrix} 1.0000 & 0.0970 & 0.0076 & -0.0293 \\ 0.0970 & 0.5777 & -0.0050 & 0.0228 \\ 0.0152 & -0.0099 & 0.6379 & 0.0452 \\ 0.0585 & -0.0457 & -0.0452 & 0.4439 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.61 \text{ dB} & \sigma_{hh} &= -12.99 \text{ dB} \\ \sigma_{vh} &= -20.74 \text{ dB} & & \\ \chi_d &= -9.10 \text{ dB} & & \\ \alpha &= 0.71 & \zeta &= 4.77^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.72 \\ m_{45} &= 0.76 & m_{135} &= 0.76 \\ m_{lhc} &= 0.55 & m_{rhc} &= 0.57 \end{aligned}$$





Target: Dry Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

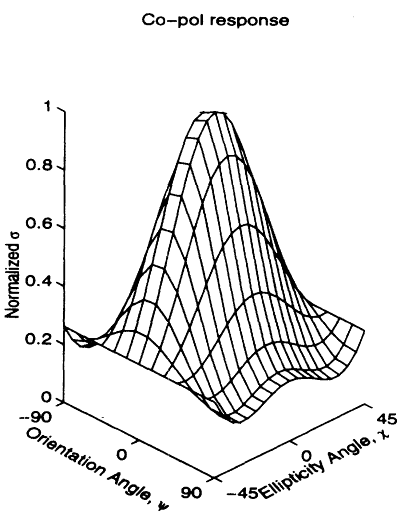
Normalized Mueller Matrix:

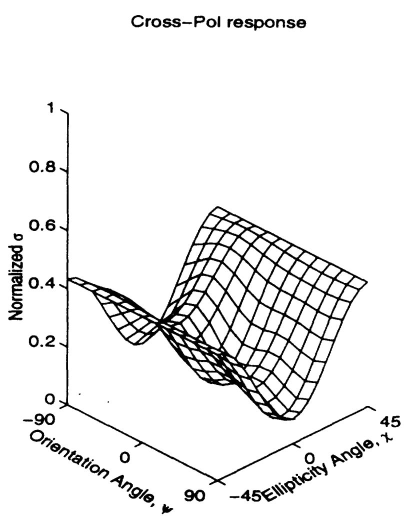
$$\mathbf{L}_m^\circ = 0.0012 \begin{bmatrix} 1.0000 & 0.0841 & -0.0437 & 0.0030 \\ 0.0841 & 0.2068 & -0.0182 & 0.0006 \\ -0.0875 & -0.0364 & 0.3422 & -0.0171 \\ -0.0061 & -0.0012 & 0.0171 & 0.1739 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -18.22 \text{ dB} & \sigma_{hh} &= -25.07 \text{ dB} \\ \sigma_{vh} &= -28.97 \text{ dB} & & \\ \chi_d &= -8.56 \text{ dB} & & \\ \alpha &= 0.57 & \zeta &= -3.80^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.44 \\ m_{45} &= 0.74 & m_{135} &= 0.78 \\ m_{lhc} &= 0.64 & m_{rhc} &= 0.64 \end{aligned}$$





Target: Dry Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

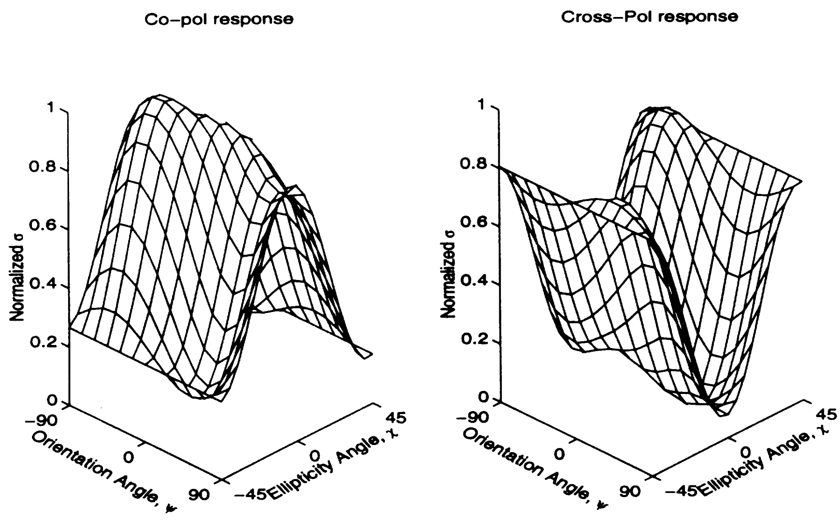
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0592 \begin{bmatrix} 1.0000 & 0.0833 & -0.0228 & -0.0231 \\ 0.0833 & 0.9163 & -0.0438 & 0.0639 \\ -0.0455 & -0.0875 & 0.7529 & -0.4103 \\ 0.0463 & -0.1278 & 0.4103 & 0.5862 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -1.28 \text{ dB} & \sigma_{hh} &= -1.66 \text{ dB} \\ \sigma_{vh} &= -12.07 \text{ dB} \\ \chi_d &= -10.61 \text{ dB} \\ \alpha &= 0.82 & \zeta &= -31.50^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.85 \\ m_{45} &= 0.80 & m_{135} &= 0.84 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.73 \end{aligned}$$



Target: Dry Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 102

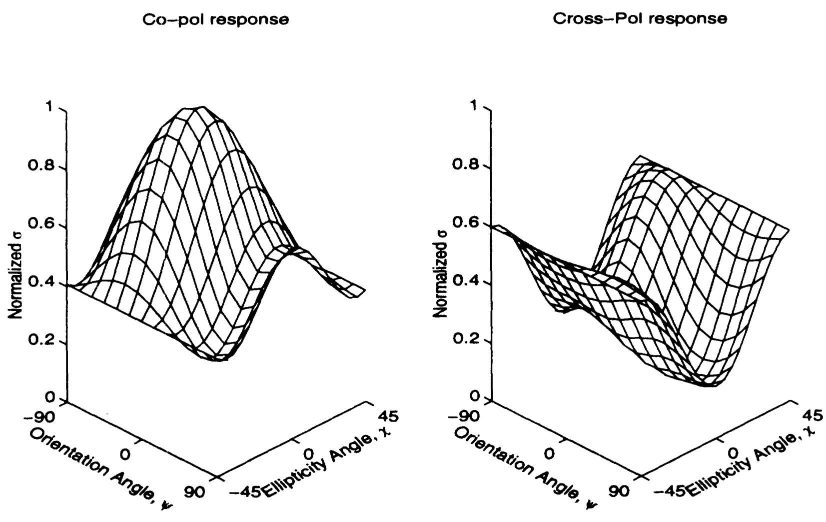
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0161 \begin{bmatrix} 1.0000 & 0.1842 & -0.0458 & 0.0142 \\ 0.1842 & 0.6757 & -0.0617 & -0.0051 \\ -0.0916 & -0.1233 & 0.5733 & -0.1809 \\ -0.0284 & 0.0102 & 0.1809 & 0.2049 \end{bmatrix}$$

$$\sigma_{vv} = -6.94 \text{ dB} \qquad \sigma_{hh} = -8.64 \text{ dB}$$
$$\sigma_{vh} = -14.28 \text{ dB}$$
$$\chi_d = -6.58 \text{ dB}$$
$$\alpha = 0.52 \qquad \zeta = -24.94°$$

Degree of Polarization:

$$m_v = 0.69 \qquad m_h = 0.59$$
$$m_{45} = 0.58 \qquad m_{135} = 0.64$$
$$m_{lhc} = 0.38 \qquad m_{rhc} = 0.26$$



Target: Dry Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

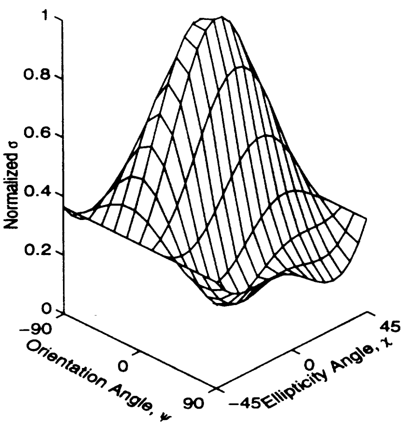
$$\mathbf{L}_m^\circ = 0.0042 \begin{bmatrix} 1.0000 & 0.0769 & -0.0654 & -0.0212 \\ 0.0769 & 0.2574 & -0.0153 & 0.0404 \\ -0.1308 & -0.0305 & 0.1811 & -0.2192 \\ 0.0425 & -0.0807 & 0.2192 & 0.0273 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.77 \text{ dB} & \sigma_{hh} &= -18.66 \text{ dB} \\ \sigma_{vh} &= -23.91 \text{ dB} & & \\ \chi_d &= -9.12 \text{ dB} & & \\ \alpha &= 0.48 & \zeta &= -64.58^\circ \end{aligned}$$

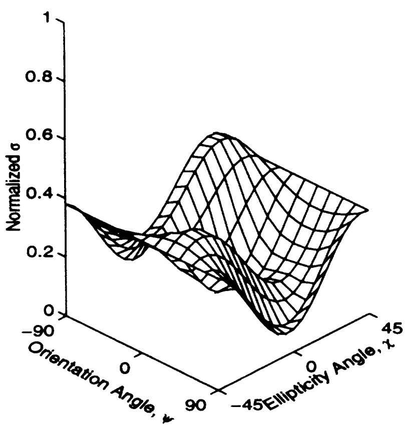
Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.60 \\ m_{45} &= 0.63 & m_{135} &= 0.70 \\ m_{lhc} &= 0.59 & m_{rhc} &= 0.67 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Wet Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

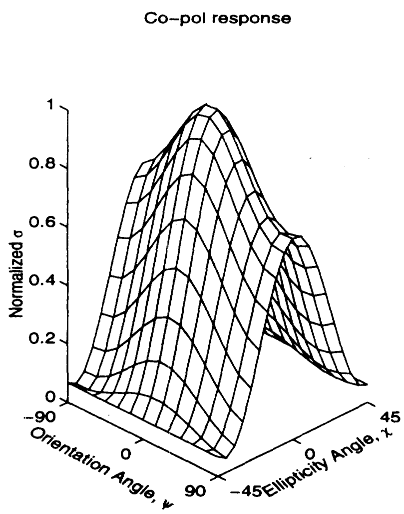
Normalized Mueller Matrix:

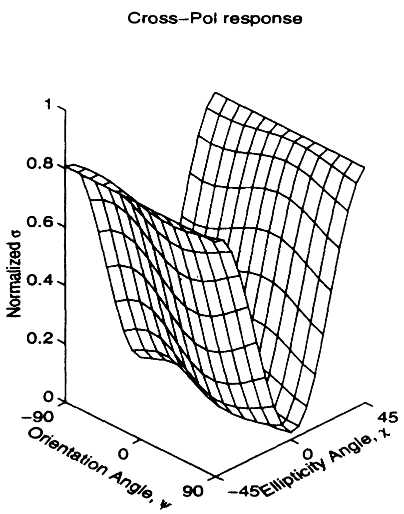
$$\mathbf{L}_m^\circ = 0.0094 \begin{bmatrix} 1.0000 & 0.0247 & -0.0177 & 0.0361 \\ 0.0247 & 0.6898 & -0.0159 & -0.0336 \\ -0.0354 & -0.0319 & 0.7912 & 0.0910 \\ -0.0722 & 0.0672 & -0.0910 & 0.7417 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.26 \text{ dB} & \sigma_{hh} &= -10.87 \text{ dB} \\ \sigma_{vh} &= -25.32 \text{ dB} & & \\ \chi_d &= -15.33 \text{ dB} & & \\ \alpha &= 0.93 & \zeta &= 6.77^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.94 \\ m_{45} &= 0.93 & m_{135} &= 0.93 \\ m_{lhc} &= 0.89 & m_{rhc} &= 0.88 \end{aligned}$$





Target: Wet Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

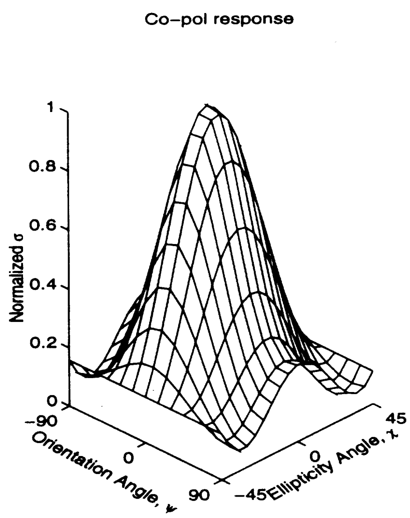
Normalized Mueller Matrix:

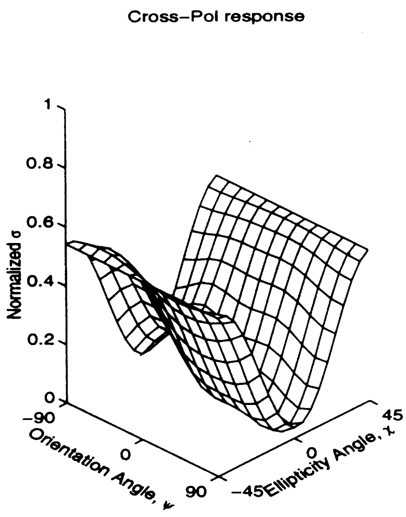
$$\mathbf{L}_m^\circ = 0.0049 \begin{bmatrix} 1.0000 & 0.0378 & -0.0611 & 0.0322 \\ 0.0378 & 0.2656 & -0.0311 & -0.0140 \\ -0.1222 & -0.0622 & 0.4736 & 0.0777 \\ -0.0644 & 0.0280 & -0.0777 & 0.3980 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.14 \text{ dB} & \sigma_{hh} &= -17.90 \text{ dB} \\ \sigma_{vh} &= -26.36 \text{ dB} & & \\ \chi_d &= -12.24 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= 10.11^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.94 & m_h &= 0.78 \\ m_{45} &= 0.90 & m_{135} &= 0.91 \\ m_{lhc} &= 0.82 & m_{rhc} &= 0.85 \end{aligned}$$





Target: Wet Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

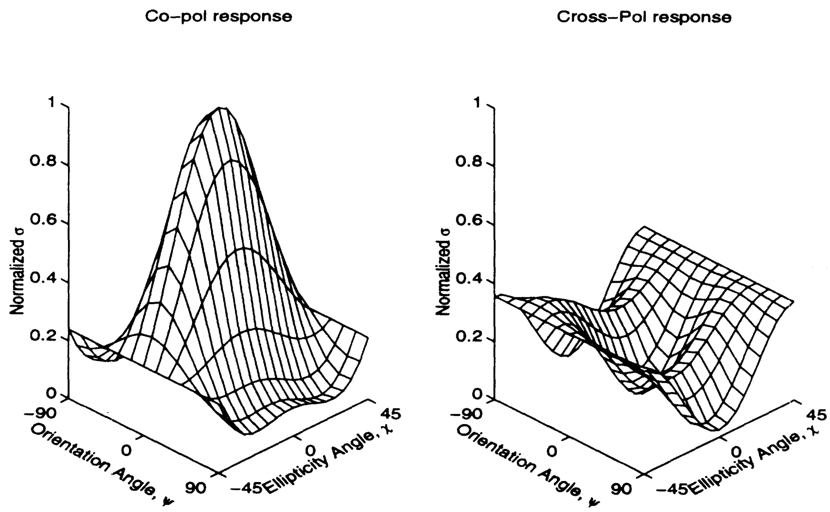
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0014 \begin{bmatrix} 1.0000 & 0.0248 & -0.0454 & 0.0067 \\ 0.0248 & 0.0982 & -0.0074 & 0.0042 \\ -0.0908 & -0.0148 & 0.1716 & 0.0663 \\ -0.0134 & -0.0083 & -0.0663 & 0.1219 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -17.41 \text{ dB} & \sigma_{hh} &= -27.49 \text{ dB} \\ \sigma_{vh} &= -33.46 \text{ dB} & & \\ \chi_d &= -13.44 \text{ dB} & & \\ \alpha &= 0.51 & \zeta &= 24.30^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.96 & m_h &= 0.61 \\ m_{45} &= 0.84 & m_{135} &= 0.86 \\ m_{lhc} &= 0.80 & m_{rhc} &= 0.86 \end{aligned}$$



Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

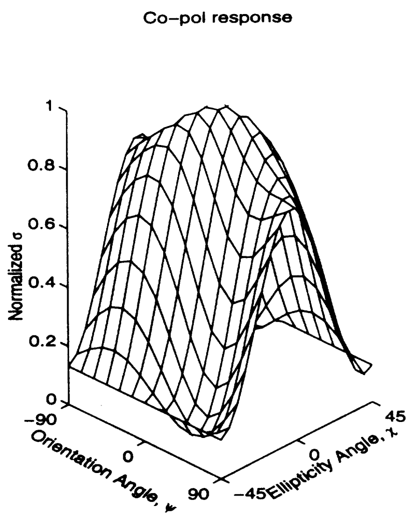
Normalized Mueller Matrix:

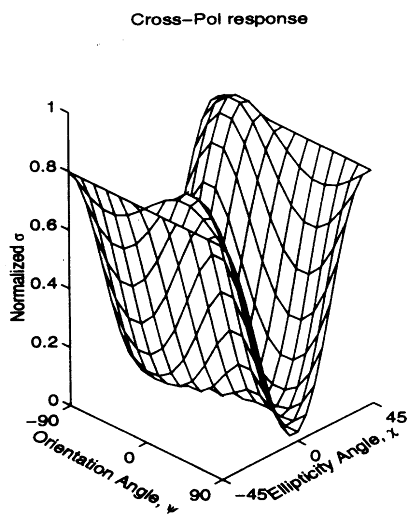
$$\mathbf{L}_m^\circ = 0.0666 \begin{bmatrix} 1.0000 & 0.0304 & -0.0172 & -0.0507 \\ 0.0304 & 0.7923 & 0.0111 & 0.0526 \\ -0.0344 & 0.0222 & 0.7296 & -0.4618 \\ 0.1014 & -0.1051 & 0.4618 & 0.6688 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -0.77 \text{ dB} & \sigma_{hh} &= -1.78 \text{ dB} \\ \sigma_{vh} &= -15.94 \text{ dB} & & \\ \chi_d &= -14.69 \text{ dB} & & \\ \alpha &= 0.94 & \zeta &= -33.45^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.94 \\ m_{45} &= 0.94 & m_{135} &= 0.94 \\ m_{lhc} &= 0.88 & m_{rhc} &= 0.91 \end{aligned}$$





Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

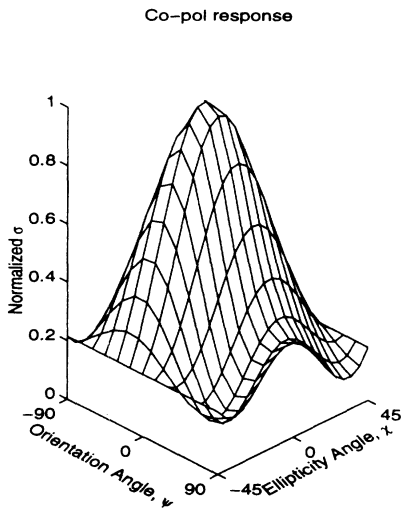
Normalized Mueller Matrix:

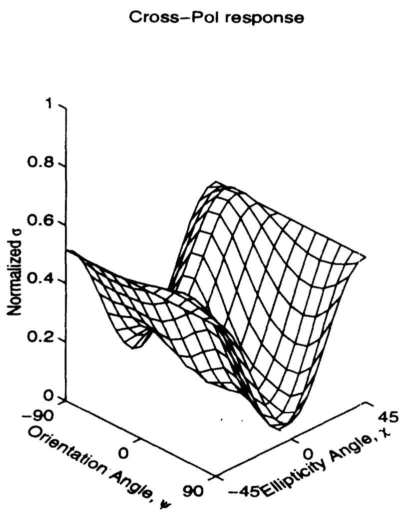
$$\mathbf{L}_m^\circ = 0.0113 \begin{bmatrix} 1.0000 & 0.0590 & -0.0809 & -0.0106 \\ 0.0590 & 0.3325 & -0.0334 & 0.0248 \\ -0.1619 & -0.0667 & 0.4360 & -0.2145 \\ 0.0213 & -0.0495 & 0.2145 & 0.3181 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -8.48 \text{ dB} & \sigma_{hh} &= -13.27 \text{ dB} \\ \sigma_{vh} &= -20.78 \text{ dB} & & \\ \chi_d &= -10.53 \text{ dB} & & \\ \alpha &= 0.75 & \zeta &= -29.63° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.90 & m_h &= 0.73 \\ m_{45} &= 0.78 & m_{135} &= 0.84 \\ m_{lhc} &= 0.73 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

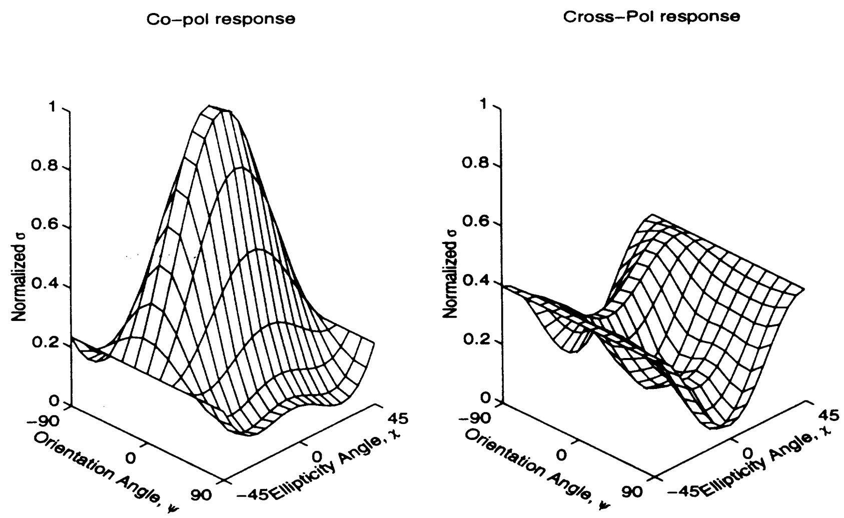
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0021 \begin{bmatrix} 1.0000 & 0.0465 & -0.0732 & -0.0020 \\ 0.0465 & 0.1236 & -0.0174 & 0.0134 \\ -0.1464 & -0.0349 & 0.2603 & -0.0558 \\ 0.0040 & -0.0268 & 0.0558 & 0.1673 \end{bmatrix}$$

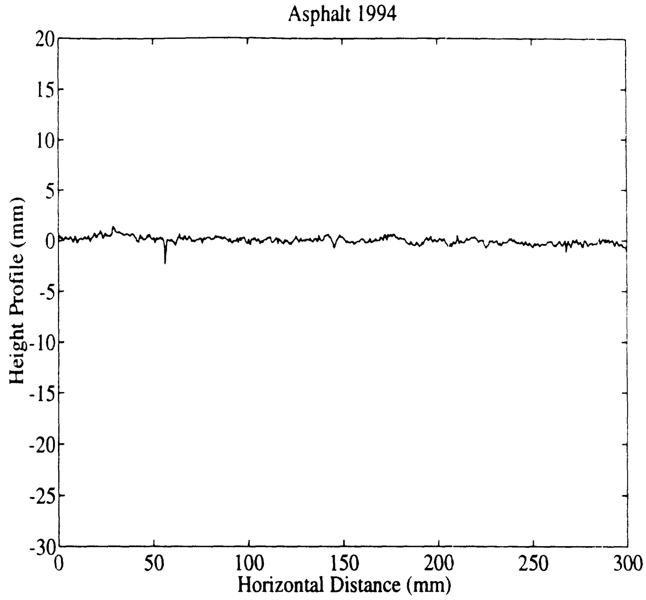
$$\begin{aligned} \sigma_{vv} &= -15.71 \text{ dB} & \sigma_{hh} &= -24.79 \text{ dB} \\ \sigma_{vh} &= -29.04 \text{ dB} & & \\ \chi_d &= -10.82 \text{ dB} & & \\ \alpha &= 0.63 & \zeta &= -14.62^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.92 & m_h &= 0.52 \\ m_{45} &= 0.81 & m_{135} &= 0.87 \\ m_{lhc} &= 0.76 & m_{rhc} &= 0.82 \end{aligned}$$



Target Name:
Recent Asphalt 1994
System: UM



Target Description: Recently laid asphalt parking lot (approx. 1 yr old).

Ground Truth:
rms height = 0.42 mm
correlation length = 20 mm

frequency	ks	kl
35 GHz	0.31	14.7

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	asph.2.1	60
30	35	dry	asph.2.2	61
45	35	dry	asph.2.3	62
60	35	dry	asph.2.4	63

References:
None

Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

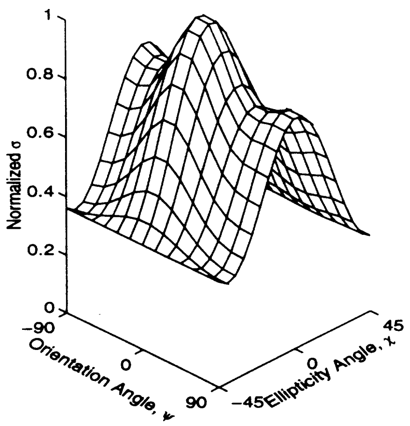
$$\mathbf{L}_m^\circ = 0.0078 \begin{bmatrix} 1.0000 & 0.1115 & -0.0348 & 0.0674 \\ 0.1115 & 0.7958 & 0.0116 & -0.0269 \\ -0.0696 & 0.0231 & 0.6020 & -0.0216 \\ -0.1347 & 0.0539 & 0.0216 & 0.3791 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.09 \text{ dB} & \sigma_{hh} &= -11.08 \text{ dB} \\ \sigma_{vh} &= -19.61 \text{ dB} \\ \chi_d &= -9.06 \text{ dB} \\ \alpha &= 0.55 & \zeta &= -2.52^\circ \end{aligned}$$

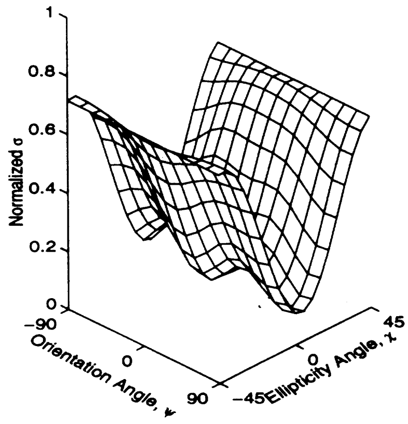
Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.76 \\ m_{45} &= 0.59 & m_{135} &= 0.63 \\ m_{lhc} &= 0.38 & m_{rhc} &= 0.43 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 100

Normalized Mueller Matrix:

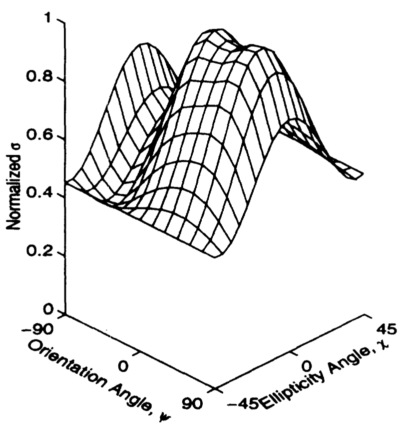
$$\mathbf{L}_m^\circ = 0.0064 \begin{bmatrix} 1.0000 & 0.2144 & -0.0010 & -0.0099 \\ 0.2144 & 0.8179 & 0.1238 & -0.0023 \\ -0.0020 & 0.2477 & 0.5959 & 0.1005 \\ 0.0198 & 0.0047 & -0.1005 & 0.1670 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.94 \text{ dB} & \sigma_{hh} &= -11.81 \text{ dB} \\ \sigma_{vh} &= -17.62 \text{ dB} & & \\ \chi_d &= -6.27 \text{ dB} & & \\ \alpha &= 0.44 & \zeta &= 14.76^\circ \end{aligned}$$

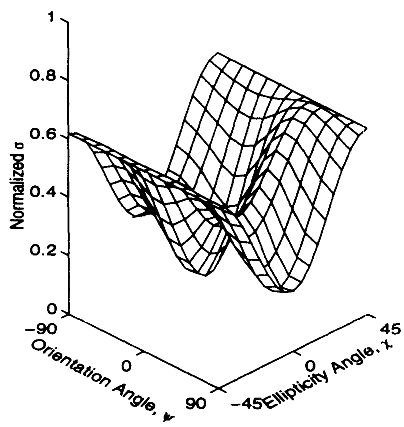
Degree of Polarization:

$$\begin{aligned} m_v &= 0.65 & m_h &= 0.63 \\ m_{45} &= 0.58 & m_{135} &= 0.53 \\ m_{lhc} &= 0.27 & m_{rhc} &= 0.16 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

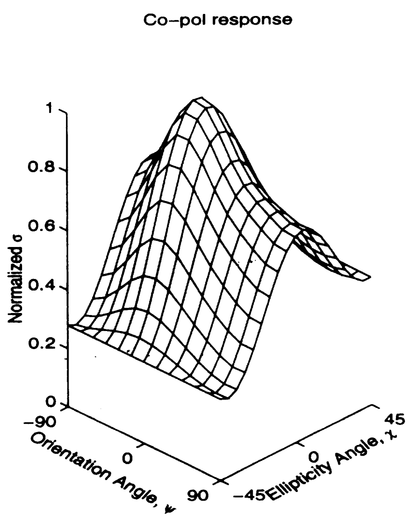
Normalized Mueller Matrix:

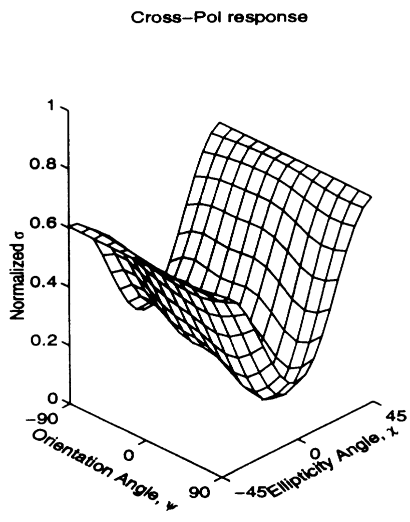
$$\mathbf{L}_m^\circ = 0.0047 \begin{bmatrix} 1.0000 & 0.2094 & -0.0646 & -0.0133 \\ 0.2094 & 0.7553 & -0.0129 & -0.0543 \\ -0.1292 & -0.0259 & 0.7340 & 0.0130 \\ 0.0265 & 0.1086 & -0.0130 & 0.3152 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.31 \text{ dB} & \sigma_{hh} &= -13.53 \text{ dB} \\ \sigma_{vh} &= -19.10 \text{ dB} & & \\ \chi_d &= -6.22 \text{ dB} & & \\ \alpha &= 0.60 & \zeta &= 1.41^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.66 & m_h &= 0.58 \\ m_{45} &= 0.66 & m_{135} &= 0.72 \\ m_{lhc} &= 0.41 & m_{rhc} &= 0.24 \end{aligned}$$





Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

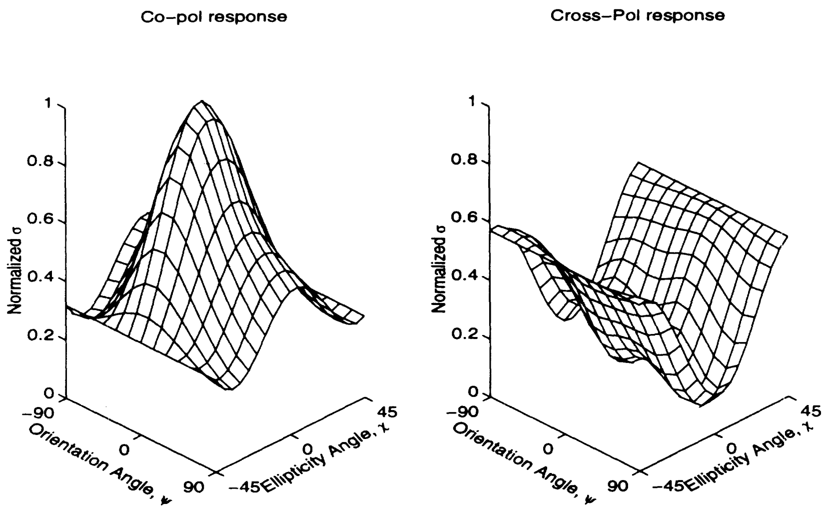
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0027 \begin{bmatrix} 1.0000 & 0.1384 & -0.0715 & 0.0465 \\ 0.1384 & 0.5097 & 0.0220 & -0.0304 \\ -0.1430 & 0.0440 & 0.5475 & 0.0386 \\ -0.0931 & 0.0608 & -0.0386 & 0.2707 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -14.76 \text{ dB} & \sigma_{hh} &= -17.69 \text{ dB} \\ \sigma_{vh} &= -23.35 \text{ dB} & & \\ \chi_d &= -7.37 \text{ dB} & & \\ \alpha &= 0.58 & \zeta &= 5.38^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.77 & m_h &= 0.58 \\ m_{45} &= 0.62 & m_{135} &= 0.73 \\ m_{lhc} &= 0.45 & m_{rhc} &= 0.39 \end{aligned}$$



Target Name: Concrete 1992
System: UM

Target Description: Large sidewalk area, possibly reinforced concrete (i.e. burried iron bars).

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	conc.1.1	65
45	35	dry	conc.1.2	66
70	35	dry	conc.1.3	67

References:
None

Target: Concrete 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

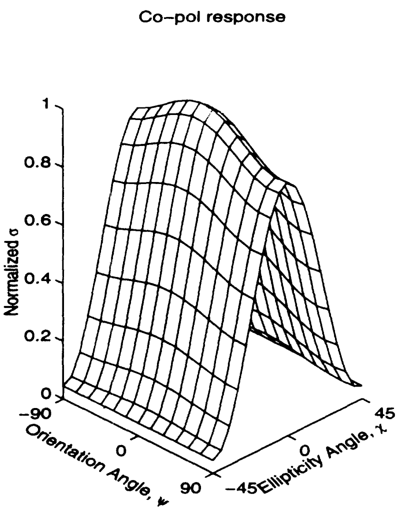
Normalized Mueller Matrix:

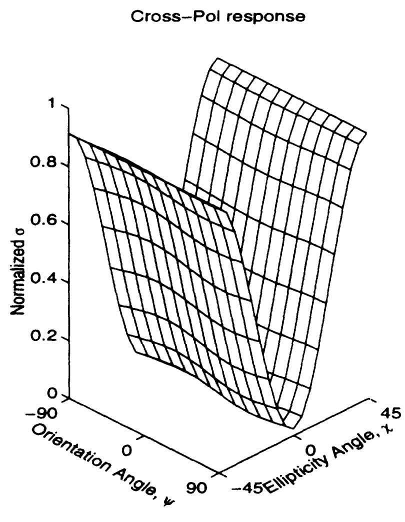
$$\mathbf{L}_m^\circ = 0.0025 \begin{bmatrix} 1.0000 & 0.0232 & -0.0082 & -0.0073 \\ 0.0232 & 0.8779 & -0.0104 & 0.0072 \\ -0.0164 & -0.0208 & 0.9192 & 0.0225 \\ 0.0147 & -0.0144 & -0.0225 & 0.8729 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -15.09 \text{ dB} & \sigma_{hh} &= -15.66 \text{ dB} \\ \sigma_{vh} &= -31.45 \text{ dB} & & \\ \chi_d &= -16.08 \text{ dB} & & \\ \alpha &= 0.96 & \zeta &= 1.44° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.95 \\ m_{45} &= 0.96 & m_{135} &= 0.96 \\ m_{lhc} &= 0.91 & m_{rhc} &= 0.91 \end{aligned}$$





Target: Concrete 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

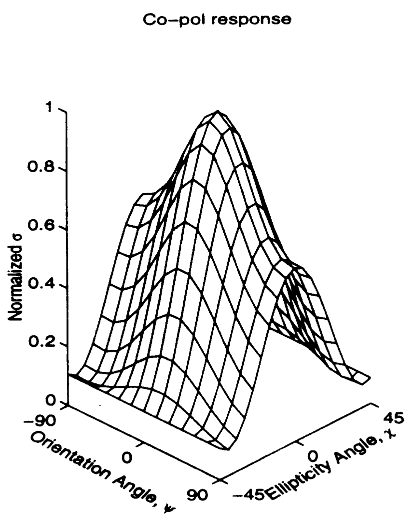
Normalized Mueller Matrix:

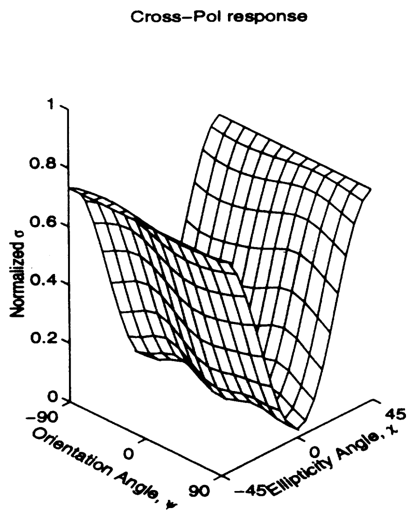
$$\mathbf{L}_m^\circ = 0.0026 \begin{bmatrix} 1.0000 & 0.0282 & 0.0029 & 0.0151 \\ 0.0282 & 0.5922 & -0.0063 & -0.0072 \\ 0.0057 & -0.0126 & 0.6872 & 0.0898 \\ -0.0301 & 0.0145 & -0.0898 & 0.6307 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -14.81 \text{ dB} & \sigma_{hh} &= -17.09 \text{ dB} \\ \sigma_{vh} &= -30.30 \text{ dB} & & \\ \chi_d &= -14.50 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= 7.76^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.91 \\ m_{45} &= 0.88 & m_{135} &= 0.87 \\ m_{lhc} &= 0.80 & m_{rhc} &= 0.82 \end{aligned}$$





Target: Concrete 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

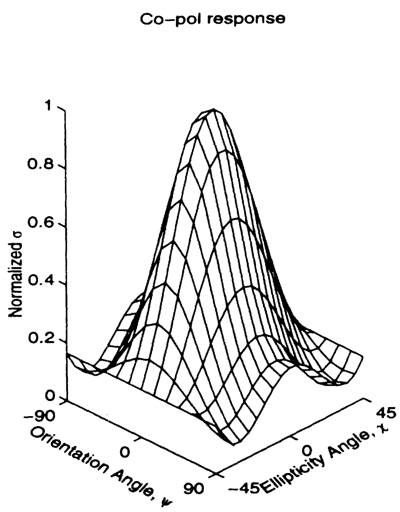
Normalized Mueller Matrix:

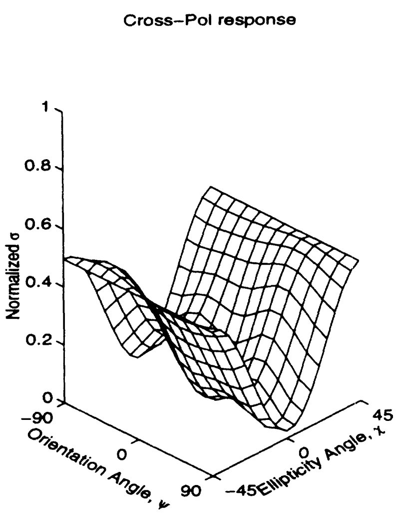
$$\mathbf{L}_m^\circ = 0.0007 \begin{bmatrix} 1.0000 & 0.0257 & -0.0346 & 0.0226 \\ 0.0257 & 0.2352 & -0.0140 & -0.0140 \\ -0.0691 & -0.0280 & 0.3871 & 0.1157 \\ -0.0451 & 0.0279 & -0.1157 & 0.3356 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -20.64 \text{ dB} & \sigma_{hh} &= -26.92 \text{ dB} \\ \sigma_{vh} &= -36.54 \text{ dB} & & \\ \chi_d &= -13.81 \text{ dB} & & \\ \alpha &= 0.78 & \zeta &= 17.75^\circ \end{aligned}$$

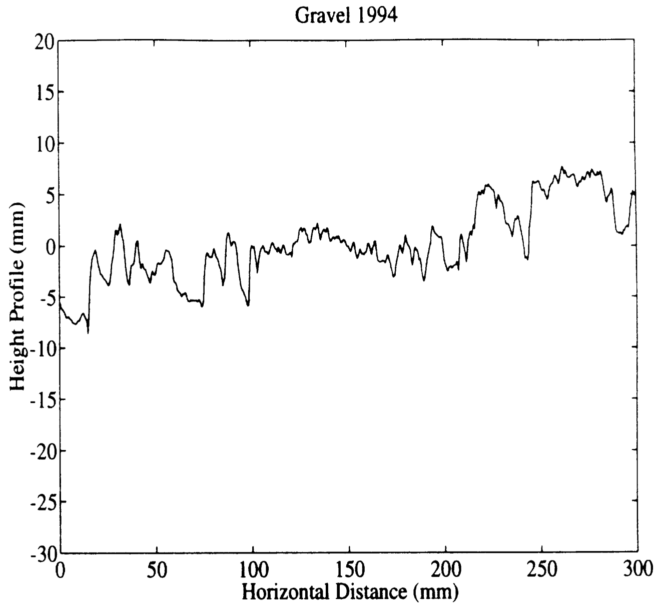
Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.82 \\ m_{45} &= 0.86 & m_{135} &= 0.87 \\ m_{lhc} &= 0.82 & m_{rhc} &= 0.81 \end{aligned}$$





Target Name: Gravel 1994
System: UM



Target Description: Measurement was of a dry gravel parking lot. Gravel stones were thumb sized mixed in with a fair amount of porous white clay. Consistency of soil and surface was much like that of a dirt road.

Ground Truth:
rms height = 2.56 mm
correlation length = 37.5 mm

frequency	ks	kl
35 GHz	1.88	27.5

Data List:

θ_i	freq.	data no.	page no.
20	35	grav.1.1	69
30	35	grav.1.2	70
45	35	grav.1.3	71
60	35	grav.1.4	72

References:
None

Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

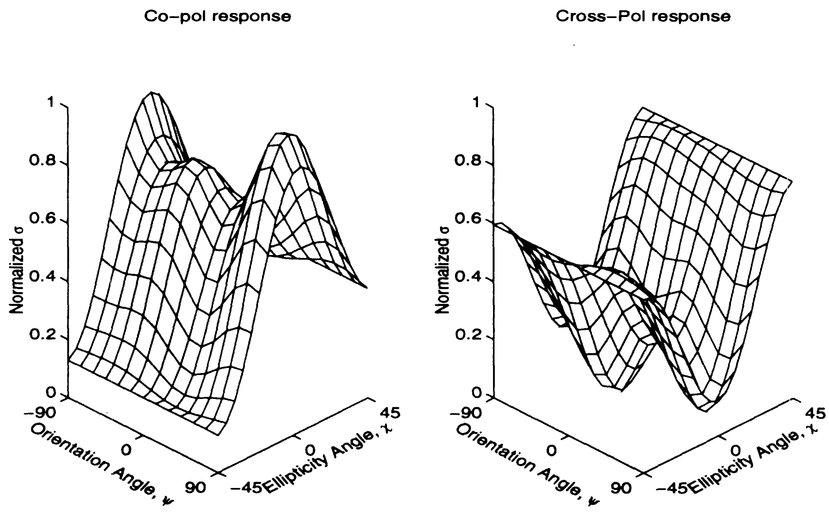
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0193 \begin{bmatrix} 1.0000 & 0.1670 & -0.0717 & -0.0429 \\ 0.1670 & 1.2641 & 0.1222 & -0.0968 \\ -0.1433 & 0.2445 & 0.9211 & -0.2237 \\ 0.0858 & 0.1937 & 0.2237 & 0.5871 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.15 \text{ dB} & \sigma_{hh} &= -5.13 \text{ dB} \\ \sigma_{vh} &= -13.92 \text{ dB} & & \\ \chi_d &= -8.31 \text{ dB} & & \\ \alpha &= 0.70 & \zeta &= -16.52^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.73 & m_h &= 0.80 \\ m_{45} &= 0.81 & m_{135} &= 0.70 \\ m_{lhc} &= 0.65 & m_{rhc} &= 0.39 \end{aligned}$$



Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 100

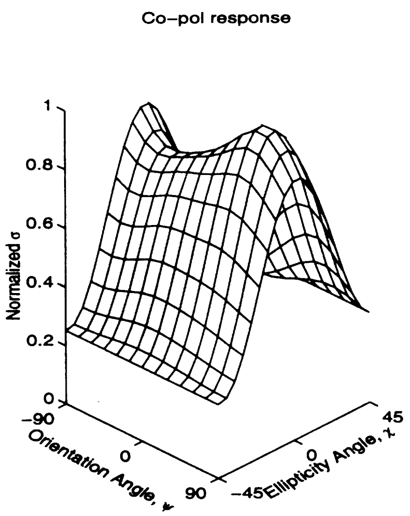
Normalized Mueller Matrix:

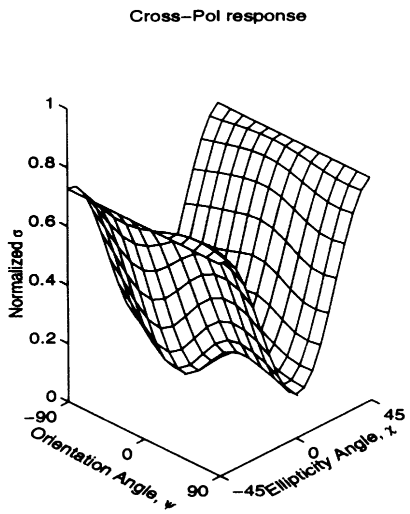
$$\mathbf{L}_m^\circ = 0.0128 \begin{bmatrix} 1.0000 & 0.1721 & 0.0319 & 0.0204 \\ 0.1721 & 1.0171 & 0.0604 & -0.0465 \\ 0.0637 & 0.1209 & 0.8789 & -0.1248 \\ -0.0408 & 0.0930 & 0.1248 & 0.5347 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -7.94 \text{ dB} & \sigma_{hh} &= -7.87 \text{ dB} \\ \sigma_{vh} &= -15.58 \text{ dB} & & \\ \chi_d &= -7.68 \text{ dB} & & \\ \alpha &= 0.71 & \zeta &= -10.02^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.71 & m_h &= 0.72 \\ m_{45} &= 0.77 & m_{135} &= 0.73 \\ m_{lhc} &= 0.49 & m_{rhc} &= 0.46 \end{aligned}$$





Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

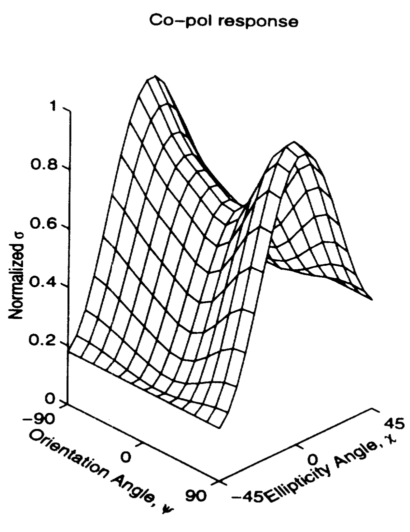
Normalized Mueller Matrix:

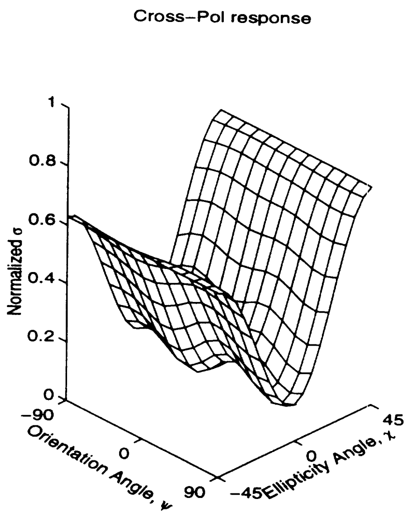
$$\mathbf{L}_m^{\circ} = 0.0080 \begin{bmatrix} 1.0000 & 0.1797 & -0.0275 & -0.0450 \\ 0.1797 & 1.4149 & 0.0532 & -0.0647 \\ -0.0549 & 0.1063 & 0.9516 & -0.0669 \\ 0.0899 & 0.1294 & 0.0669 & 0.5922 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.00 \text{ dB} & \sigma_{hh} &= -8.49 \text{ dB} \\ \sigma_{vh} &= -17.46 \text{ dB} & & \\ \chi_d &= -8.27 \text{ dB} & & \\ \alpha &= 0.65 & \zeta &= -4.96^{\circ} \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.70 & m_h &= 0.78 \\ m_{45} &= 0.73 & m_{135} &= 0.69 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.36 \end{aligned}$$





Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

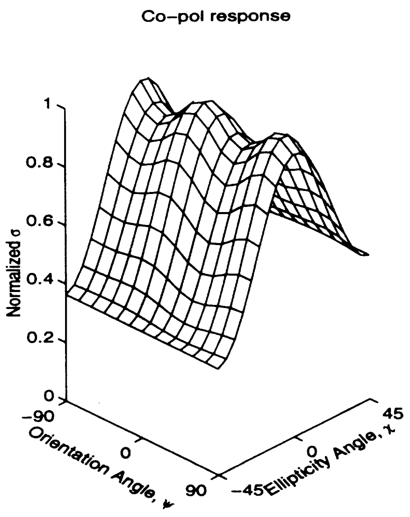
Normalized Mueller Matrix:

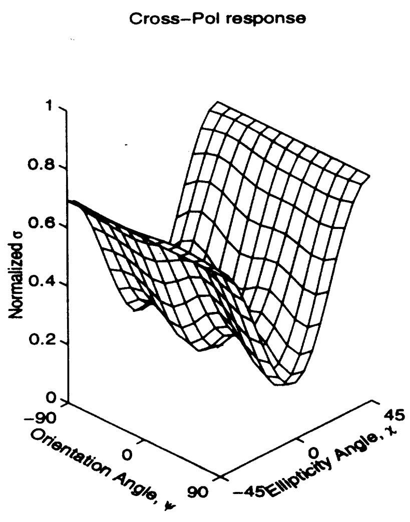
$$\mathbf{L}_m^\circ = 0.0051 \begin{bmatrix} 1.0000 & 0.1986 & -0.0378 & -0.0315 \\ 0.1986 & 0.9966 & 0.0425 & -0.0215 \\ -0.0756 & 0.0849 & 0.7105 & -0.0596 \\ 0.0630 & 0.0429 & 0.0596 & 0.3133 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -11.89 \text{ dB} & \sigma_{hh} &= -11.91 \text{ dB} \\ \sigma_{vh} &= -18.91 \text{ dB} & & \\ \chi_d &= -7.01 \text{ dB} & & \\ \alpha &= 0.52 & \zeta &= -6.64° \end{aligned}$$

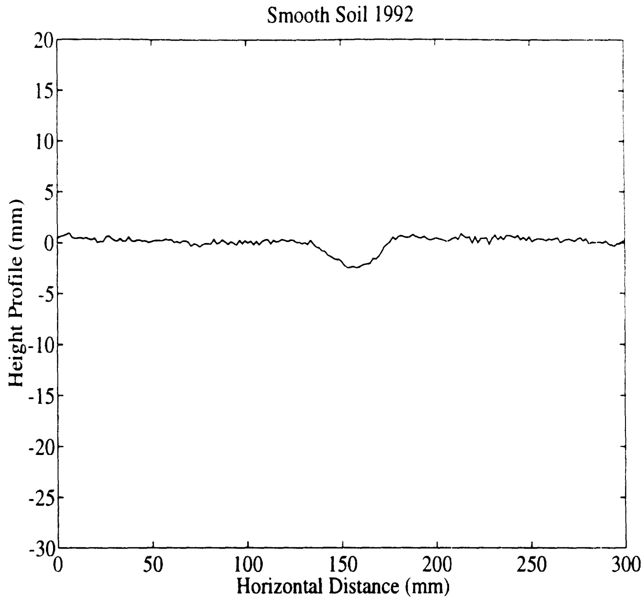
Degree of Polarization:

$$\begin{aligned} m_v &= 0.67 & m_h &= 0.67 \\ m_{45} &= 0.61 & m_{135} &= 0.60 \\ m_{lhc} &= 0.32 & m_{rhc} &= 0.21 \end{aligned}$$





Target Name: Smooth Soil 1992
System: UM



Target Description: Soil surface was initially cleared from grass, vegetation debris and large stones. A heavy roller was then moved across the surface to create a compact, very smooth soil surface. Soil moisture was introduced by continuously saturating the soil with a fine mist tree sprayer. See [1] for detailed soil analysis.

Ground Truth:
rms height = 0.66 mm
correlation length = 27 mm
bulk soil density = 1.69 g/cm^3
air-voids volume fraction = 0.36

frequency	ks	kl
35 GHz	0.48	19.8
94 GHz	1.3	53.2

soil moisture	m_v 0-1 cm	2-3 cm
dry	0.02	0.08
wet	0.23	0.19

References:

[1] Nashashibi, Ulaby and Sarabandi, "Measurement and Modelling Millimeter-Wave Response from Soil Surfaces," UM Technical Report 029721-2-T, 1993.

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	soil.1.1	75
45	35	dry	soil.1.2	76
70	35	dry	soil.1.3	77
20	35	wet	soil.1.4	78
45	35	wet	soil.1.5	79
70	35	wet	soil.1.6	80
20	94	dry	soil.1.7	81
45	94	dry	soil.1.8	82
70	94	dry	soil.1.9	83
20	94	wet	soil.1.10	84
45	94	wet	soil.1.11	85
70	94	wet	soil.1.12	86

Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

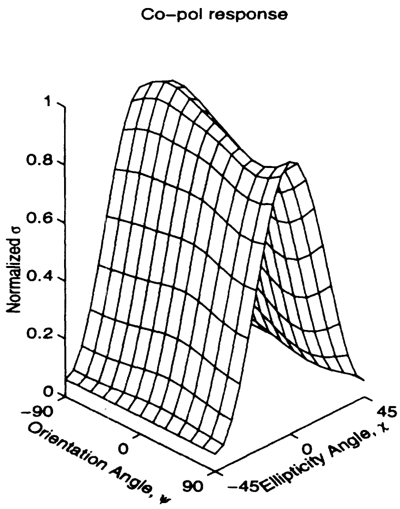
Normalized Mueller Matrix:

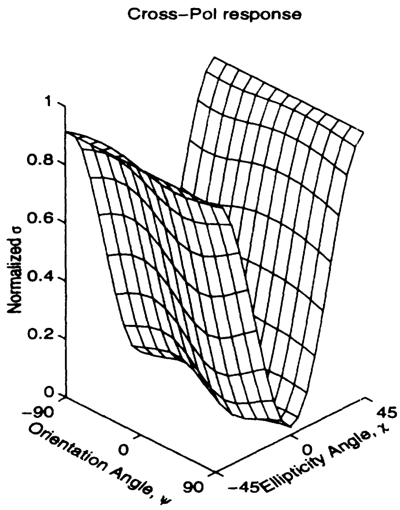
$$\mathbf{L}_m^\circ = 0.0017 \begin{bmatrix} 1.0000 & 0.0296 & -0.0160 & 0.0204 \\ 0.0296 & 0.9917 & -0.0344 & -0.0185 \\ -0.0320 & -0.0688 & 0.9632 & 0.0926 \\ -0.0409 & 0.0370 & -0.0926 & 0.9039 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -16.72 \text{ dB} & \sigma_{hh} &= -16.76 \text{ dB} \\ \sigma_{vh} &= -32.00 \text{ dB} \\ \chi_d &= -15.26 \text{ dB} \\ \alpha &= 0.94 & \zeta &= 5.67^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.94 & m_h &= 0.95 \\ m_{45} &= 0.94 & m_{135} &= 0.95 \\ m_{lhc} &= 0.88 & m_{rhc} &= 0.90 \end{aligned}$$





Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

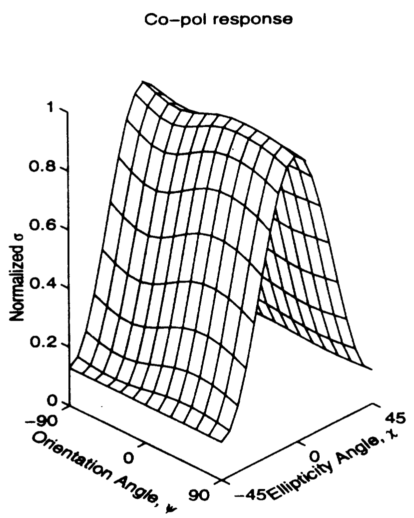
Normalized Mueller Matrix:

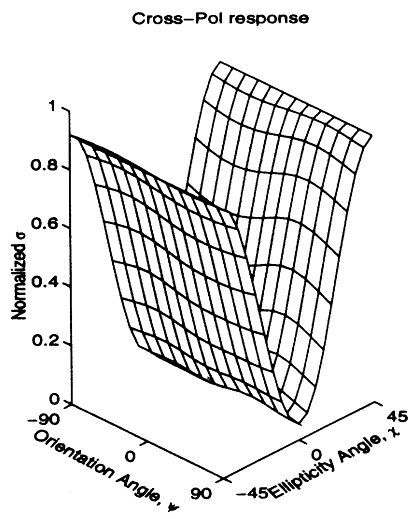
$$\mathbf{L}_m^\circ = 0.0006 \begin{bmatrix} 1.0000 & 0.0554 & 0.0109 & 0.0061 \\ 0.0554 & 0.9862 & 0.0126 & 0.0000 \\ 0.0219 & 0.0251 & 0.9132 & 0.0645 \\ -0.0122 & -0.0000 & -0.0645 & 0.8024 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -21.22 \text{ dB} & \sigma_{hh} &= -21.28 \text{ dB} \\ \sigma_{vh} &= -33.78 \text{ dB} & & \\ \chi_d &= -12.53 \text{ dB} & & \\ \alpha &= 0.87 & \zeta &= 4.30^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.90 & m_h &= 0.89 \\ m_{45} &= 0.88 & m_{135} &= 0.87 \\ m_{lhc} &= 0.76 & m_{rhc} &= 0.78 \end{aligned}$$





Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

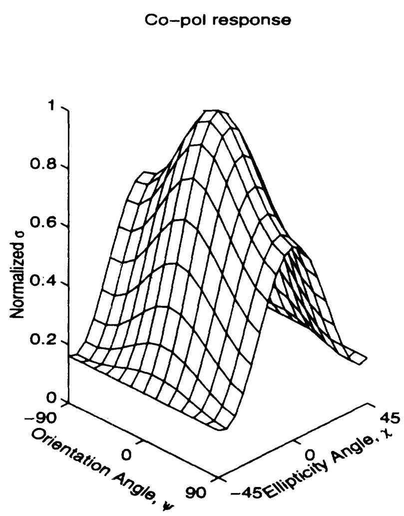
Normalized Mueller Matrix:

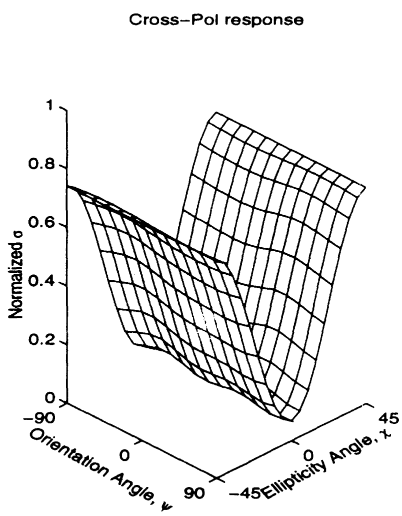
$$\mathbf{L}_m^\circ = 0.0002 \begin{bmatrix} 1.0000 & 0.0681 & -0.0060 & 0.0011 \\ 0.0681 & 0.6608 & 0.0044 & 0.0016 \\ -0.0122 & 0.0087 & 0.7176 & 0.0410 \\ -0.0023 & -0.0032 & -0.0410 & 0.5814 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -27.09 \text{ dB} & \sigma_{hh} &= -28.89 \text{ dB} \\ \sigma_{vh} &= -38.76 \text{ dB} & & \\ \chi_d &= -10.86 \text{ dB} & & \\ \alpha &= 0.80 & \zeta &= 3.61^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.81 \\ m_{45} &= 0.82 & m_{135} &= 0.82 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.68 \end{aligned}$$





Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

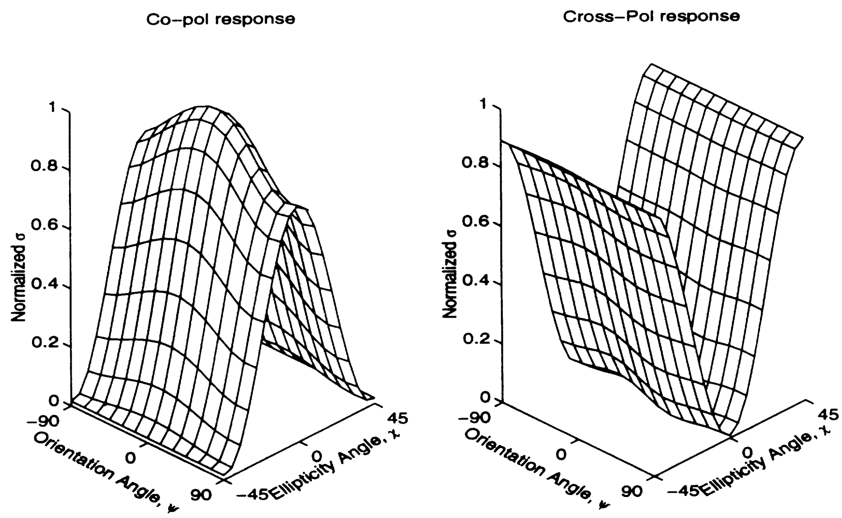
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0064 \begin{bmatrix} 1.0000 & 0.0087 & -0.0064 & -0.0047 \\ 0.0087 & 0.8042 & -0.0207 & 0.0037 \\ -0.0128 & -0.0415 & 0.8934 & 0.0179 \\ 0.0094 & -0.0073 & -0.0179 & 0.8760 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.95 \text{ dB} & \sigma_{hh} &= -11.90 \text{ dB} \\ \sigma_{vh} &= -31.55 \text{ dB} & & \\ \chi_d &= -20.15 \text{ dB} & & \\ \alpha &= 0.99 & \zeta &= 1.16^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.98 & m_h &= 0.98 \\ m_{45} &= 0.99 & m_{135} &= 0.99 \\ m_{lhc} &= 0.97 & m_{rhc} &= 0.97 \end{aligned}$$



Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

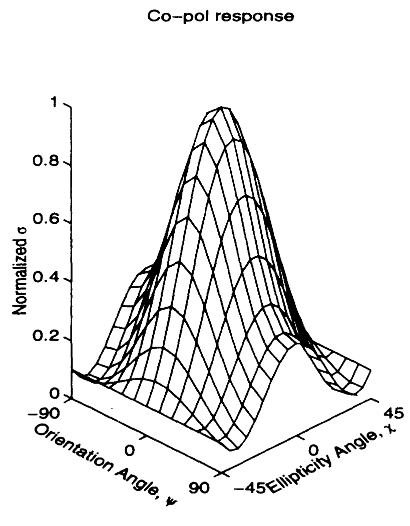
Normalized Mueller Matrix:

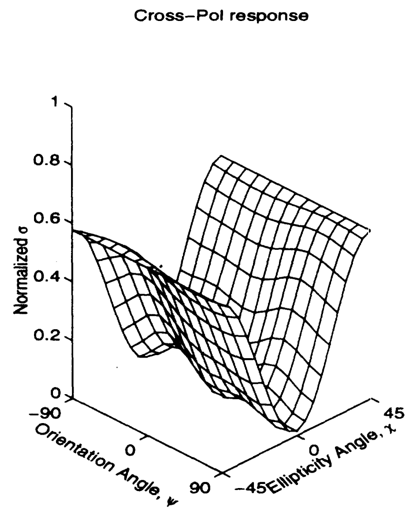
$$\mathbf{L}_m^\circ = 0.0018 \begin{bmatrix} 1.0000 & 0.0154 & -0.0198 & -0.0064 \\ 0.0154 & 0.3197 & -0.0101 & 0.0077 \\ -0.0396 & -0.0202 & 0.5074 & 0.0868 \\ 0.0127 & -0.0153 & -0.0868 & 0.4765 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -16.35 \text{ dB} & \sigma_{hh} &= -21.30 \text{ dB} \\ \sigma_{vh} &= -34.47 \text{ dB} \\ \chi_d &= -16.32 \text{ dB} \\ \alpha &= 0.88 & \zeta &= 10.00° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.97 & m_h &= 0.91 \\ m_{45} &= 0.91 & m_{135} &= 0.92 \\ m_{lhc} &= 0.86 & m_{rhc} &= 0.90 \end{aligned}$$





Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

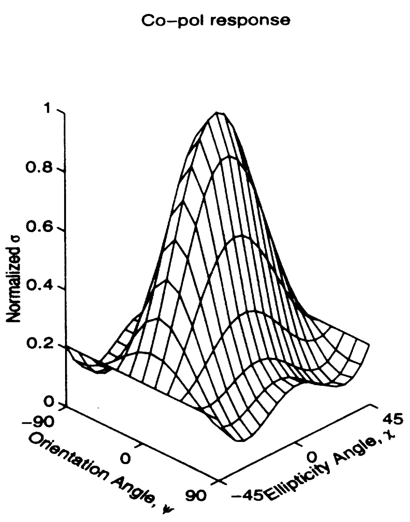
Normalized Mueller Matrix:

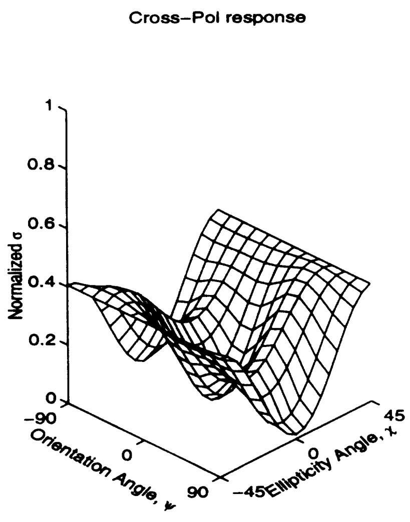
$$\mathbf{L}_m^\circ = 0.0005 \begin{bmatrix} 1.0000 & 0.0151 & -0.0243 & 0.0115 \\ 0.0151 & 0.1917 & -0.0013 & -0.0097 \\ -0.0487 & -0.0026 & 0.2286 & 0.1019 \\ -0.0229 & 0.0195 & -0.1019 & 0.1984 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -22.02 \text{ dB} & \sigma_{hh} &= -29.20 \text{ dB} \\ \sigma_{vh} &= -40.23 \text{ dB} & & \\ \chi_d &= -15.96 \text{ dB} & & \\ \alpha &= 0.54 & \zeta &= 25.52^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.97 & m_h &= 0.86 \\ m_{45} &= 0.76 & m_{135} &= 0.80 \\ m_{lhc} &= 0.77 & m_{rhc} &= 0.74 \end{aligned}$$





Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

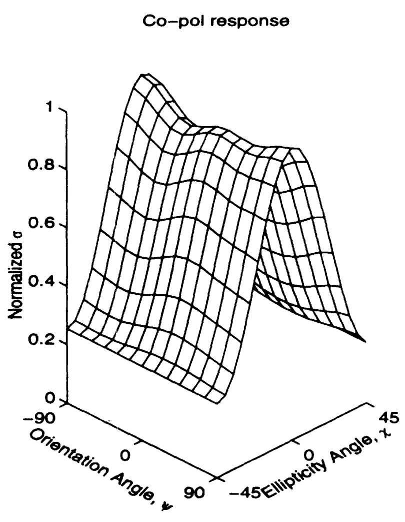
Normalized Mueller Matrix:

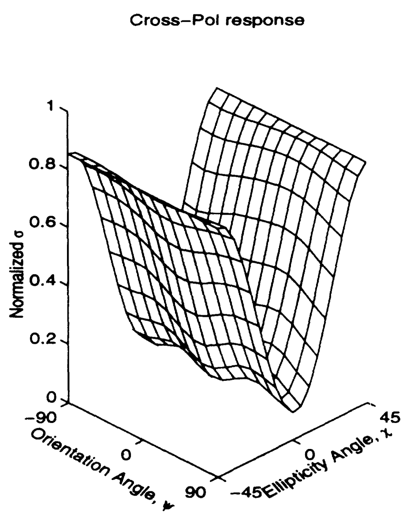
$$\mathbf{L}_m^\circ = 0.0090 \begin{bmatrix} 1.0000 & 0.0990 & 0.0143 & 0.0397 \\ 0.0990 & 1.0547 & -0.0009 & -0.0194 \\ 0.0286 & -0.0018 & 0.8384 & 0.0436 \\ -0.0793 & 0.0388 & -0.0436 & 0.6404 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.47 \text{ dB} & \sigma_{hh} &= -9.24 \text{ dB} \\ \sigma_{vh} &= -19.52 \text{ dB} & & \\ \chi_d &= -10.16 \text{ dB} & & \\ \alpha &= 0.72 & \zeta &= 3.37^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.83 \\ m_{45} &= 0.75 & m_{135} &= 0.74 \\ m_{lhc} &= 0.54 & m_{rhc} &= 0.60 \end{aligned}$$





Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

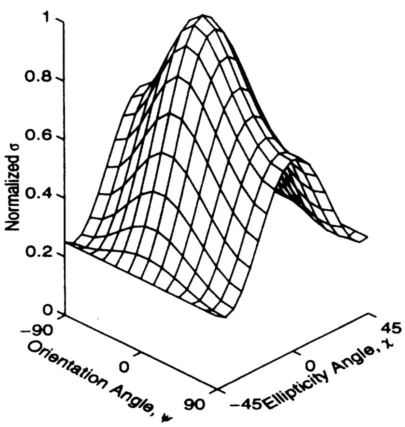
$$\mathbf{L}_m^\circ = 0.0067 \begin{bmatrix} 1.0000 & 0.1284 & -0.0418 & 0.0160 \\ 0.1284 & 0.6697 & -0.0112 & -0.0201 \\ -0.0836 & -0.0225 & 0.6956 & 0.0491 \\ -0.0320 & 0.0402 & -0.0491 & 0.4388 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.75 \text{ dB} & \sigma_{hh} &= -12.49 \text{ dB} \\ \sigma_{vh} &= -19.67 \text{ dB} & & \\ \chi_d &= -8.13 \text{ dB} & & \\ \alpha &= 0.70 & \zeta &= 4.95^\circ \end{aligned}$$

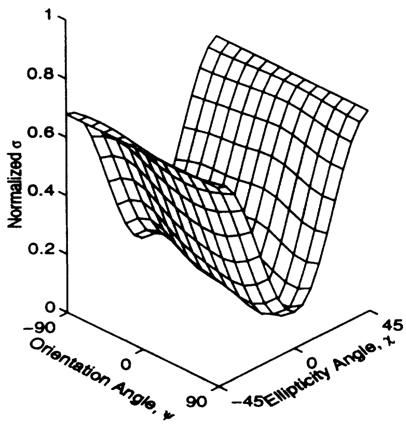
Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.68 \\ m_{45} &= 0.72 & m_{135} &= 0.76 \\ m_{lhc} &= 0.51 & m_{rhc} &= 0.48 \end{aligned}$$

Co–pol response



Cross–Pol response



Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

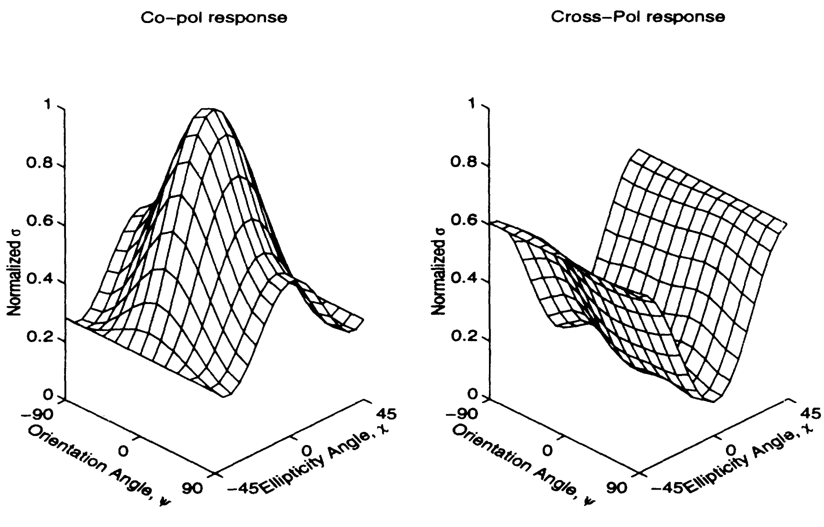
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0013 \begin{bmatrix} 1.0000 & 0.1170 & -0.0192 & 0.0150 \\ 0.1170 & 0.5317 & -0.0087 & -0.0115 \\ -0.0384 & -0.0174 & 0.5603 & 0.0644 \\ -0.0300 & 0.0230 & -0.0644 & 0.3262 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -17.77 \text{ dB} & \sigma_{hh} &= -20.51 \text{ dB} \\ \sigma_{vh} &= -27.09 \text{ dB} & & \\ \chi_d &= -8.16 \text{ dB} & & \\ \alpha &= 0.61 & \zeta &= 8.26^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.79 & m_h &= 0.64 \\ m_{45} &= 0.68 & m_{135} &= 0.70 \\ m_{lhc} &= 0.47 & m_{rhc} &= 0.46 \end{aligned}$$



Target: Smooth Soil 1992(wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

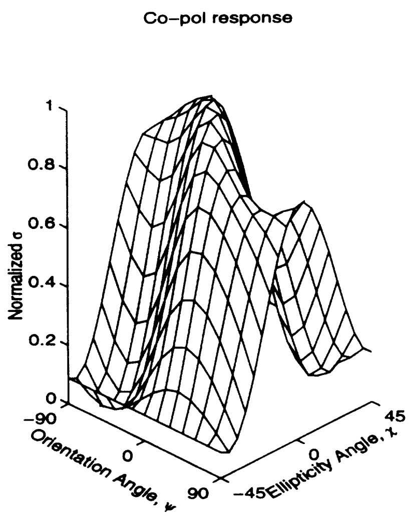
Normalized Mueller Matrix:

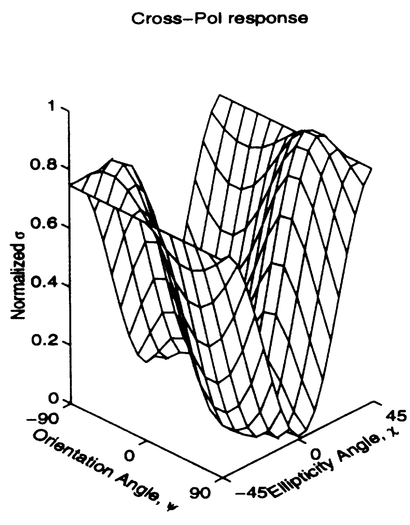
$$\mathbf{L}_m^\circ = 0.0159 \begin{bmatrix} 1.0000 & 0.0108 & -0.0370 & 0.0332 \\ 0.0108 & 0.8013 & -0.0141 & -0.0665 \\ -0.0739 & -0.0282 & 0.6726 & 0.5296 \\ -0.0664 & 0.1330 & -0.5296 & 0.6510 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.98 \text{ dB} & \sigma_{hh} &= -7.94 \text{ dB} \\ \sigma_{vh} &= -26.64 \text{ dB} & & \\ \chi_d &= -19.21 \text{ dB} & & \\ \alpha &= 0.95 & \zeta &= 38.67° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.98 & m_h &= 0.99 \\ m_{45} &= 0.93 & m_{135} &= 0.96 \\ m_{lhc} &= 0.98 & m_{rhc} &= 0.90 \end{aligned}$$





Target: Smooth Soil 1992(wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

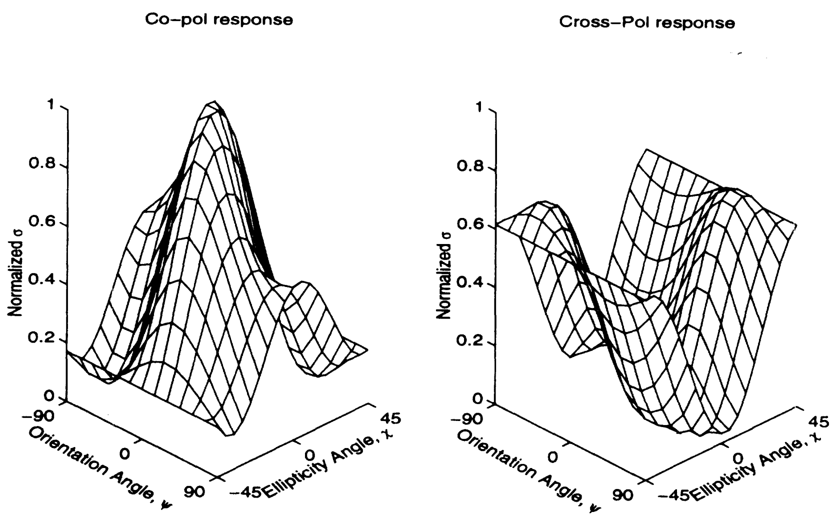
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0031 \begin{bmatrix} 1.0000 & 0.0343 & -0.0492 & 0.0461 \\ 0.0343 & 0.5232 & -0.0114 & -0.0504 \\ -0.0983 & -0.0227 & 0.5106 & 0.4184 \\ -0.0922 & 0.1007 & -0.4184 & 0.4420 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -14.10 \text{ dB} & \sigma_{hh} &= -16.92 \text{ dB} \\ \sigma_{vh} &= -28.75 \text{ dB} & & \\ \chi_d &= -13.47 \text{ dB} & & \\ \alpha &= 0.88 & \zeta &= 41.30^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.94 & m_h &= 0.90 \\ m_{45} &= 0.88 & m_{135} &= 0.89 \\ m_{lhc} &= 0.84 & m_{rhc} &= 0.83 \end{aligned}$$



Target: Smooth Soil 1992(wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

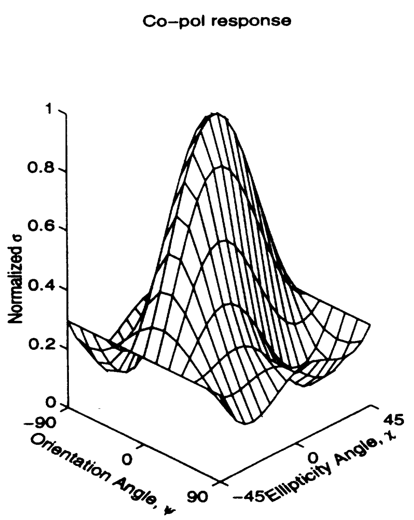
Normalized Mueller Matrix:

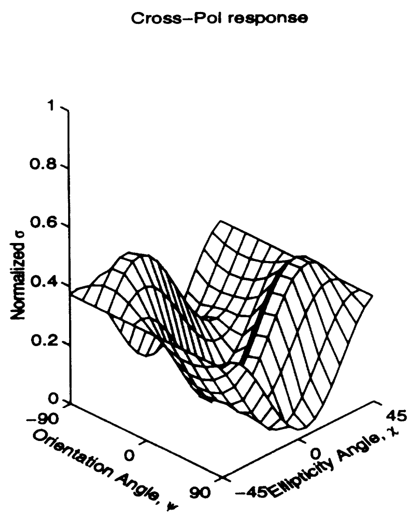
$$\mathbf{L}_m^\circ = 0.0005 \begin{bmatrix} 1.0000 & 0.0319 & -0.0603 & 0.0391 \\ 0.0319 & 0.2429 & 0.0080 & -0.0302 \\ -0.1207 & 0.0160 & 0.1458 & 0.3225 \\ -0.0782 & 0.0604 & -0.3225 & 0.0820 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -22.41 \text{ dB} & \sigma_{hh} &= -28.55 \text{ dB} \\ \sigma_{vh} &= -37.37 \text{ dB} \\ \chi_d &= -12.90 \text{ dB} \\ \alpha &= 0.69 & \zeta &= 70.55° \end{aligned}$$

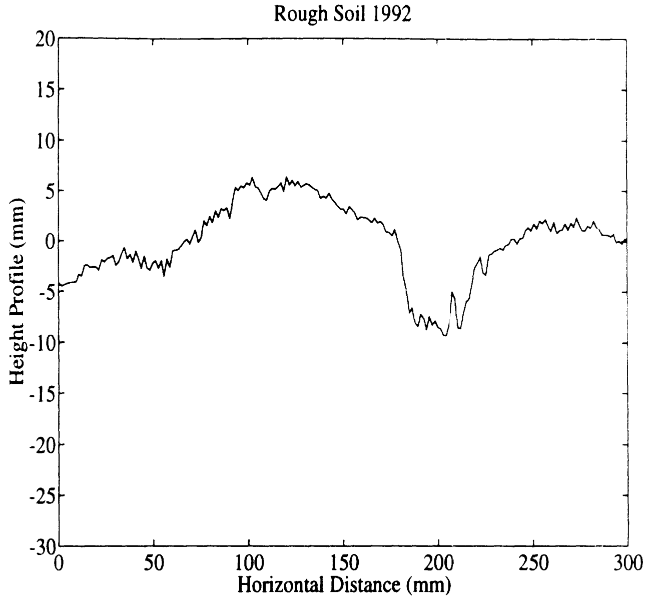
Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.80 \\ m_{45} &= 0.77 & m_{135} &= 0.82 \\ m_{lhc} &= 0.80 & m_{rhc} &= 0.77 \end{aligned}$$





Target Name: Rough Soil 1992
System: UM



Target Description: Soil surface was initially cleared from grass and vegetation debris. The soil had the appearance of a naturally weathered surface. Soil moisture was introduced by continuously saturating the soil with a fine mist tree sprayer. See [1] for detailed soil analysis.

Ground Truth:
rms height = 2.62 mm
correlation length = 30 mm
bulk soil density = 1.37 g/cm^3
air-voids volume fraction = 0.45

frequency	ks	kl
35 GHz	1.92	22.0
94 GHz	5.16	59.1

soil	m_v	
moisture	0-1 cm	2-3 cm
dry	0.04	0.07
wet	0.12	0.12

References:

[1] Nashashibi, Ulaby and Sarabandi, "Measurement and Modelling Millimeter-Wave Response from Soil Surfaces," UM Technical Report 029721-2-T, 1993.

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	soil.2.1	89
45	35	dry	soil.2.2	90
70	35	dry	soil.2.3	91
20	35	wet	soil.2.4	92
45	35	wet	soil.2.5	93
70	35	wet	soil.2.6	94
20	94	dry	soil.2.7	95
45	94	dry	soil.2.8	96
70	94	dry	soil.2.9	97
20	94	wet	soil.2.10	98
45	94	wet	soil.2.11	99
70	94	wet	soil.2.12	100

Target: Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

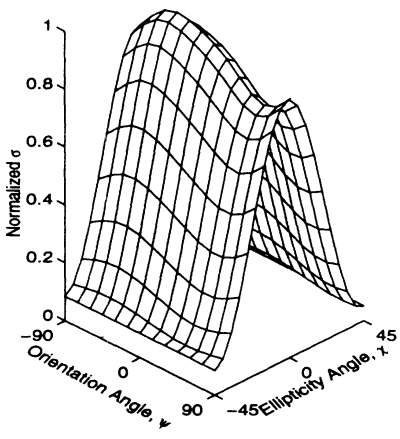
$$\mathbf{L}_m^{\circ} = 0.0037 \begin{bmatrix} 1.0000 & 0.0356 & -0.0206 & -0.0082 \\ 0.0356 & 0.9325 & -0.0440 & 0.0221 \\ -0.0413 & -0.0880 & 0.9305 & -0.0247 \\ 0.0164 & -0.0443 & 0.0247 & 0.8593 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -13.34 \text{ dB} & \sigma_{hh} &= -13.64 \text{ dB} \\ \sigma_{vh} &= -27.83 \text{ dB} & & \\ \chi_d &= -14.34 \text{ dB} & & \\ \alpha &= 0.93 & \zeta &= -1.58^{\circ} \end{aligned}$$

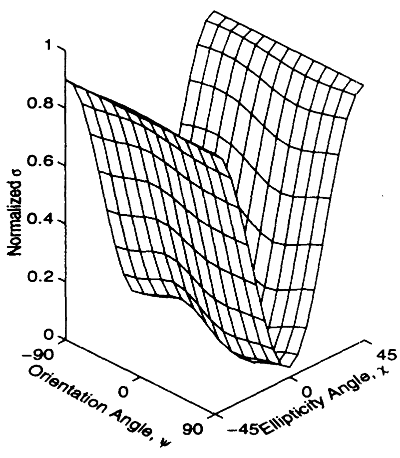
Degree of Polarization:

$$\begin{aligned} m_v &= 0.93 & m_h &= 0.93 \\ m_{45} &= 0.93 & m_{135} &= 0.93 \\ m_{lhc} &= 0.84 & m_{rhc} &= 0.89 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

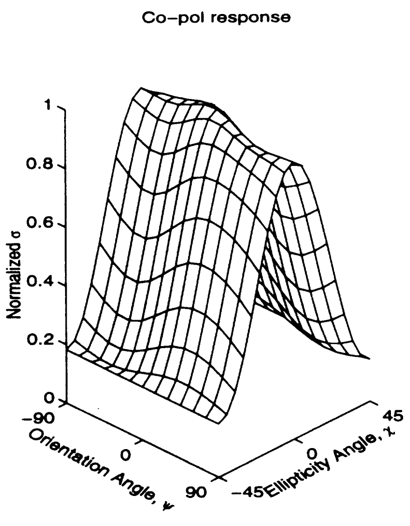
Normalized Mueller Matrix:

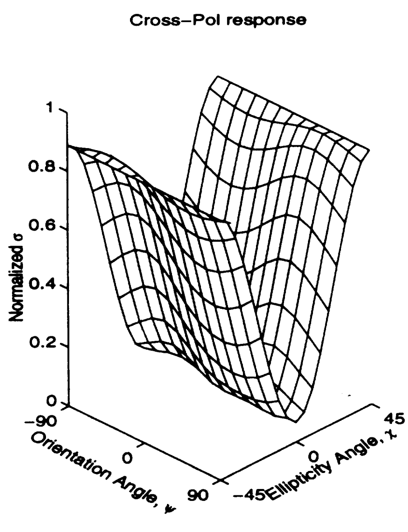
$$\mathbf{L}_m^\circ = 0.0017 \begin{bmatrix} 1.0000 & 0.0676 & -0.0046 & 0.0117 \\ 0.0676 & 0.9463 & -0.0009 & 0.0035 \\ -0.0093 & -0.0017 & 0.8492 & 0.1769 \\ -0.0235 & -0.0070 & -0.1769 & 0.7140 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -16.79 \text{ dB} & \sigma_{hh} &= -17.03 \text{ dB} \\ \sigma_{vh} &= -28.49 \text{ dB} & & \\ \chi_d &= -11.58 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= 12.75° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.87 \\ m_{45} &= 0.84 & m_{135} &= 0.83 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.73 \end{aligned}$$





Target: Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

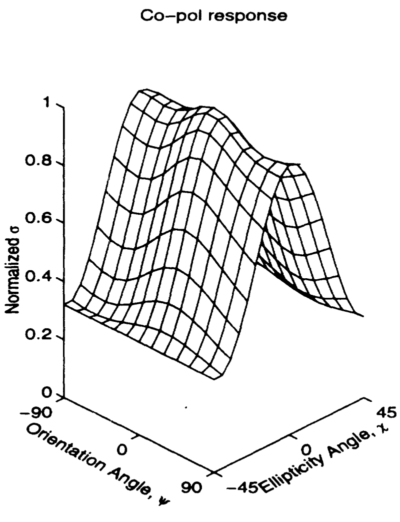
Normalized Mueller Matrix:

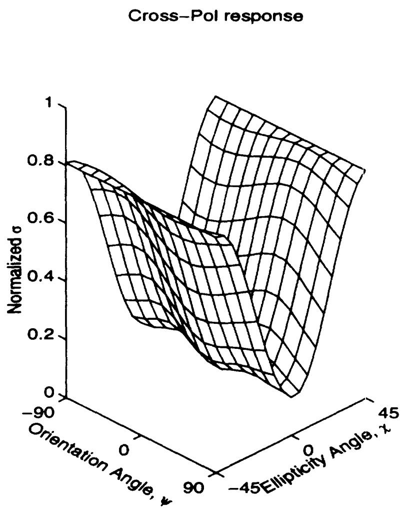
$$\mathbf{L}_m^\circ = 0.0010 \begin{bmatrix} 1.0000 & 0.1305 & 0.0037 & 0.0379 \\ 0.1305 & 0.9291 & -0.0033 & -0.0212 \\ 0.0074 & -0.0066 & 0.7572 & 0.1162 \\ -0.0757 & 0.0424 & -0.1162 & 0.4962 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -18.84 \text{ dB} & \sigma_{hh} &= -19.16 \text{ dB} \\ \sigma_{vh} &= -27.69 \text{ dB} & & \\ \chi_d &= -8.69 \text{ dB} & & \\ \alpha &= 0.66 & \zeta &= 10.51^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.77 & m_h &= 0.75 \\ m_{45} &= 0.70 & m_{135} &= 0.70 \\ m_{lhc} &= 0.45 & m_{rhc} &= 0.49 \end{aligned}$$





Target: Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

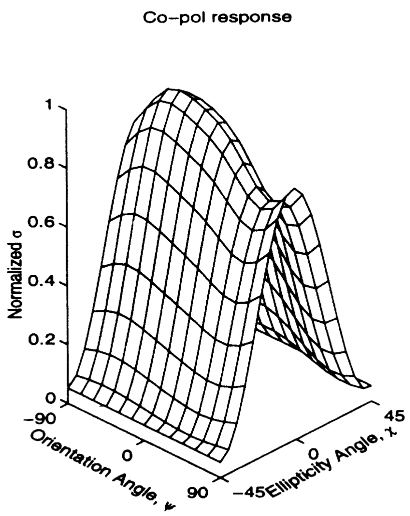
Normalized Mueller Matrix:

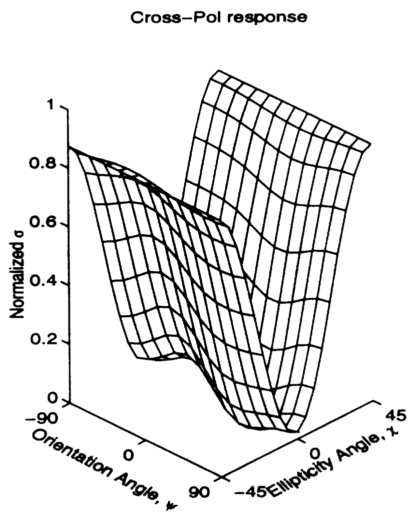
$$\mathbf{L}_m^\circ = 0.0179 \begin{bmatrix} 1.0000 & 0.0248 & -0.0237 & -0.0276 \\ 0.0248 & 0.8973 & -0.0612 & 0.0277 \\ -0.0474 & -0.1224 & 0.9135 & 0.0269 \\ 0.0551 & -0.0555 & -0.0269 & 0.8638 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.48 \text{ dB} & \sigma_{hh} &= -6.95 \text{ dB} \\ \sigma_{vh} &= -22.53 \text{ dB} & & \\ \chi_d &= -15.82 \text{ dB} & & \\ \alpha &= 0.94 & \zeta &= 1.74^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.95 & m_h &= 0.96 \\ m_{45} &= 0.94 & m_{135} &= 0.94 \\ m_{lhc} &= 0.89 & m_{rhc} &= 0.90 \end{aligned}$$





Target: Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

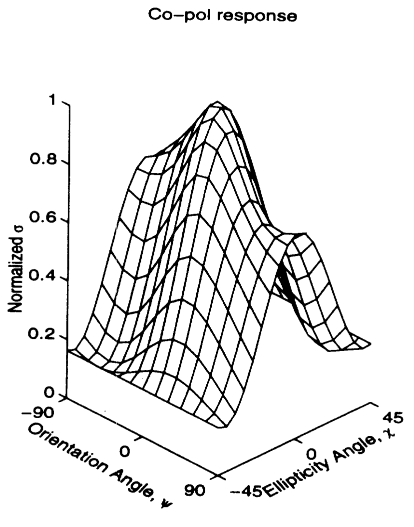
Normalized Mueller Matrix:

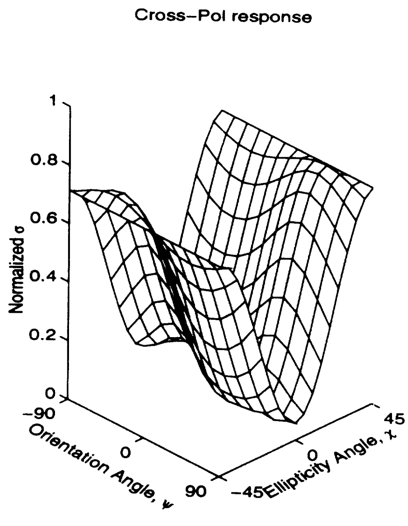
$$\mathbf{L}_m^\circ = 0.0068 \begin{bmatrix} 1.0000 & 0.0567 & -0.0154 & 0.0009 \\ 0.0567 & 0.7003 & -0.0190 & -0.0163 \\ -0.0309 & -0.0379 & 0.6580 & 0.2775 \\ -0.0018 & 0.0325 & -0.2775 & 0.5445 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.68 \text{ dB} & \sigma_{hh} &= -12.22 \text{ dB} \\ \sigma_{vh} &= -23.14 \text{ dB} \\ \chi_d &= -11.76 \text{ dB} \\ \alpha &= 0.79 & \zeta &= 24.78^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.89 & m_h &= 0.85 \\ m_{45} &= 0.79 & m_{135} &= 0.81 \\ m_{lhc} &= 0.71 & m_{rhc} &= 0.68 \end{aligned}$$





Target: Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

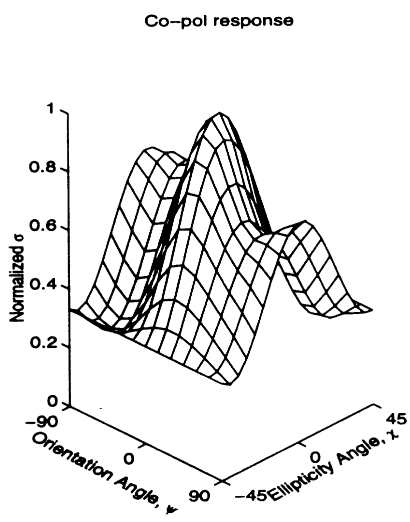
Normalized Mueller Matrix:

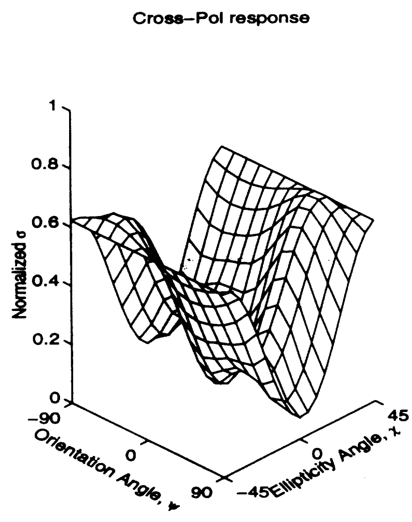
$$\mathbf{L}_m^\circ = 0.0014 \begin{bmatrix} 1.0000 & 0.0735 & -0.0106 & 0.0296 \\ 0.0735 & 0.7441 & -0.0055 & -0.0257 \\ -0.0213 & -0.0109 & 0.4413 & 0.2569 \\ -0.0592 & 0.0514 & -0.2569 & 0.2943 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -17.64 \text{ dB} & \sigma_{hh} &= -18.92 \text{ dB} \\ \sigma_{vh} &= -28.97 \text{ dB} & & \\ \chi_d &= -10.74 \text{ dB} & & \\ \alpha &= 0.52 & \zeta &= 34.93^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.82 \\ m_{45} &= 0.55 & m_{135} &= 0.56 \\ m_{lhc} &= 0.44 & m_{rhc} &= 0.44 \end{aligned}$$





Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

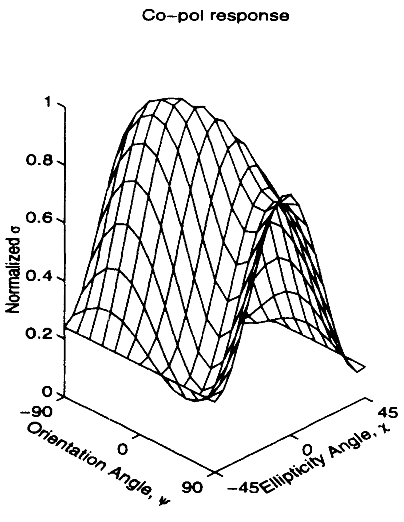
Normalized Mueller Matrix:

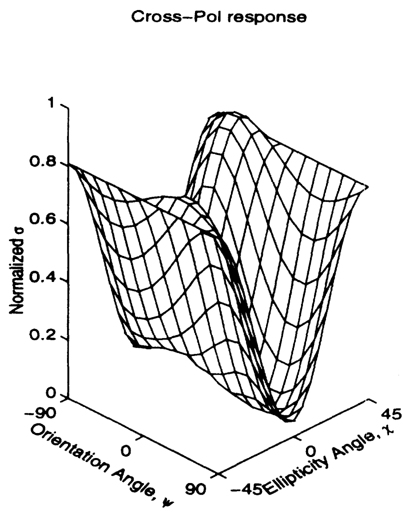
$$\mathbf{L}_m^{\circ} = 0.0161 \begin{bmatrix} 1.0000 & 0.0555 & -0.0432 & -0.0144 \\ 0.0555 & 0.8659 & -0.0392 & 0.0700 \\ -0.0863 & -0.0784 & 0.7353 & -0.4164 \\ 0.0287 & -0.1400 & 0.4164 & 0.6243 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.95 \text{ dB} & \sigma_{hh} &= -7.57 \text{ dB} \\ \sigma_{vh} &= -19.50 \text{ dB} & & \\ \chi_d &= -12.26 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= -31.49^{\circ} \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.90 & m_h &= 0.90 \\ m_{45} &= 0.83 & m_{135} &= 0.88 \\ m_{lhc} &= 0.72 & m_{rhc} &= 0.83 \end{aligned}$$





Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

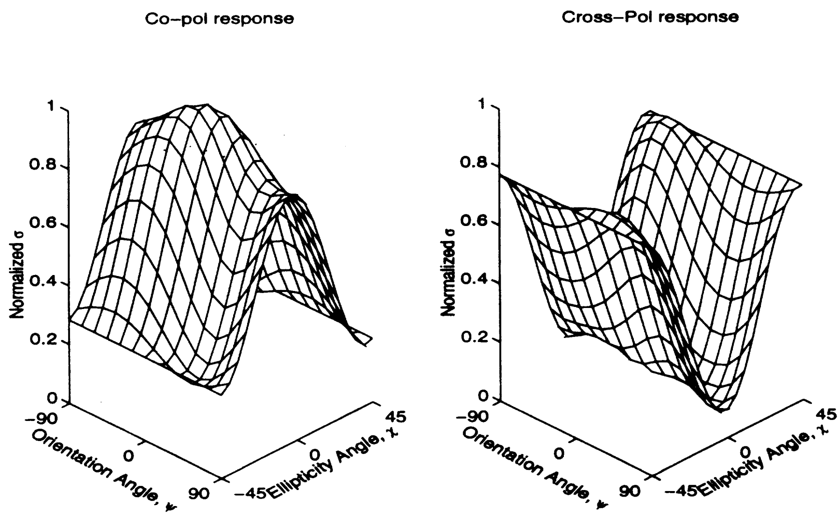
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0095 \begin{bmatrix} 1.0000 & 0.0998 & -0.0409 & -0.0275 \\ 0.0998 & 0.8591 & -0.0124 & 0.0552 \\ -0.0818 & -0.0248 & 0.7180 & -0.2759 \\ 0.0549 & -0.1104 & 0.2759 & 0.5184 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.21 \text{ dB} & \sigma_{hh} &= -9.87 \text{ dB} \\ \sigma_{vh} &= -19.22 \text{ dB} & & \\ \chi_d &= -9.69 \text{ dB} & & \\ \alpha &= 0.73 & \zeta &= -24.05^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.80 \\ m_{45} &= 0.73 & m_{135} &= 0.77 \\ m_{lhc} &= 0.56 & m_{rhc} &= 0.61 \end{aligned}$$



Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

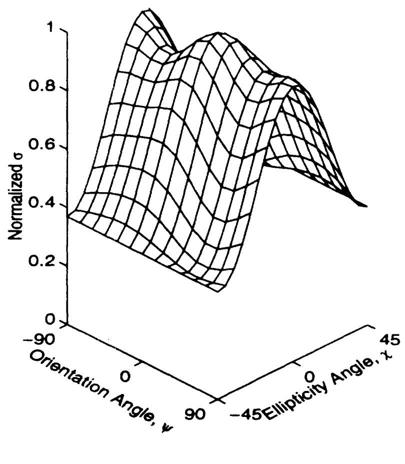
$$\mathbf{L}_m^\circ = 0.0041 \begin{bmatrix} 1.0000 & 0.1477 & 0.0069 & 0.0043 \\ 0.1477 & 0.9434 & 0.0083 & -0.0184 \\ 0.0137 & 0.0166 & 0.6408 & -0.1741 \\ -0.0085 & 0.0368 & 0.1741 & 0.3453 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.88 \text{ dB} & \sigma_{hh} &= -13.13 \text{ dB} \\ \sigma_{vh} &= -21.19 \text{ dB} & & \\ \chi_d &= -8.18 \text{ dB} & & \\ \alpha &= 0.54 & \zeta &= -19.45^\circ \end{aligned}$$

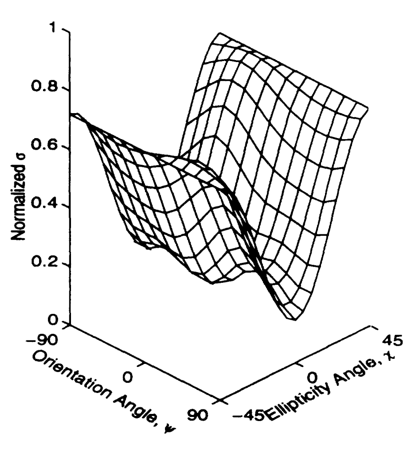
Degree of Polarization:

$$\begin{aligned} m_v &= 0.74 & m_h &= 0.73 \\ m_{45} &= 0.60 & m_{135} &= 0.59 \\ m_{lhc} &= 0.36 & m_{rhc} &= 0.34 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

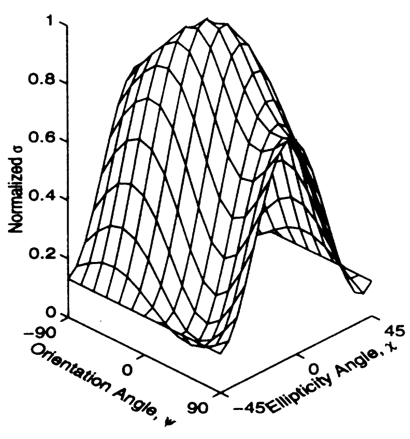
$$\mathbf{L}_m^{\circ} = 0.0292 \begin{bmatrix} 1.0000 & 0.0382 & -0.0361 & -0.0641 \\ 0.0382 & 0.7430 & -0.0138 & 0.0693 \\ -0.0722 & -0.0276 & 0.7327 & -0.3399 \\ 0.1283 & -0.1387 & 0.3399 & 0.6564 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -4.36 \text{ dB} & \sigma_{hh} &= -5.65 \text{ dB} \\ \sigma_{vh} &= -18.54 \text{ dB} & & \\ \chi_d &= -13.59 \text{ dB} & & \\ \alpha &= 0.90 & \zeta &= -26.08^{\circ} \end{aligned}$$

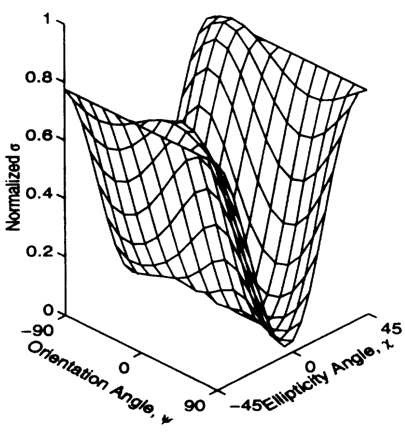
Degree of Polarization:

$$\begin{aligned} m_v &= 0.94 & m_h &= 0.92 \\ m_{45} &= 0.89 & m_{135} &= 0.91 \\ m_{lhc} &= 0.83 & m_{rhc} &= 0.85 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

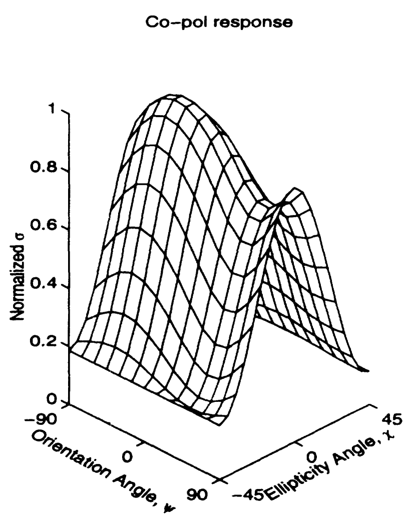
Normalized Mueller Matrix:

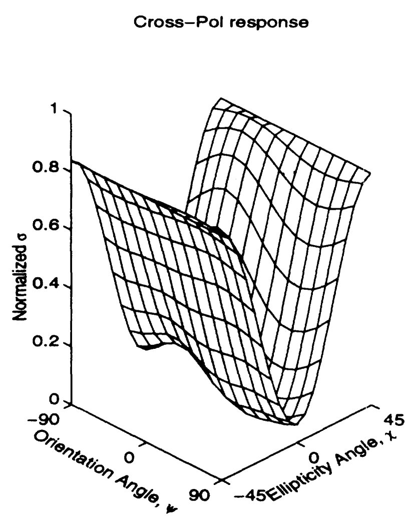
$$\mathbf{L}_m^{\circ} = 0.0086 \begin{bmatrix} 1.0000 & 0.0652 & -0.0411 & 0.0119 \\ 0.0652 & 0.9320 & -0.0590 & 0.0183 \\ -0.0821 & -0.1181 & 0.8437 & -0.1304 \\ -0.0238 & -0.0367 & 0.1304 & 0.7133 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.65 \text{ dB} & \sigma_{hh} &= -9.96 \text{ dB} \\ \sigma_{vh} &= -21.51 \text{ dB} & & \\ \chi_d &= -11.71 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= -9.51^{\circ} \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.88 \\ m_{45} &= 0.81 & m_{135} &= 0.85 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.74 \end{aligned}$$





Target: Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

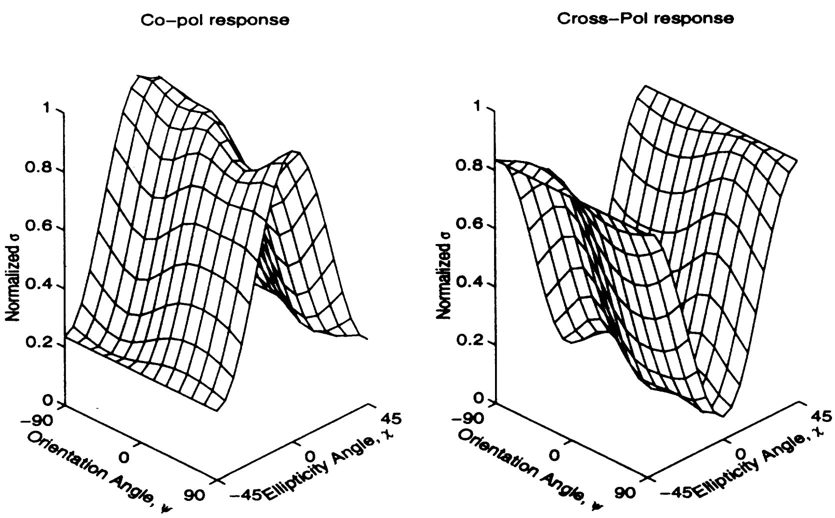
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0021 \begin{bmatrix} 1.0000 & 0.0802 & -0.0202 & 0.0123 \\ 0.0802 & 1.0277 & -0.0196 & -0.0067 \\ -0.0404 & -0.0392 & 0.7828 & 0.2241 \\ -0.0246 & 0.0135 & -0.2241 & 0.6225 \end{bmatrix}$$

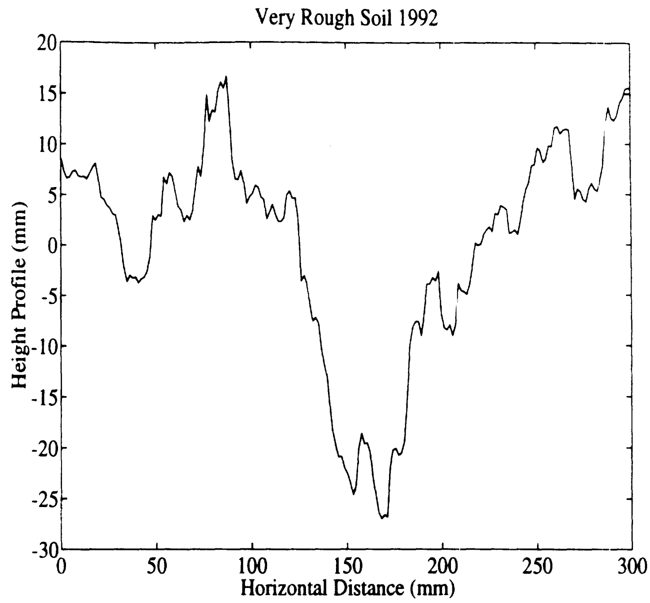
$$\begin{aligned} \sigma_{vv} &= -15.86 \text{ dB} & \sigma_{hh} &= -15.74 \text{ dB} \\ \sigma_{vh} &= -26.82 \text{ dB} \\ \chi_d &= -11.02 \text{ dB} \\ \alpha &= 0.73 & \zeta &= 17.69^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.86 \\ m_{45} &= 0.74 & m_{135} &= 0.75 \\ m_{lhc} &= 0.59 & m_{rhc} &= 0.63 \end{aligned}$$



Target Name:
Very Rough Soil 1992
System: UM



Target Description: Soil surface was initially cleared from grass, vegetation debris. The soil surface was then made rough by churning the soil with a garden shovel. Soil moisture was introduced by continuously saturating the soil with a fine mist tree sprayer. See [1] for detailed soil analysis.

Ground Truth:
rms height = 7.77 mm
correlation length = 20 mm
bulk soil density = 1.32 g/cm^3
air-voids volume fraction = 0.50

frequency	ks	kl
35 GHz	5.69	14.7
94 GHz	15.3	39.4

soil moisture	m_v 0-1 cm	2-3 cm
dry	0.04	0.07
wet	0.19	0.18

References:
[1] Nashashibi, Ulaby and Sarabandi, "Measurement and Modelling Millimeter-Wave Response from Soil Surfaces," UM Technical Report 029721-2-T, 1993.

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	dry	soil.3.1	103
45	35	dry	soil.3.2	104
70	35	dry	soil.3.3	105
20	35	wet	soil.3.4	106
45	35	wet	soil.3.5	107
70	35	wet	soil.3.6	108
20	94	dry	soil.3.7	109
45	94	dry	soil.3.8	110
70	94	dry	soil.3.9	111
20	94	wet	soil.3.10	112
45	94	wet	soil.3.11	113
70	94	wet	soil.3.12	114

Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

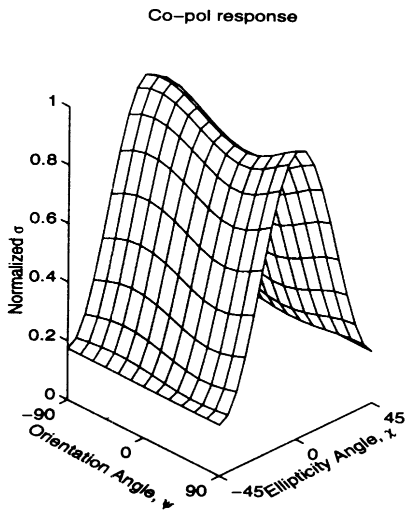
Normalized Mueller Matrix:

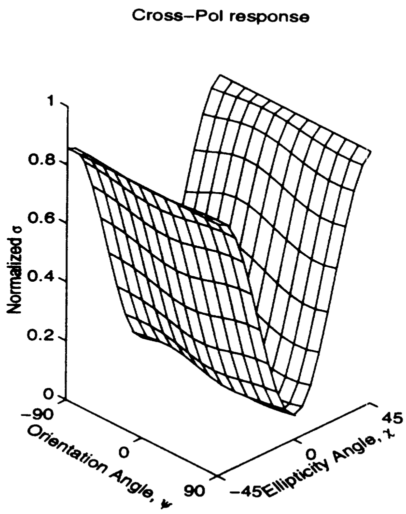
$$\mathbf{L}_m^{\circ} = 0.0045 \begin{bmatrix} 1.0000 & 0.0928 & -0.0165 & 0.0226 \\ 0.0928 & 1.0817 & -0.0197 & -0.0221 \\ -0.0330 & -0.0394 & 0.9355 & -0.0367 \\ -0.0453 & 0.0442 & 0.0367 & 0.7498 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.49 \text{ dB} & \sigma_{hh} &= -12.15 \text{ dB} \\ \sigma_{vh} &= -22.81 \text{ dB} & & \\ \chi_d &= -10.50 \text{ dB} & & \\ \alpha &= 0.81 & \zeta &= -2.49^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.84 \\ m_{45} &= 0.82 & m_{135} &= 0.83 \\ m_{lhc} &= 0.66 & m_{rhc} &= 0.67 \end{aligned}$$





Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

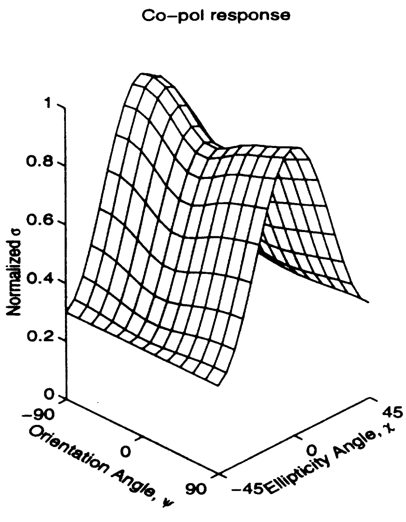
Normalized Mueller Matrix:

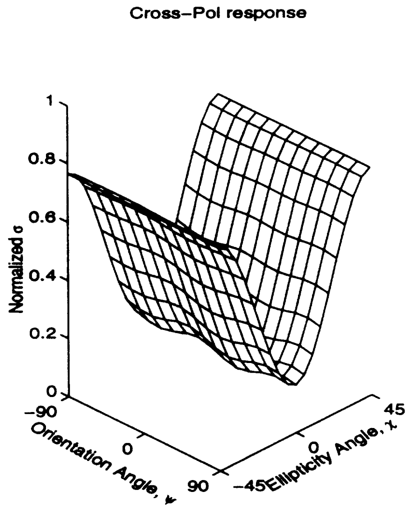
$$\mathbf{L}_m^\circ = 0.0022 \begin{bmatrix} 1.0000 & 0.1918 & 0.0124 & -0.0067 \\ 0.1918 & 1.1549 & -0.0170 & -0.0057 \\ 0.0249 & -0.0339 & 0.9208 & 0.0198 \\ 0.0133 & 0.0114 & -0.0198 & 0.5372 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -15.59 \text{ dB} & \sigma_{hh} &= -14.97 \text{ dB} \\ \sigma_{vh} &= -22.77 \text{ dB} & & \\ \chi_d &= -7.50 \text{ dB} & & \\ \alpha &= 0.68 & \zeta &= 1.56° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.68 & m_h &= 0.72 \\ m_{45} &= 0.73 & m_{135} &= 0.73 \\ m_{lhc} &= 0.44 & m_{rhc} &= 0.41 \end{aligned}$$





Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

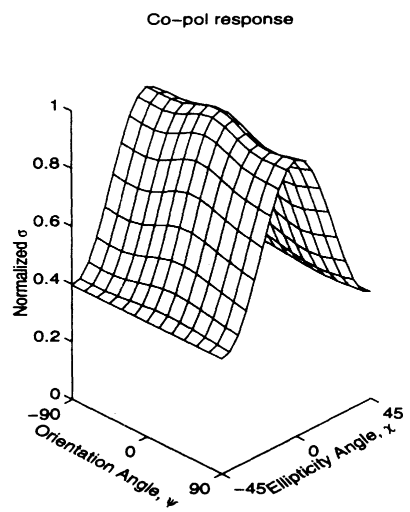
Normalized Mueller Matrix:

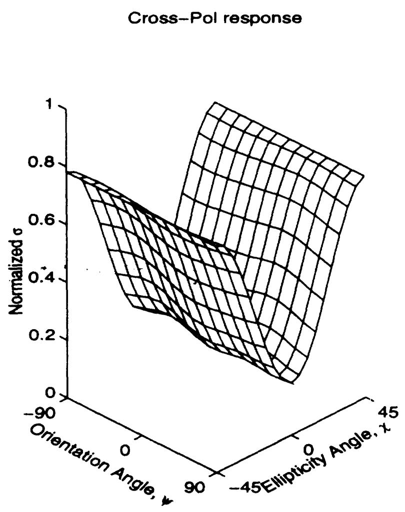
$$\mathbf{L}_m^\circ = 0.0018 \begin{bmatrix} 1.0000 & 0.1789 & -0.0041 & 0.0161 \\ 0.1789 & 0.9536 & -0.0030 & -0.0053 \\ -0.0082 & -0.0061 & 0.7484 & 0.0446 \\ -0.0322 & 0.0107 & -0.0446 & 0.3906 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -16.40 \text{ dB} & \sigma_{hh} &= -16.61 \text{ dB} \\ \sigma_{vh} &= -23.87 \text{ dB} & & \\ \chi_d &= -7.37 \text{ dB} & & \\ \alpha &= 0.58 & \zeta &= 4.48^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.70 & m_h &= 0.68 \\ m_{45} &= 0.65 & m_{135} &= 0.65 \\ m_{lhc} &= 0.33 & m_{rhc} &= 0.35 \end{aligned}$$





Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

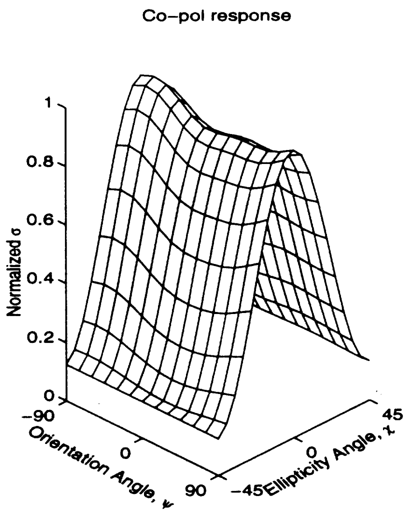
Normalized Mueller Matrix:

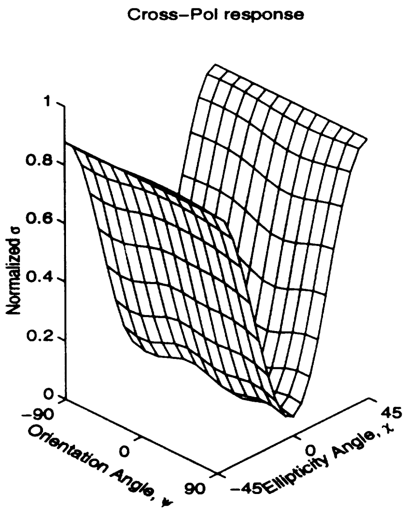
$$\mathbf{L}_m^\circ = 0.0217 \begin{bmatrix} 1.0000 & 0.0715 & 0.0078 & -0.0182 \\ 0.0715 & 1.0765 & -0.0217 & 0.0138 \\ 0.0155 & -0.0434 & 0.9667 & -0.0419 \\ 0.0365 & -0.0277 & 0.0419 & 0.8238 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -5.63 \text{ dB} & \sigma_{hh} &= -5.31 \text{ dB} \\ \sigma_{vh} &= -17.09 \text{ dB} & & \\ \chi_d &= -11.62 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= -2.68^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.88 \\ m_{45} &= 0.87 & m_{135} &= 0.88 \\ m_{lhc} &= 0.75 & m_{rhc} &= 0.74 \end{aligned}$$





Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

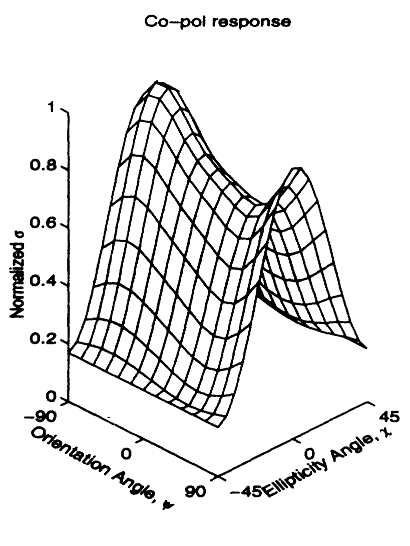
Normalized Mueller Matrix:

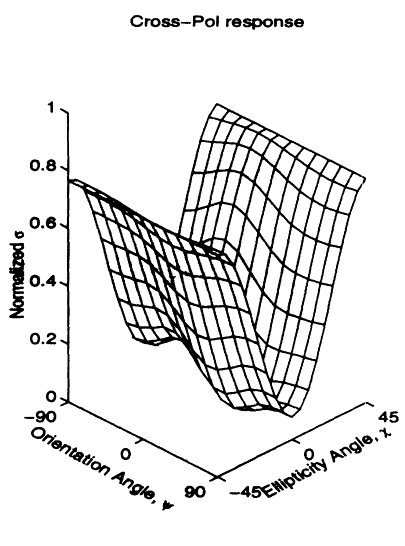
$$\mathbf{L}_m^\circ = 0.0163 \begin{bmatrix} 1.0000 & 0.0964 & -0.0250 & 0.0229 \\ 0.0964 & 1.1629 & -0.0796 & -0.0308 \\ -0.0499 & -0.1591 & 0.9305 & -0.0439 \\ -0.0458 & 0.0616 & 0.0439 & 0.7378 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.88 \text{ dB} & \sigma_{hh} &= -6.23 \text{ dB} \\ \sigma_{vh} &= -17.04 \text{ dB} & & \\ \chi_d &= -10.50 \text{ dB} & & \\ \alpha &= 0.77 & \zeta &= -3.01° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.86 \\ m_{45} &= 0.77 & m_{135} &= 0.81 \\ m_{lhc} &= 0.65 & m_{rhc} &= 0.63 \end{aligned}$$





Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

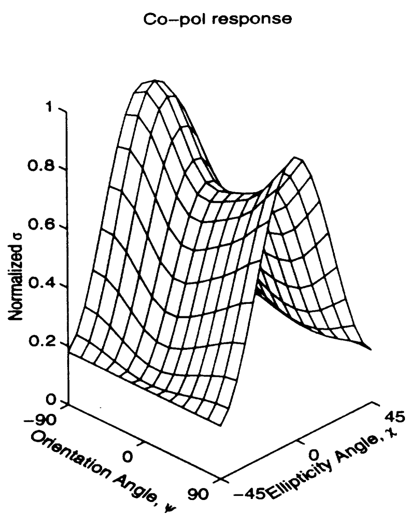
Normalized Mueller Matrix:

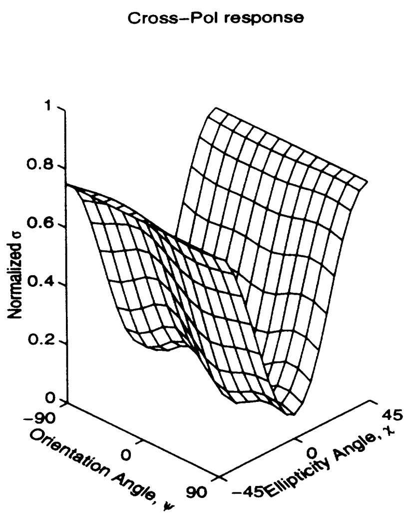
$$\mathbf{L}_m^\circ = 0.0021 \begin{bmatrix} 1.0000 & 0.1126 & 0.0081 & -0.0114 \\ 0.1126 & 1.3341 & -0.0623 & 0.0124 \\ 0.0163 & -0.1246 & 1.0114 & 0.0898 \\ 0.0228 & -0.0248 & -0.0898 & 0.7862 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -15.76 \text{ dB} & \sigma_{hh} &= -14.51 \text{ dB} \\ \sigma_{vh} &= -25.24 \text{ dB} \\ \chi_d &= -10.15 \text{ dB} \\ \alpha &= 0.78 & \zeta &= 5.70^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.80 & m_h &= 0.85 \\ m_{45} &= 0.79 & m_{135} &= 0.82 \\ m_{lhc} &= 0.63 & m_{rhc} &= 0.64 \end{aligned}$$





Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

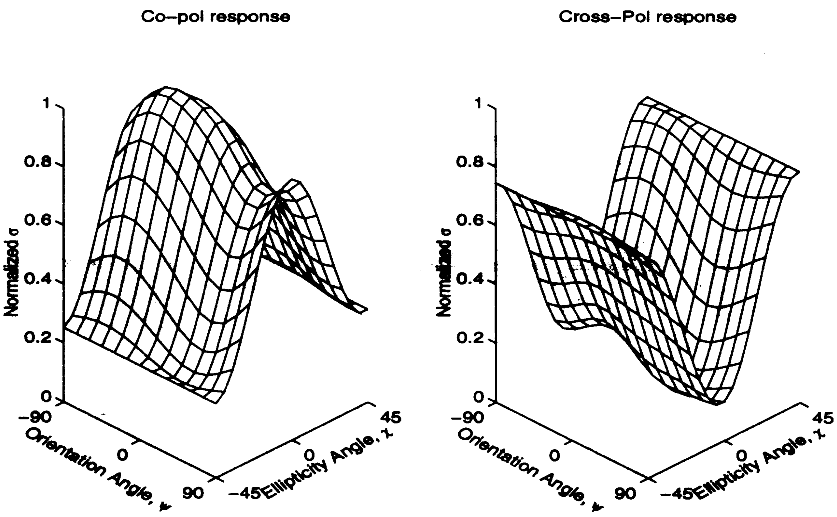
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0147 \begin{bmatrix} 1.0000 & 0.1391 & -0.0338 & -0.0418 \\ 0.1391 & 0.9361 & -0.0540 & 0.0151 \\ -0.0676 & -0.1080 & 0.7864 & -0.0874 \\ 0.0836 & -0.0303 & 0.0874 & 0.5083 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -7.34 \text{ dB} & \sigma_{hh} &= -7.63 \text{ dB} \\ \sigma_{vh} &= -15.91 \text{ dB} & & \\ \chi_d &= -8.43 \text{ dB} & & \\ \alpha &= 0.68 & \zeta &= -7.69^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.76 & m_h &= 0.75 \\ m_{45} &= 0.70 & m_{135} &= 0.73 \\ m_{lhc} &= 0.52 & m_{rhc} &= 0.43 \end{aligned}$$



Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

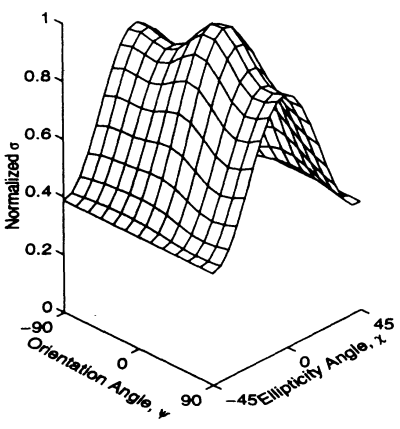
$$\mathbf{L}_m^\circ = 0.0187 \begin{bmatrix} 1.0000 & 0.1622 & 0.0255 & -0.0081 \\ 0.1622 & 0.8801 & -0.0109 & 0.0135 \\ 0.0510 & -0.0218 & 0.6619 & -0.0704 \\ 0.0162 & -0.0271 & 0.0704 & 0.3375 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.28 \text{ dB} & \sigma_{hh} &= -6.83 \text{ dB} \\ \sigma_{vh} &= -14.18 \text{ dB} \\ \chi_d &= -7.63 \text{ dB} \\ \alpha &= 0.54 & \zeta &= -8.01^\circ \end{aligned}$$

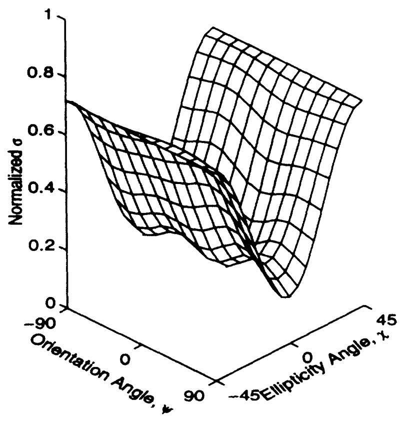
Degree of Polarization:

$$\begin{aligned} m_v &= 0.72 & m_h &= 0.69 \\ m_{45} &= 0.61 & m_{135} &= 0.60 \\ m_{lhc} &= 0.31 & m_{rhc} &= 0.33 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

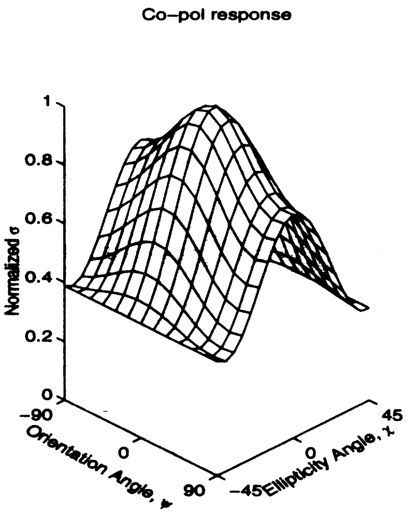
Normalized Mueller Matrix:

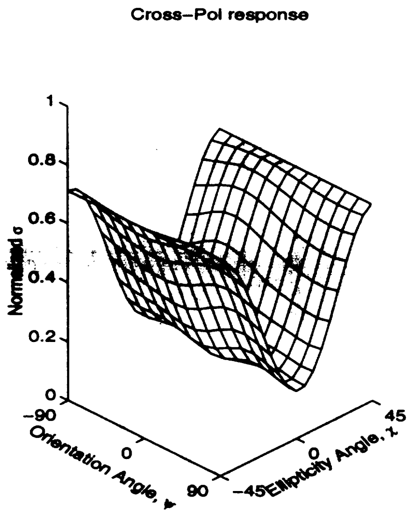
$$\mathbf{L}_m^\circ = 0.0086 \begin{bmatrix} 1.0000 & 0.1614 & -0.0013 & 0.0341 \\ 0.1614 & 0.7581 & -0.0088 & -0.0041 \\ -0.0025 & -0.0176 & 0.6600 & -0.0680 \\ -0.0683 & 0.0082 & 0.0680 & 0.3372 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.68 \text{ dB} & \sigma_{hh} &= -10.88 \text{ dB} \\ \sigma_{vh} &= -17.60 \text{ dB} & & \\ \chi_d &= -7.36 \text{ dB} & & \\ \alpha &= 0.58 & \zeta &= -7.77^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.72 & m_h &= 0.65 \\ m_{45} &= 0.64 & m_{135} &= 0.65 \\ m_{lhc} &= 0.33 & m_{rhc} &= 0.38 \end{aligned}$$





Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

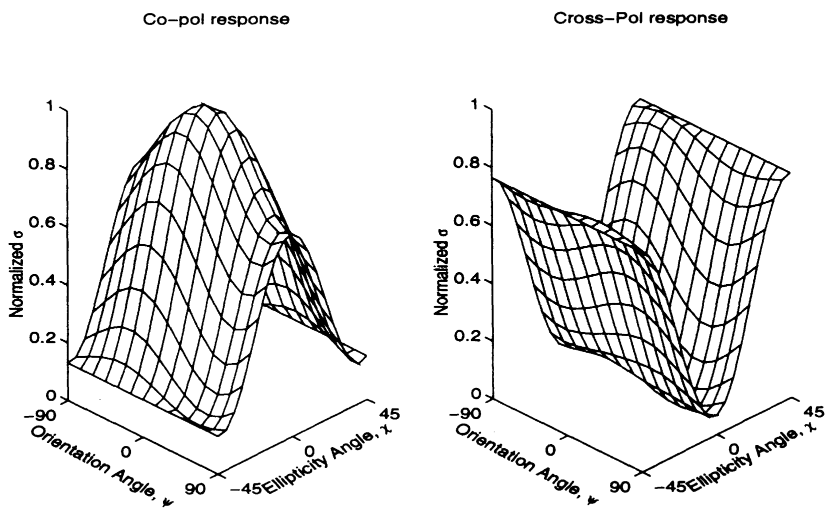
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0415 \begin{bmatrix} 1.0000 & 0.0669 & -0.0245 & -0.0287 \\ 0.0669 & 0.7095 & -0.0283 & 0.0202 \\ -0.0490 & -0.0566 & 0.7701 & -0.1735 \\ 0.0574 & -0.0403 & 0.1735 & 0.6362 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -2.83 \text{ dB} & \sigma_{hh} &= -4.32 \text{ dB} \\ \sigma_{vh} &= -14.57 \text{ dB} & & \\ \chi_d &= -11.06 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= -13.86^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.83 \\ m_{45} &= 0.87 & m_{135} &= 0.87 \\ m_{lhc} &= 0.76 & m_{rhc} &= 0.72 \end{aligned}$$



Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

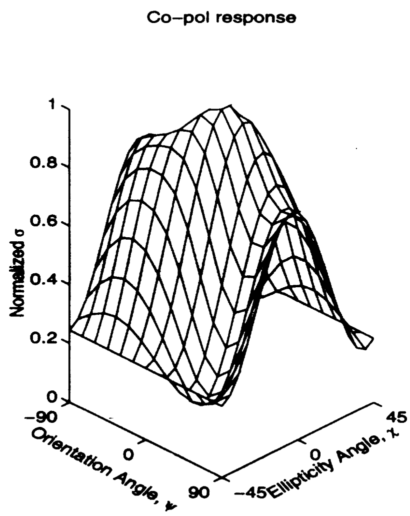
Normalized Mueller Matrix:

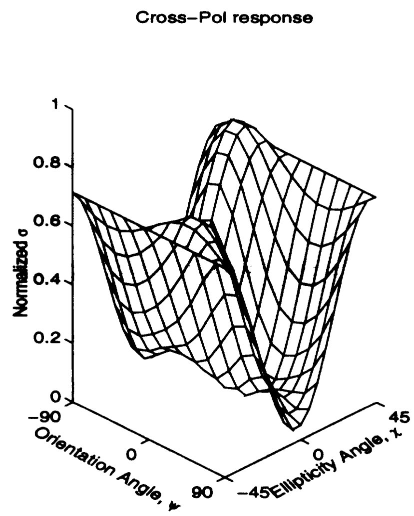
$$\mathbf{L}_m^\circ = 0.0210 \begin{bmatrix} 1.0000 & 0.0499 & -0.0200 & -0.0478 \\ 0.0499 & 0.7753 & -0.0201 & 0.0589 \\ -0.0401 & -0.0403 & 0.5759 & -0.4126 \\ 0.0957 & -0.1177 & 0.4126 & 0.4761 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -5.78 \text{ dB} & \sigma_{hh} &= -6.89 \text{ dB} \\ \sigma_{vh} &= -18.81 \text{ dB} \\ \chi_d &= -12.50 \text{ dB} \\ \alpha &= 0.76 & \zeta &= -38.11^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.91 & m_h &= 0.89 \\ m_{45} &= 0.76 & m_{135} &= 0.77 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.70 \end{aligned}$$





Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

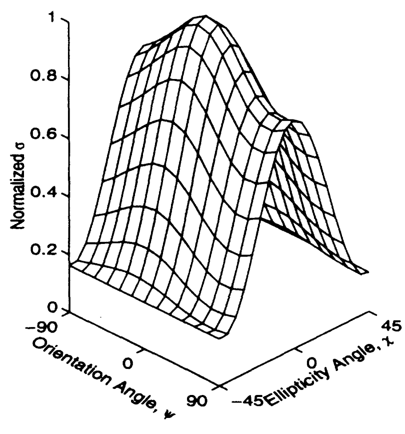
$$\mathbf{L}_m^\circ = 0.0059 \begin{bmatrix} 1.0000 & 0.0624 & -0.0231 & 0.0094 \\ 0.0624 & 0.7971 & -0.0225 & 0.0012 \\ -0.0461 & -0.0449 & 0.7839 & -0.0461 \\ -0.0188 & -0.0024 & 0.0461 & 0.6592 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -11.31 \text{ dB} & \sigma_{hh} &= -12.30 \text{ dB} \\ \sigma_{vh} &= -23.37 \text{ dB} & & \\ \chi_d &= -11.59 \text{ dB} & & \\ \alpha &= 0.81 & \zeta &= -3.65° \end{aligned}$$

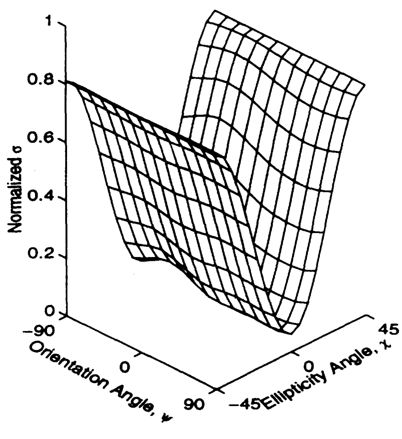
Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.86 \\ m_{45} &= 0.82 & m_{135} &= 0.83 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.71 \end{aligned}$$

Co-pol response



Cross-Pol response



Target Name: Sand 1989
System: UMass
Spotsize: 0.7 m (6 dB two-way)

Target Description: October 1989 measurement of wet and dry sand with a low percentage of stones (diameter $\leq$ 10 mm).

Ground Truth:
grain size = 0.2-1 mm

Data List:

θ_i	freq.	condition	data no.	page no.
26	225	dry, $m_g = 0.0$	sand.1.1	116
26	225	wet, $m_g = 0.10$	sand.1.2	117

References:
James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Sand 1989
System/Frequency: UM - 225 GHz.
Incidence Angle: 26°
Independent Samples: 1000

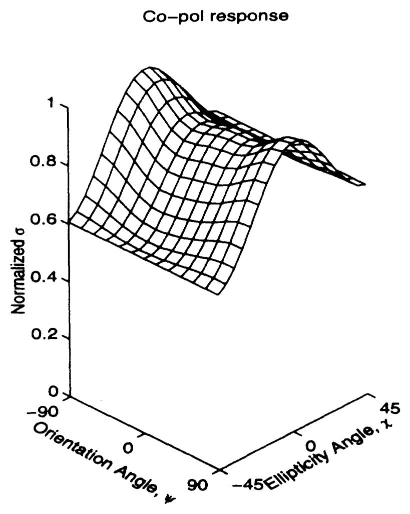
Modified Mueller Matrix:

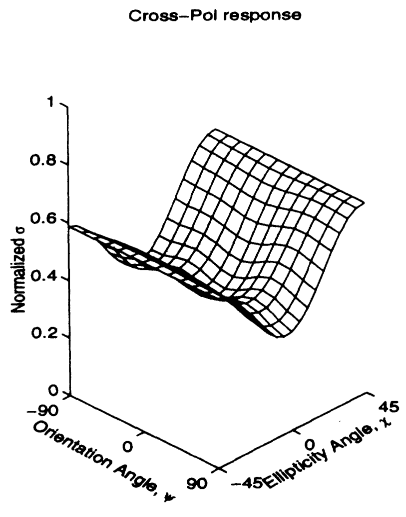
$$\mathbf{L}_m^\circ = 0.0853 \begin{bmatrix} 1.0000 & 0.3804 & 0.0096 & -0.0391 \\ 0.3804 & 1.1124 & 0.0055 & -0.0144 \\ 0.0192 & 0.0110 & 0.5812 & 0.0137 \\ 0.0781 & 0.0288 & -0.0137 & -0.0466 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 0.30 \text{ dB} & \sigma_{hh} &= 0.76\ dB \\ \sigma_{vh} &= -3.90 \text{ dB} & & \\ \chi_d &= -4.44 \text{ dB} & & \\ \alpha &= 0.25 & \zeta &= 2.93° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.45 & m_h &= 0.49 \\ m_{45} &= 0.41 & m_{135} &= 0.40 \\ m_{lhc} &= 0.06 & m_{rhc} &= 0.07 \end{aligned}$$





Target: Sand 1989
System/Frequency: UM - 225 GHz.
Incidence Angle: 26°
Independent Samples: 1000

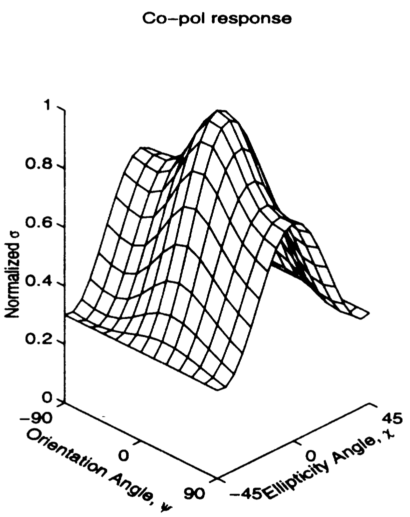
Modified Mueller Matrix:

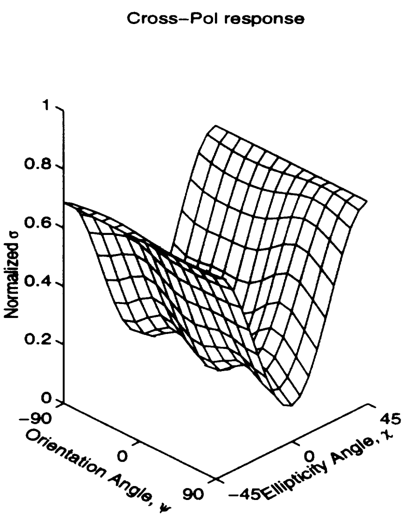
$$\mathbf{L}_m^\circ = 0.0152 \begin{bmatrix} 1.0000 & 0.1216 & 0.0196 & -0.0049 \\ 0.1216 & 0.7431 & 0.0000 & 0.0020 \\ 0.0392 & 0.0000 & 0.6039 & 0.0824 \\ 0.0098 & -0.0039 & -0.0824 & 0.3853 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -7.19 \text{ dB} & \sigma_{hh} &= -8.48\ dB \\ \sigma_{vh} &= -16.34 \text{ dB} & & \\ \chi_d &= -8.55 \text{ dB} & & \\ \alpha &= 0.58 & \zeta &= 9.46^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.72 \\ m_{45} &= 0.64 & m_{135} &= 0.62 \\ m_{lhc} &= 0.42 & m_{rhc} &= 0.41 \end{aligned}$$





Target Name: Short Grass 1989
System: UMass
Spotsize: 1 m (6 dB two-way)

Target Description: October 1989 measurement of field grass.

Ground Truth:
grass height = 3-5 cm
grass width = 1-5 mm
grass density = 2.9 kg m^{-2}
grass gravimetric liquid water content = 0.65
soil gravimetric liquid water content = 0.27

Data List:

θ_i	freq.	condition	data no.	page no.
40 ± 10	225	short	grass.1.1	119

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept, 1991.

Target: Short Grass 1989
System/Frequency: UM - 225 GHz.
Incidence Angle: 30°
Independent Samples: 1000

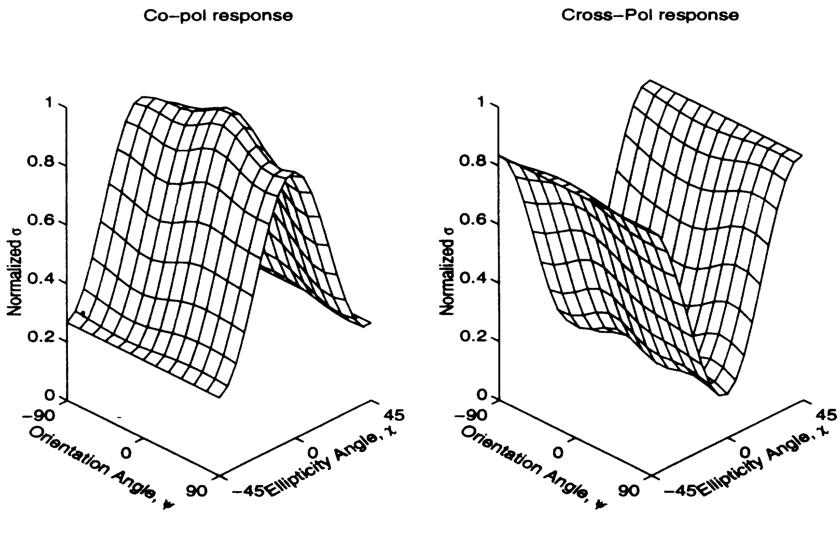
Modified Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0178 \begin{bmatrix} 1.0000 & 0.1498 & 0.0148 & -0.0269 \\ 0.1498 & 0.9135 & -0.0148 & 0.0280 \\ 0.0295 & -0.0295 & 0.7711 & 0.0580 \\ 0.0538 & -0.0559 & -0.0580 & 0.5738 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.50 \text{ dB} & \sigma_{hh} &= -6.90 \text{ dB} \\ \sigma_{vh} &= -14.75 \text{ dB} & & \\ \chi_d &= -8.05 \text{ dB} & & \\ \alpha &= 0.71 & \zeta &= 4.93° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.74 & m_h &= 0.72 \\ m_{45} &= 0.70 & m_{135} &= 0.70 \\ m_{lhc} &= 0.52 & m_{rhc} &= 0.53 \end{aligned}$$



Target Name: Short Grass 1994
System: UM

Target Description: July morning measurement of a cultivated lawn. The majority of the measurements occurred between 10 am and 1 pm when most of the morning dew had evaporated.

Ground Truth:
grass height = 5-7 cm
grass width = 2-5 mm
grass density = 2.22 kg m^{-2}

soil moisture profile, m_g				
	depth			
	top grass	0-1"	1-2"	2-3"
8:10 am	0.41	0.19	–	–
9:30 am	0.32	0.24	–	–
10:00 am	0.30	0.24	0.16	0.16
12:30 pm	0.24	0.20	0.18	0.18

Data List:

θ_i	freq.	time	condition	data no.	page no.
20	35	11:55	short	grass.2.1	121
30	35	10:46	short	grass.2.2	122
45	35	9:50	short	grass.2.3	123
60	35	12:49	short	grass.2.4	124

References:
None

Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

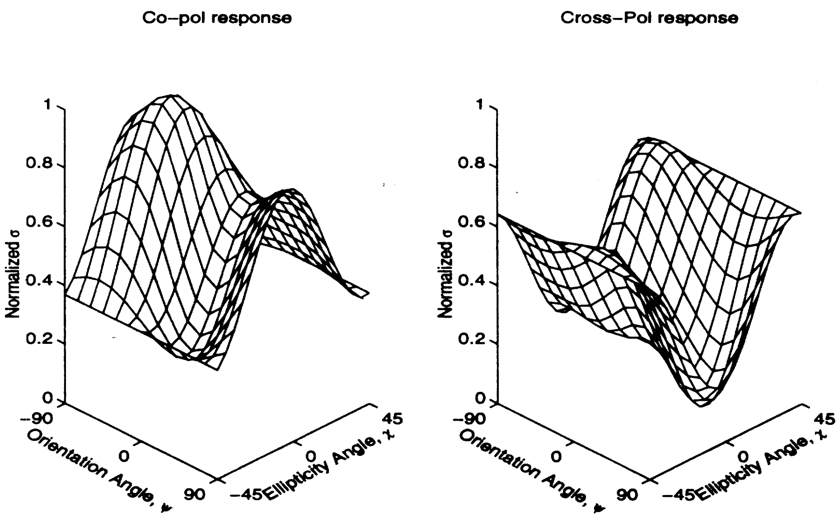
$$\mathbf{L}_m^\circ = 0.0076 \begin{bmatrix} 1.0000 & 0.2628 & -0.1088 & -0.0673 \\ 0.2628 & 1.1098 & -0.0289 & 0.0643 \\ -0.2177 & -0.0578 & 0.8800 & -0.2676 \\ 0.1347 & -0.1286 & 0.2676 & 0.3543 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.19 \text{ dB} & \sigma_{hh} &= -9.74 \text{ dB} \\ \sigma_{vh} &= -15.99 \text{ dB} & & \\ \chi_d &= -6.04 \text{ dB} & & \\ \alpha &= 0.64 & \zeta^\dagger &= -23.44^\circ \end{aligned}$$

† value may be inaccurate (see pg. 39 for details).

Degree of Polarization:

$$\begin{aligned} m_v &= 0.62 & m_h &= 0.63 \\ m_{45} &= 0.68 & m_{135} &= 0.72 \\ m_{lhc} &= 0.43 & m_{rhc} &= 0.29 \end{aligned}$$



Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 100

Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0030 \begin{bmatrix} 1.0000 & 0.4207 & -0.1914 & -0.0364 \\ 0.4207 & 0.8952 & -0.1173 & 0.0354 \\ -0.3829 & -0.2347 & 0.6782 & 0.0073 \\ 0.0728 & -0.0708 & -0.0073 & -0.1631 \end{bmatrix}$$

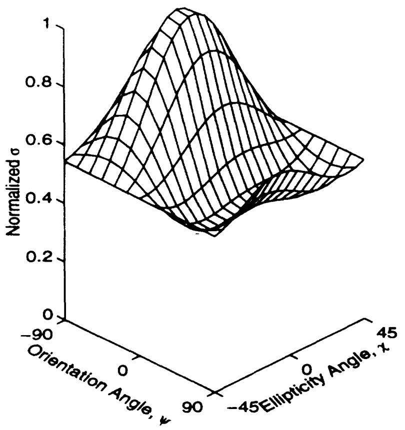
$$\begin{aligned} \sigma_{vv} &= -14.28 \text{ dB} & \sigma_{hh} &= -14.76 \text{ dB} \\ \sigma_{vh} &= -18.04 \text{ dB} & & \\ \chi_d &= -3.53 \text{ dB} & & \\ \alpha &= 0.27 & \zeta^\dagger &= 1.62^\circ \end{aligned}$$

† value may be inaccurate (see pg. 39 for details).

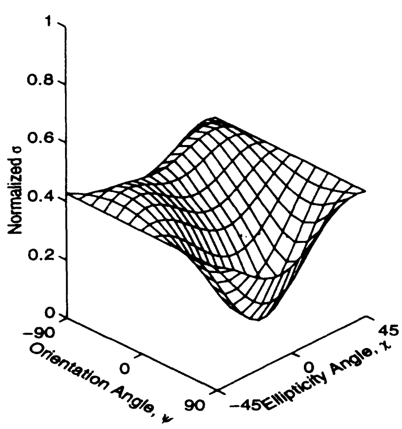
Degree of Polarization:

$$\begin{aligned} m_v &= 0.49 & m_h &= 0.41 \\ m_{45} &= 0.35 & m_{135} &= 0.59 \\ m_{lhc} &= 0.25 & m_{rhc} &= 0.28 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0030 \begin{bmatrix} 1.0000 & 0.2344 & -0.0510 & -0.0753 \\ 0.2344 & 1.0740 & 0.0700 & 0.0468 \\ -0.1020 & 0.1400 & 0.7741 & 0.2694 \\ 0.1506 & -0.0935 & -0.2694 & 0.3052 \end{bmatrix}$$

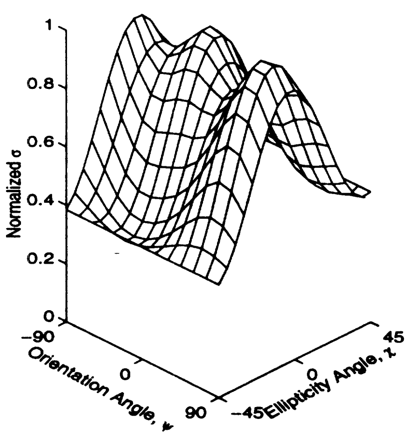
$$\begin{aligned} \sigma_{vv} &= -14.29 \text{ dB} & \sigma_{hh} &= -13.98 \text{ dB} \\ \sigma_{vh} &= -20.59 \text{ dB} & & \\ \chi_d &= -6.46 \text{ dB} & & \\ \alpha &= 0.58 & \zeta^\dagger &= 26.53^\circ \end{aligned}$$

† value may be inaccurate (see pg. 39 for details).

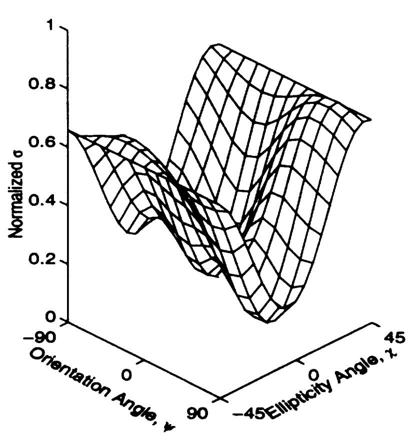
Degree of Polarization:

$$\begin{aligned} m_v &= 0.64 & m_h &= 0.65 \\ m_{45} &= 0.65 & m_{135} &= 0.65 \\ m_{lhc} &= 0.38 & m_{rhc} &= 0.29 \end{aligned}$$

Co–pol response



Cross–Pol response



Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

Normalized Mueller Matrix:

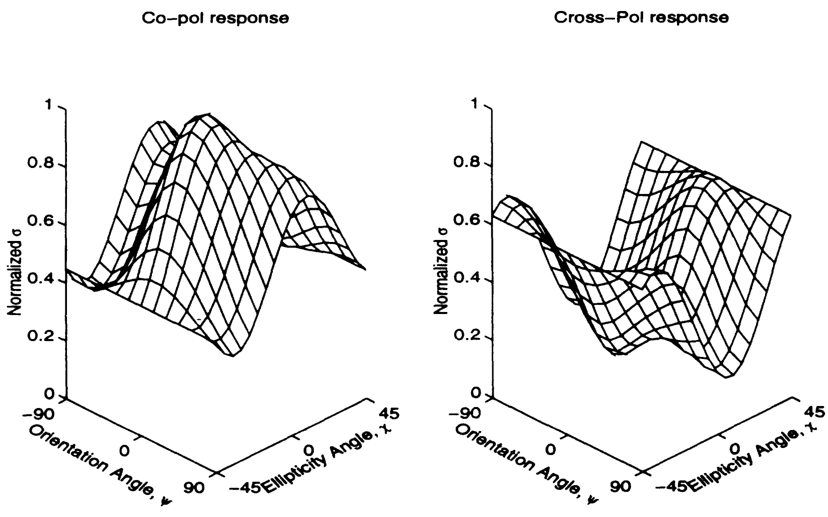
$$\mathbf{L}_m^\circ = 0.0024 \begin{bmatrix} 1.0000 & 0.2235 & -0.0007 & 0.1134 \\ 0.2235 & 0.7826 & 0.0539 & -0.1117 \\ -0.0015 & 0.1077 & 0.6364 & 0.0545 \\ -0.2268 & 0.2234 & -0.0545 & 0.1894 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -15.23 \text{ dB} & \sigma_{hh} &= -16.30 \text{ dB} \\ \sigma_{vh} &= -21.74 \text{ dB} & & \\ \chi_d &= -6.01 \text{ dB} & & \\ \alpha &= 0.47 & \zeta^\dagger &= 7.52^\circ \end{aligned}$$

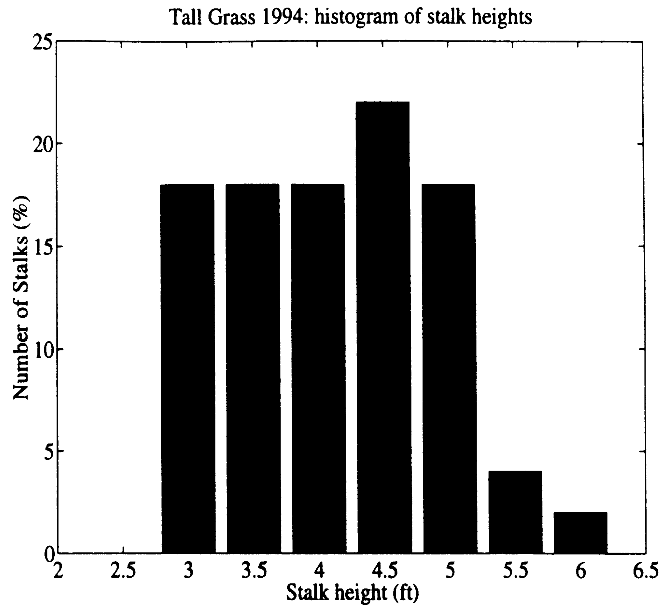
† value may be inaccurate (see pg. 39 for details).

Degree of Polarization:

$$\begin{aligned} m_v &= 0.66 & m_h &= 0.61 \\ m_{45} &= 0.59 & m_{135} &= 0.57 \\ m_{lhc} &= 0.36 & m_{rhc} &= 0.20 \end{aligned}$$



Target Name: Tall Grass 1994
System: UM



Target Description: July measurement of wild, tall grasses located in the University of Michigan Arboretum Prarie.

Ground Truth:
stalk density = 80.4 stalks/ft^2
avg. stalk height = 4.15 ± 0.78 ft
avg. above ground biomass = 762.6 g/ft^2
avg. above ground water = 438.9 g/ft^2

soil moisture profile				
	depth			
	0-1"	1-2"	2-3"	3-4"
m_g	0.11	0.11	0.12	0.12

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	tall	grass.3.1	126
30	35	tall	grass.3.2	127
45	35	tall	grass.3.3	128
60	35	tall	grass.3.4	129

References:
None

Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

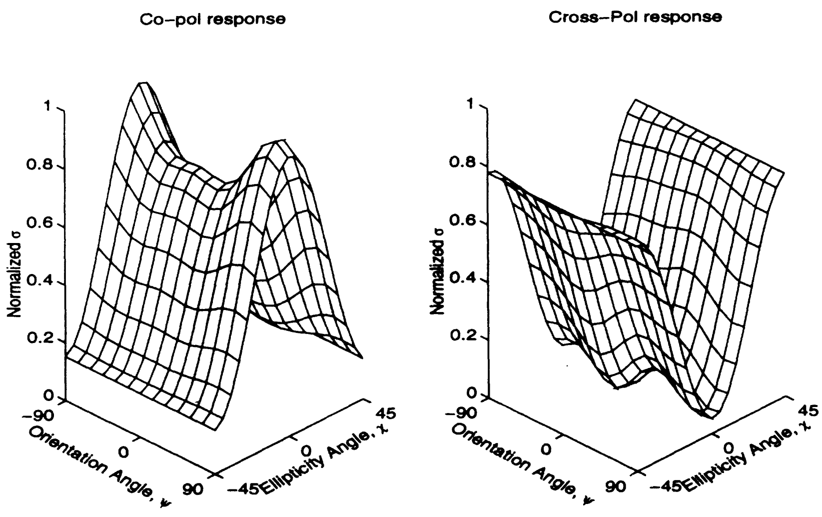
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0078 \begin{bmatrix} 1.0000 & 0.0683 & -0.0113 & 0.0433 \\ 0.0683 & 1.2485 & 0.0645 & -0.0372 \\ -0.0226 & 0.1290 & 0.9519 & -0.0464 \\ -0.0865 & 0.0743 & 0.0464 & 0.8152 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.08 \text{ dB} & \sigma_{hh} &= -9.11 \text{ dB} \\ \sigma_{vh} &= -21.73 \text{ dB} & & \\ \chi_d &= -12.16 \text{ dB} & & \\ \alpha &= 0.79 & \zeta &= -3.00° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.90 \\ m_{45} &= 0.82 & m_{135} &= 0.79 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.72 \end{aligned}$$



Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 100

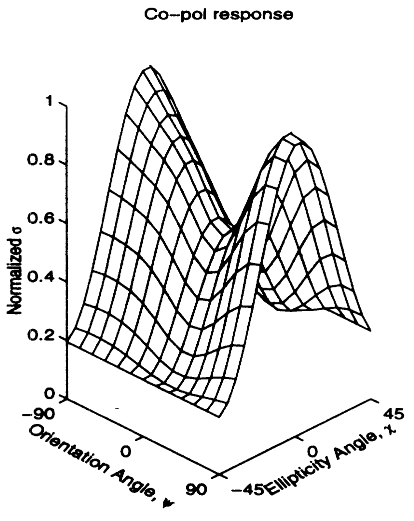
Normalized Mueller Matrix:

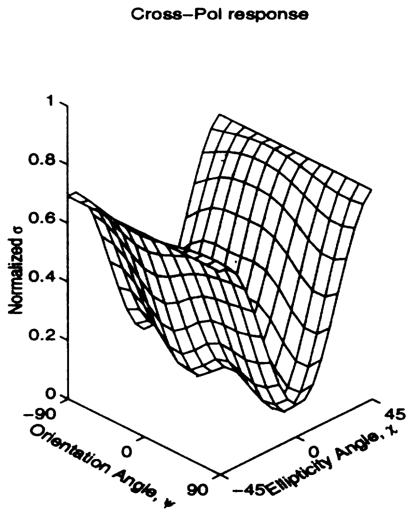
$$\mathbf{L}_m^\circ = 0.0047 \begin{bmatrix} 1.0000 & 0.1764 & -0.0686 & 0.0521 \\ 0.1764 & 1.5993 & 0.0421 & -0.0761 \\ -0.1371 & 0.0843 & 1.1419 & -0.1264 \\ -0.1042 & 0.1522 & 0.1264 & 0.7891 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -12.29 \text{ dB} & \sigma_{hh} &= -10.25 \text{ dB} \\ \sigma_{vh} &= -19.82 \text{ dB} & & \\ \chi_d &= -8.67 \text{ dB} & & \\ \alpha &= 0.77 & \zeta &= -7.46^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.72 & m_h &= 0.81 \\ m_{45} &= 0.83 & m_{135} &= 0.79 \\ m_{lhc} &= 0.58 & m_{rhc} &= 0.59 \end{aligned}$$





Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

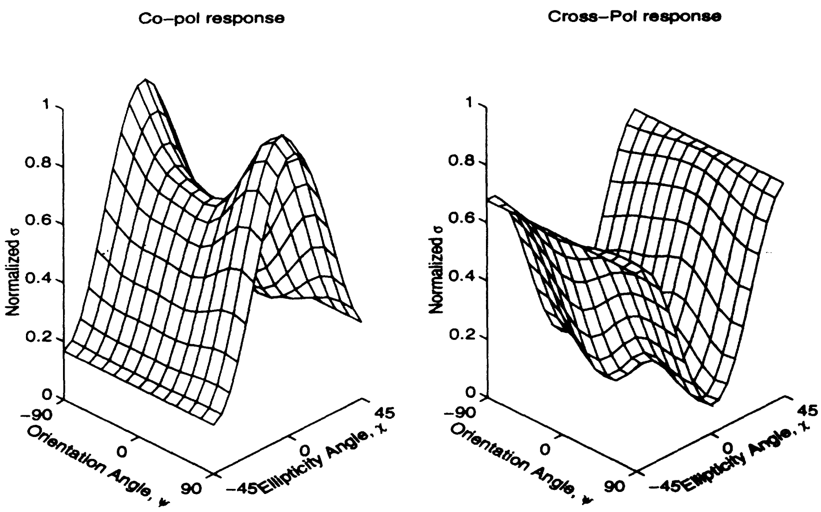
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0025 \begin{bmatrix} 1.0000 & 0.1428 & -0.0001 & 0.0399 \\ 0.1428 & 1.3775 & 0.0751 & -0.0938 \\ -0.0001 & 0.1502 & 0.9969 & -0.0761 \\ -0.0799 & 0.1876 & 0.0761 & 0.7113 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -15.02 \text{ dB} & \sigma_{hh} &= -13.63 \text{ dB} \\ \sigma_{vh} &= -23.47 \text{ dB} & & \\ \chi_d &= -9.20 \text{ dB} & & \\ \alpha &= 0.73 & \zeta &= -5.09° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.75 & m_h &= 0.83 \\ m_{45} &= 0.79 & m_{135} &= 0.74 \\ m_{lhc} &= 0.60 & m_{rhc} &= 0.54 \end{aligned}$$



Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

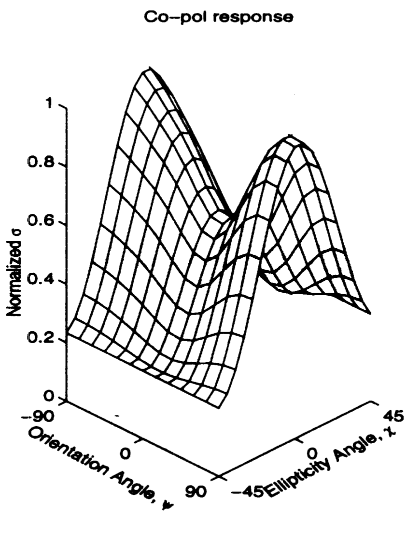
Normalized Mueller Matrix:

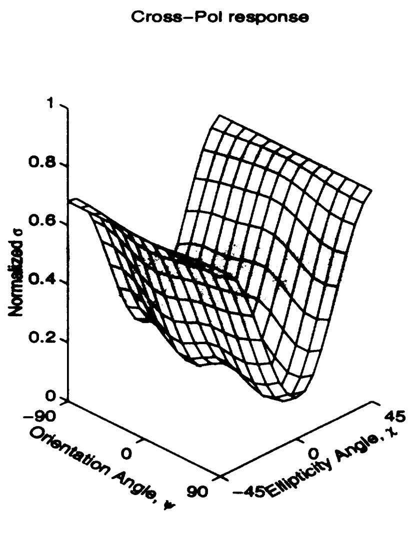
$$\mathbf{L}_m^\circ = 0.0011 \begin{bmatrix} 1.0000 & 0.2164 & -0.0432 & 0.0234 \\ 0.2164 & 1.5238 & 0.0327 & -0.0623 \\ -0.0864 & 0.0654 & 1.0990 & -0.0308 \\ -0.0467 & 0.1246 & 0.0308 & 0.6662 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -18.54 \text{ dB} & \sigma_{hh} &= -16.71 \text{ dB} \\ \sigma_{vh} &= -25.19 \text{ dB} & & \\ \chi_d &= -7.66 \text{ dB} & & \\ \alpha &= 0.72 & \zeta &= -2.00^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.65 & m_h &= 0.76 \\ m_{45} &= 0.78 & m_{135} &= 0.76 \\ m_{lhc} &= 0.51 & m_{rhc} &= 0.47 \end{aligned}$$





Target Name: American Elm 1990
System: UMass
Spotsize: 1 m (6 dB two-way)

Target Description: Measurement of Ulmus americana (planophil) between April and July, 1990. Leaf shapes are ovate.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.1.1	131
horizontal	225	66	tree.1.2	132

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: American Elm 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

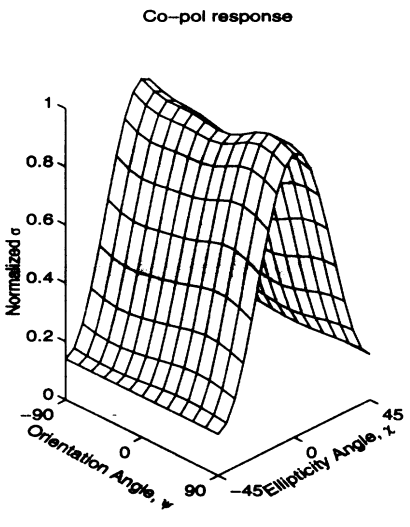
Modified Mueller Matrix:

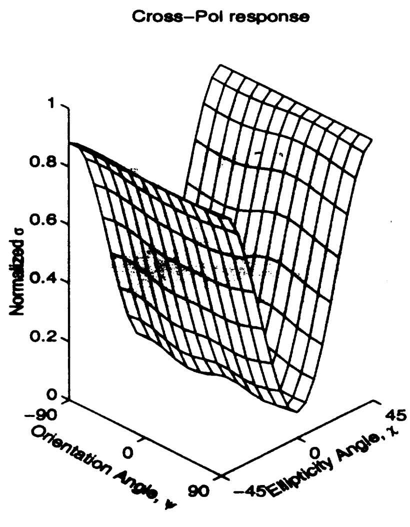
$$\mathbf{L}_m^\circ = 0.0219 \begin{bmatrix} 1.0000 & 0.0939 & -0.0020 & 0.0097 \\ 0.0939 & 1.0502 & 0.0204 & -0.0171 \\ -0.0041 & 0.0407 & 0.9568 & 0.0420 \\ -0.0194 & 0.0341 & -0.0420 & 0.7988 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -5.60 \text{ dB} & \sigma_{hh} &= -5.39 \text{ dB} \\ \sigma_{vh} &= -15.88 \text{ dB} & & \\ \chi_d &= -10.38 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= 2.74^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.84 \\ m_{45} &= 0.86 & m_{135} &= 0.85 \\ m_{lhc} &= 0.73 & m_{rhc} &= 0.70 \end{aligned}$$





Target: American Elm 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

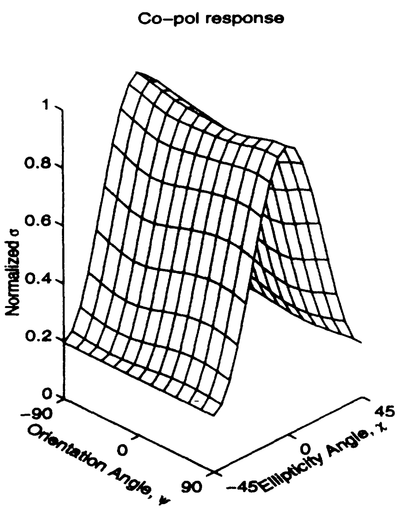
Modified Mueller Matrix:

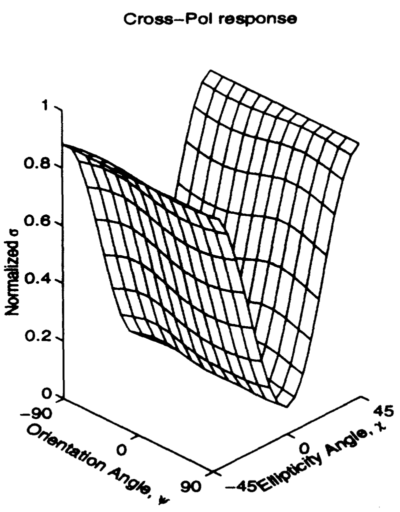
$$\mathbf{L}_m^\circ = 0.0123 \begin{bmatrix} 1.0000 & 0.0968 & -0.0022 & 0.0071 \\ 0.0968 & 1.0437 & 0.0017 & -0.0039 \\ -0.0044 & 0.0034 & 0.9016 & 0.0698 \\ -0.0142 & 0.0077 & -0.0698 & 0.7199 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -8.11 \text{ dB} & \sigma_{hh} &= -7.92 \text{ dB} \\ \sigma_{vh} &= -18.25 \text{ dB} \\ \chi_d &= -10.24 \text{ dB} \\ \alpha &= 0.80 & \zeta &= 4.92^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.83 \\ m_{45} &= 0.81 & m_{135} &= 0.81 \\ m_{lhc} &= 0.64 & m_{rhc} &= 0.65 \end{aligned}$$





Target Name: Arborvitae
1990
System: UMass
Spotsize: 1-2 m (6 dB two-way)

Target Description: Measurement of Thuja occidentalis (coniferous) between June and October, 1990.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.2.1	134
horizontal	225	31	tree.2.2	135

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Arborvitae 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

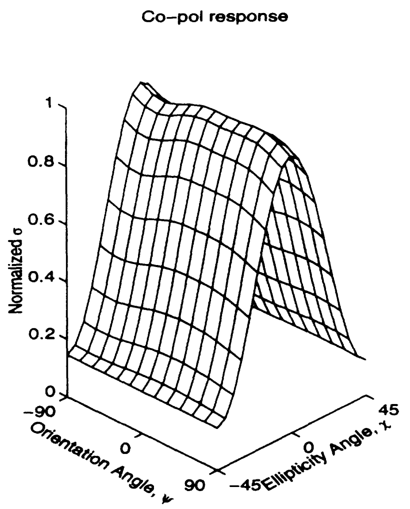
Modified Mueller Matrix:

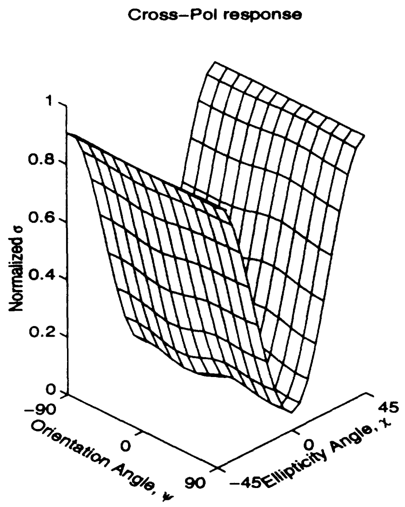
$$\mathbf{L}_m^\circ = 0.0098 \begin{bmatrix} 1.0000 & 0.0613 & 0.0007 & 0.0132 \\ 0.0613 & 0.9715 & 0.0210 & -0.0039 \\ 0.0014 & 0.0420 & 0.9216 & 0.0067 \\ -0.0263 & 0.0078 & -0.0067 & 0.7747 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -9.10 \text{ dB} & \sigma_{hh} &= -9.22 \text{ dB} \\ \sigma_{vh} &= -21.22 \text{ dB} & & \\ \chi_d &= -12.06 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= 0.45^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.88 \\ m_{45} &= 0.88 & m_{135} &= 0.88 \\ m_{lhc} &= 0.73 & m_{rhc} &= 0.76 \end{aligned}$$





Target: Arborvitae 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

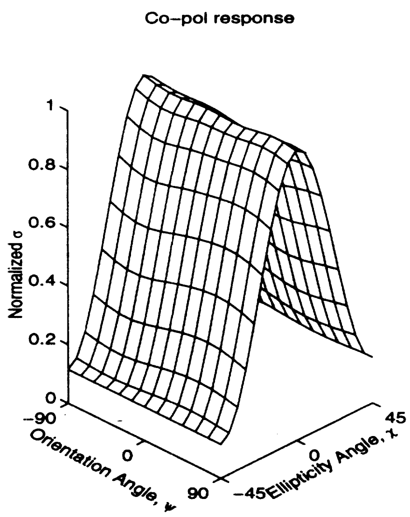
Modified Mueller Matrix:

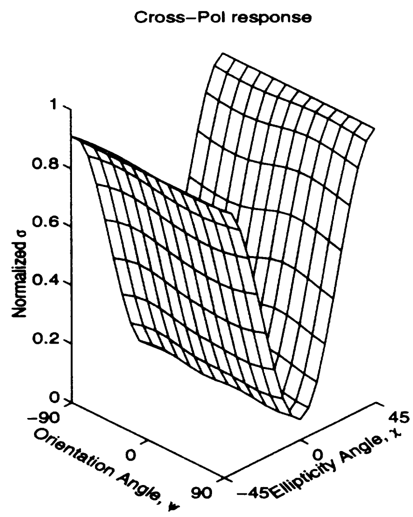
$$\mathbf{L}_m^\circ = 0.0068 \begin{bmatrix} 1.0000 & 0.0713 & -0.0025 & -0.0030 \\ 0.0713 & 1.0078 & 0.0087 & -0.0131 \\ -0.0051 & 0.0174 & 0.9239 & 0.0519 \\ 0.0059 & 0.0263 & -0.0519 & 0.7995 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -10.68 \text{ dB} & \sigma_{hh} &= -10.65 \text{ dB} \\ \sigma_{vh} &= -22.15 \text{ dB} & & \\ \chi_d &= -11.49 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= 3.45^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.87 \\ m_{45} &= 0.86 & m_{135} &= 0.86 \\ m_{lhc} &= 0.77 & m_{rhc} &= 0.72 \end{aligned}$$





Target Name: Norway Maple 1990
System: UMass
Spotsize: 1 m (6 dB two-way)

Target Description: Measurement of Norway maple (planophil) between April and July, 1990. Leaves are oblate, five lobed.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.3.1	137

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Norway Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

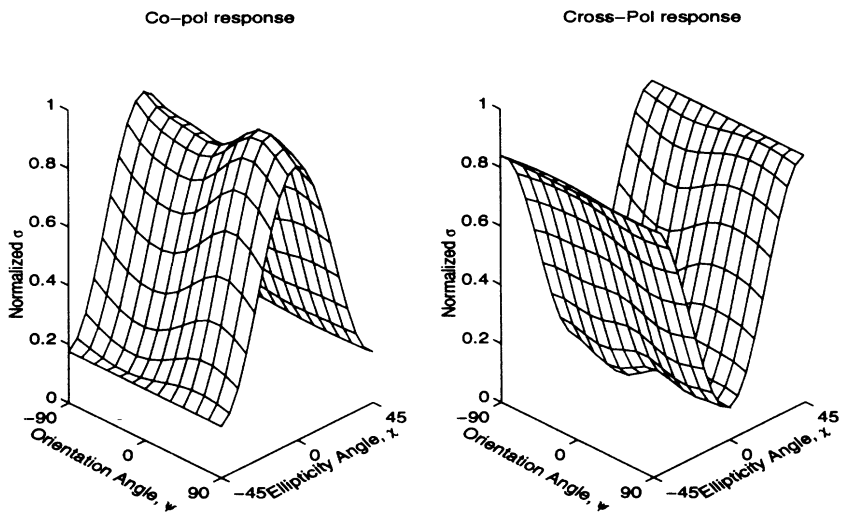
Modified Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0264 \begin{bmatrix} 1.0000 & 0.1249 & 0.0189 & -0.0083 \\ 0.1249 & 1.0643 & 0.0328 & 0.0094 \\ 0.0379 & 0.0655 & 0.9802 & 0.0931 \\ 0.0166 & -0.0187 & -0.0931 & 0.7592 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -4.79 \text{ dB} & \sigma_{hh} &= -4.52 \text{ dB} \\ \sigma_{vh} &= -13.83 \text{ dB} & & \\ \chi_d &= -9.17 \text{ dB} & & \\ \alpha &= 0.85 & \zeta &= 6.11^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.79 \\ m_{45} &= 0.86 & m_{135} &= 0.84 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.66 \end{aligned}$$



Target Name: Pinoak 1994
System: UMass
Spotsize: 1-3 m (6 dB two-way)

Target Description: Measurement of Quercus palustris, a tree characterized by the pyramidal manner of growth of its branches and deeply pinnated leaves.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	35	8	tree.4.1	139
horizontal	95	7	tree.4.2	140
horizontal	225	8	tree.4.3	141

References:
None

Target: Pinoak 1994
System/Frequency: UMass - 35 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

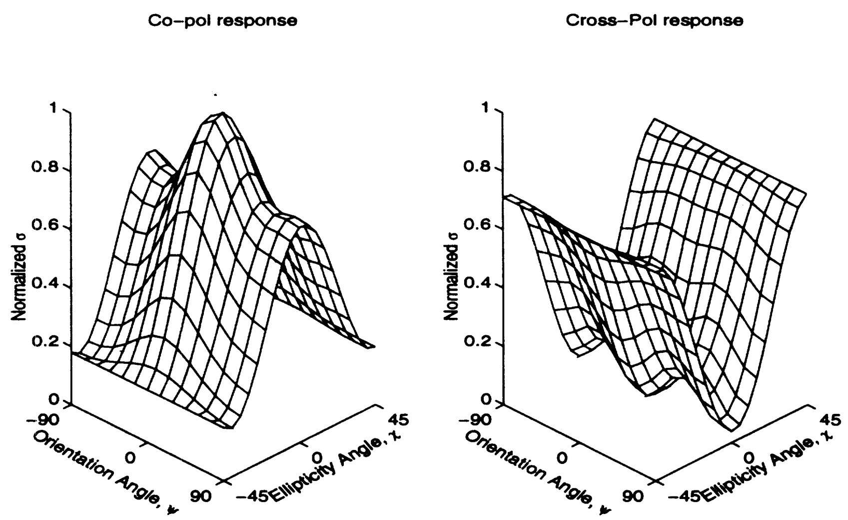
$$\mathbf{L}\,_m^{\circ} = 0.0040 \begin{bmatrix} 1.0000 & 0.0380 & -0.0120 & 0.0268 \\ 0.0380 & 0.7350 & 0.0157 & -0.0345 \\ -0.0240 & 0.0313 & 0.6047 & -0.0011 \\ -0.0536 & 0.0691 & 0.0011 & 0.5287 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -13.02 \text{ dB} & \sigma_{hh} &= -14.36 \text{ dB} \\ \sigma_{vh} &= -27.22 \text{ dB} \\ \chi_d &= -13.58 \text{ dB} \\ \alpha^{\ddagger} &= 0.66 & \zeta &= -0.11^{\circ} \end{aligned}$$

‡ value may be underestimated (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.93 & m_h &= 0.91 \\ m_{45} &= 0.68 & m_{135} &= 0.69 \\ m_{lhc} &= 0.64 & m_{rhc} &= 0.58 \end{aligned}$$



Target: Pinoak 1994
System/Frequency: UMass - 95 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

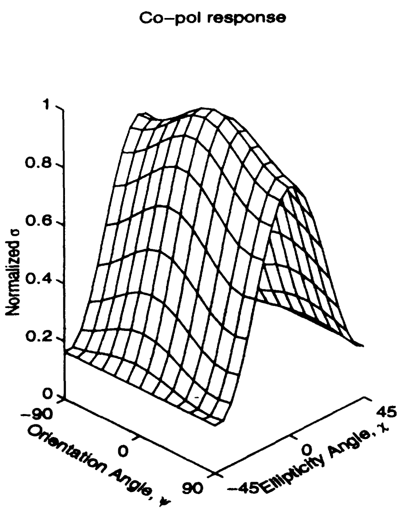
Modified Mueller Matrix:

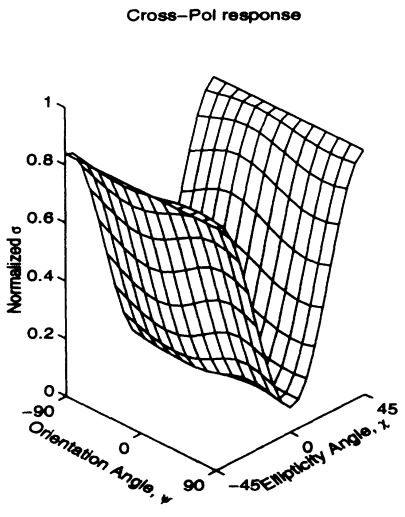
$$\mathbf{L}^{\circ}_{m} = 0.0017 \begin{bmatrix} 1.0000 & 0.0845 & 0.0051 & 0.0194 \\ 0.0845 & 0.8548 & 0.0026 & -0.0244 \\ 0.0102 & 0.0052 & 0.8228 & -0.0922 \\ -0.0389 & 0.0488 & 0.0922 & 0.6730 \end{bmatrix} .$$

$$\sigma_{vv} = -16.62 \text{ dB} \qquad \sigma_{hh} = -17.30 \text{ dB}$$
$$\sigma_{vh} = -27.35 \text{ dB}$$
$$\chi_d = -10.40 \text{ dB}$$
$$\alpha = 0.82 \qquad \zeta = -7.03^{\circ}$$

Degree of Polarization:

$$m_v = 0.84 \qquad m_h = 0.82$$
$$m_{45} = 0.82 \qquad m_{135} = 0.82$$
$$m_{lhc} = 0.69 \qquad m_{rhc} = 0.66$$





Target: Pinoak 1994
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

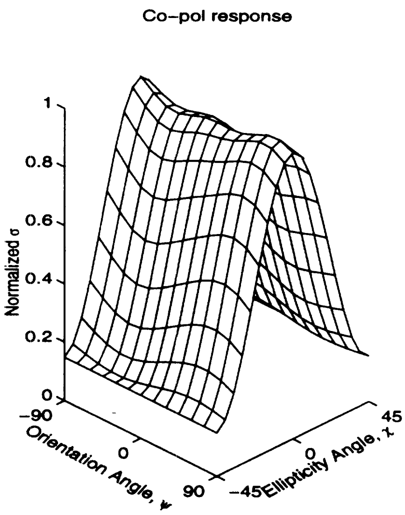
Modified Mueller Matrix:

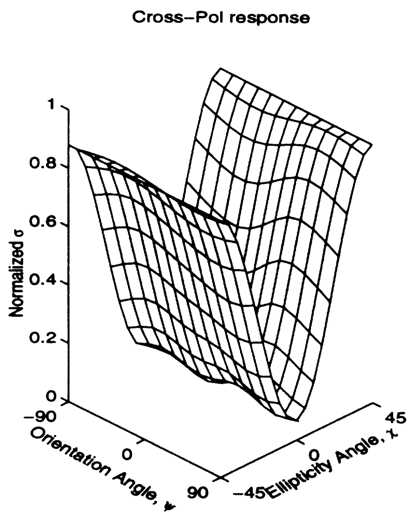
$$\mathbf{L}\,^{\circ}_{m} = 0.0013 \begin{bmatrix} 1.0000 & 0.0694 & -0.0001 & -0.0109 \\ 0.0694 & 1.0266 & 0.0239 & 0.0075 \\ -0.0002 & 0.0478 & 0.9034 & 0.1127 \\ 0.0218 & -0.0150 & -0.1127 & 0.7647 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -17.96 \text{ dB} & \sigma_{hh} &= -17.85 \text{ dB} \\ \sigma_{vh} &= -29.55 \text{ dB} & & \\ \chi_d &= -11.65 \text{ dB} & & \\ \alpha &= 0.83 & \zeta &= 7.69^{\circ} \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.87 & m_h &= 0.87 \\ m_{45} &= 0.84 & m_{135} &= 0.84 \\ m_{lhc} &= 0.72 & m_{rhc} &= 0.71 \end{aligned}$$





Target Name: Red Maple
1990
System: UMass
Spotsize: 1 m (6 dB two-way)

Target Description: Measurement of Acer rubrum (planophil) between June and October, 1990. Leaves are oblate, five lobed, 6-12 cm in diameter.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.5.1	143

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Red Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

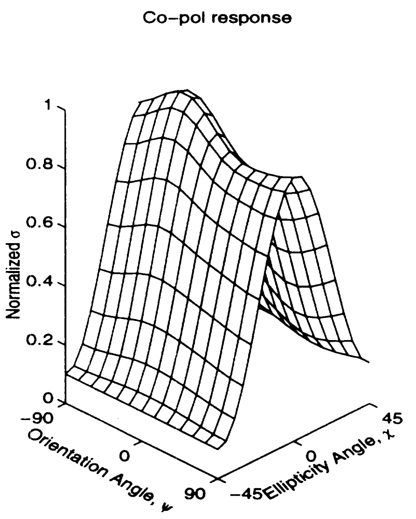
Modified Mueller Matrix:

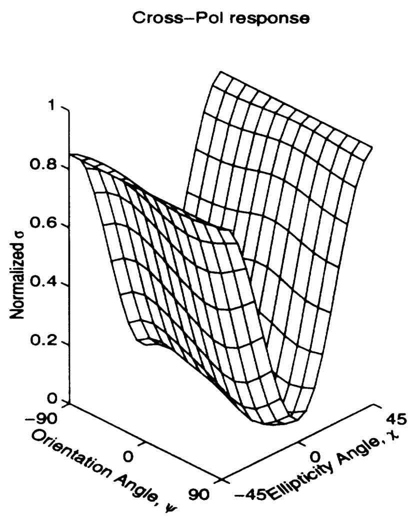
$$\mathbf{L}_m^\circ = 0.0469 \begin{bmatrix} 1.0000 & 0.0793 & -0.0385 & 0.0123 \\ 0.0793 & 0.9767 & -0.0217 & -0.0296 \\ -0.0771 & -0.0433 & 0.9508 & 0.0732 \\ -0.0246 & 0.0592 & -0.0732 & 0.8058 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -2.30 \text{ dB} & \sigma_{hh} &= -2.40 \text{ dB} \\ \sigma_{vh} &= -13.30 \text{ dB} \\ \chi_d &= -10.96 \text{ dB} \\ \alpha &= 0.89 & \zeta &= 4.76^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.85 \\ m_{45} &= 0.89 & m_{135} &= 0.90 \\ m_{lhc} &= 0.79 & m_{rhc} &= 0.74 \end{aligned}$$





Target Name: Silver Maple 1990
System: UMass
Spotsize: 1-2 m (6 dB two-way)

Target Description: Measurement of Acer saccharinum (planophil) between April and July, 1990. Leaves are oblate, five lobed, 10 - 15 cm long and wide.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.6.1	145
horizontal	225	65	tree.6.2	146

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Silver Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

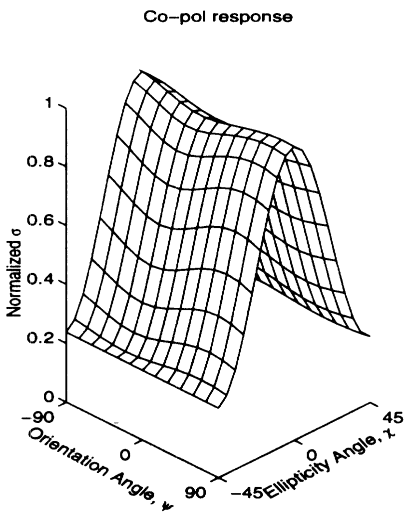
Modified Mueller Matrix:

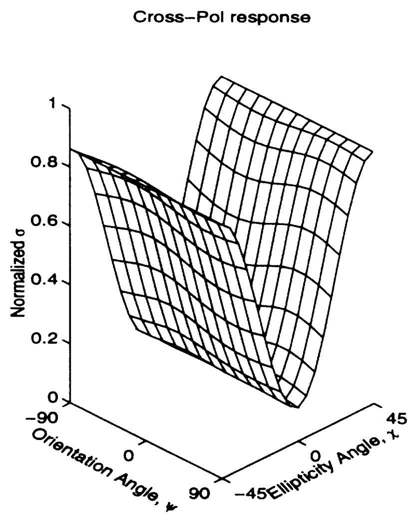
$$\mathbf{L}_m^\circ = 0.0399 \begin{bmatrix} 1.0000 & 0.1198 & 0.0079 & -0.0064 \\ 0.1198 & 1.0473 & 0.0044 & 0.0118 \\ 0.0157 & 0.0089 & 0.8958 & 0.0717 \\ 0.0127 & -0.0236 & -0.0717 & 0.6583 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -3.00 \text{ dB} & \sigma_{hh} &= -2.80 \text{ dB} \\ \sigma_{vh} &= -12.21 \text{ dB} & & \\ \chi_d &= -9.32 \text{ dB} & & \\ \alpha &= 0.76 & \zeta &= 5.27° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.79 & m_h &= 0.79 \\ m_{45} &= 0.79 & m_{135} &= 0.78 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.59 \end{aligned}$$





Target: Silver Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

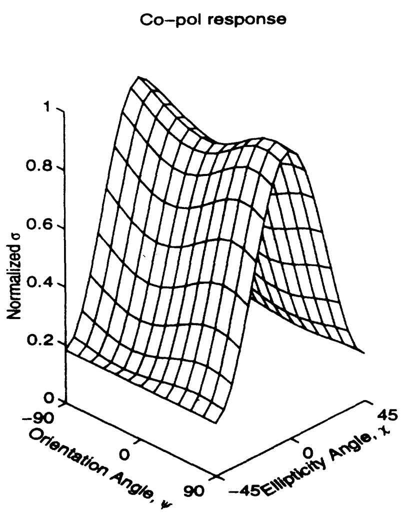
Modified Mueller Matrix:

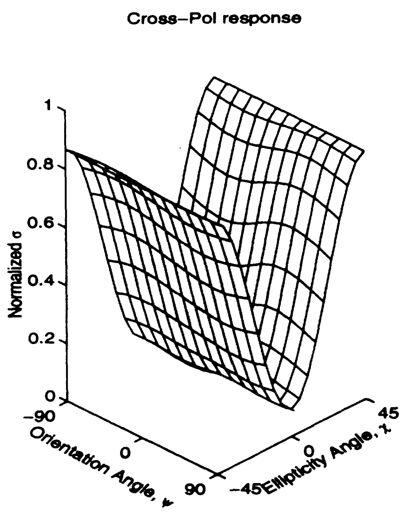
$$\mathbf{L}_m^\circ = 0.0120 \begin{bmatrix} 1.0000 & 0.1045 & 0.0076 & 0.0052 \\ 0.1045 & 1.1115 & 0.0162 & 0.0041 \\ 0.0152 & 0.0323 & 0.9508 & 0.0788 \\ -0.0103 & -0.0081 & -0.0788 & 0.7723 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -8.22 \text{ dB} & \sigma_{hh} &= -7.76 \text{ dB} \\ \sigma_{vh} &= -18.02 \text{ dB} & & \\ \chi_d &= -10.04 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= 5.23° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.83 \\ m_{45} &= 0.83 & m_{135} &= 0.82 \\ m_{lhc} &= 0.66 & m_{rhc} &= 0.68 \end{aligned}$$





Target Name: Sugar Maple 1990
System: UMass
Spotsize: 1-3 m (6 dB two-way)

Target Description: Measurement of Acer saccharum (planophil) between April and July, 1990. Leaves are ovate, five lobed, 6-12 cm diameter.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	71	tree.7.1	148

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Sugar Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

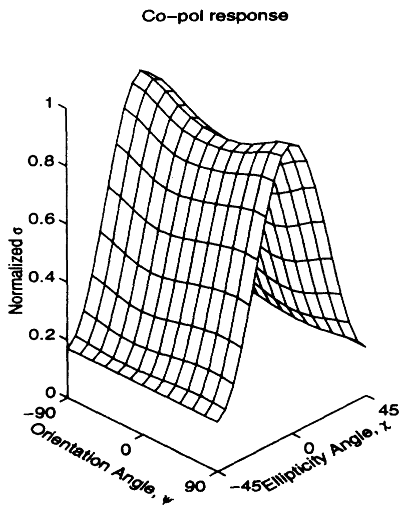
Modified Mueller Matrix:

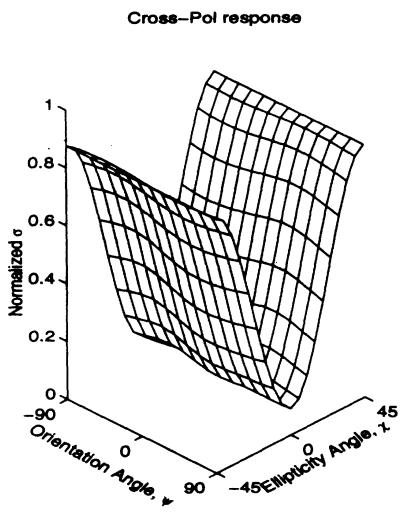
$$\mathbf{L}_m^\circ = 0.0258 \begin{bmatrix} 1.0000 & 0.0996 & -0.0007 & 0.0090 \\ 0.0996 & 1.1023 & -0.0033 & -0.0076 \\ -0.0015 & -0.0066 & 0.9201 & 0.0558 \\ -0.0179 & 0.0151 & -0.0558 & 0.7792 \end{bmatrix}$$

$$\sigma_{vv} = -4.89 \text{ dB} \qquad \sigma_{hh} = -4.47 \text{ dB}$$
$$\sigma_{vh} = -14.91 \text{ dB}$$
$$\chi_d = -10.23 \text{ dB}$$
$$\alpha = 0.81 \qquad \zeta = 3.76^\circ$$

Degree of Polarization:

$$m_v = 0.82 \qquad m_h = 0.83$$
$$m_{45} = 0.80 \qquad m_{135} = 0.80$$
$$m_{lhc} = 0.68 \qquad m_{rhc} = 0.68$$





Target Name: Willow 1994
System: UMass
Spotsize: 1-3 m (6 dB two-way)

Target Description: Measurement of Salix babylonica (planophil) between June and October, 1990 and also July 1994. Leaves are lance shaped (6-13 cm long and 6-12 mm wide).

Data List:

θ_i	freq.	# of expmts.	year	data no.	page no.
horizontal	225	1	1990	tree.8.1	150
horizontal	225	99	1990	tree.8.2	151
horizontal	35	12	1994	tree.8.3	152
horizontal	95	12	1994	tree.8.4	153
horizontal	225	12	1994	tree.8.5	154

References:

James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept. 1991.

Target: Weeping Willow
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

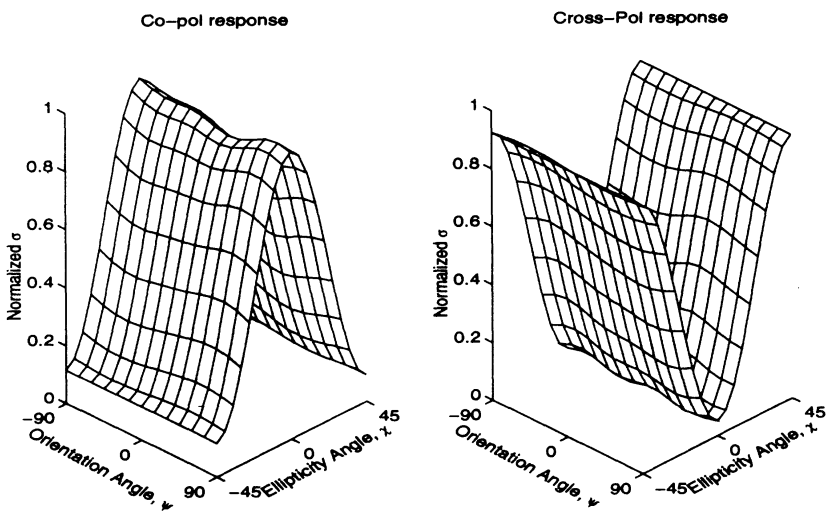
Modified Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0296 \begin{bmatrix} 1.0000 & 0.0536 & -0.0117 & 0.0109 \\ 0.0536 & 1.0403 & 0.0125 & -0.0019 \\ -0.0234 & 0.0250 & 0.9627 & 0.0627 \\ -0.0219 & 0.0037 & -0.0627 & 0.8545 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -4.29 \text{ dB} & \sigma_{hh} &= -4.12 \text{ dB} \\ \sigma_{vh} &= -17.00 \text{ dB} & & \\ \chi_d &= -12.79 \text{ dB} & & \\ \alpha &= 0.89 & \zeta &= 3.95^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.90 & m_h &= 0.90 \\ m_{45} &= 0.90 & m_{135} &= 0.90 \\ m_{lhc} &= 0.78 & m_{rhc} &= 0.81 \end{aligned}$$



Target: Weeping Willow
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

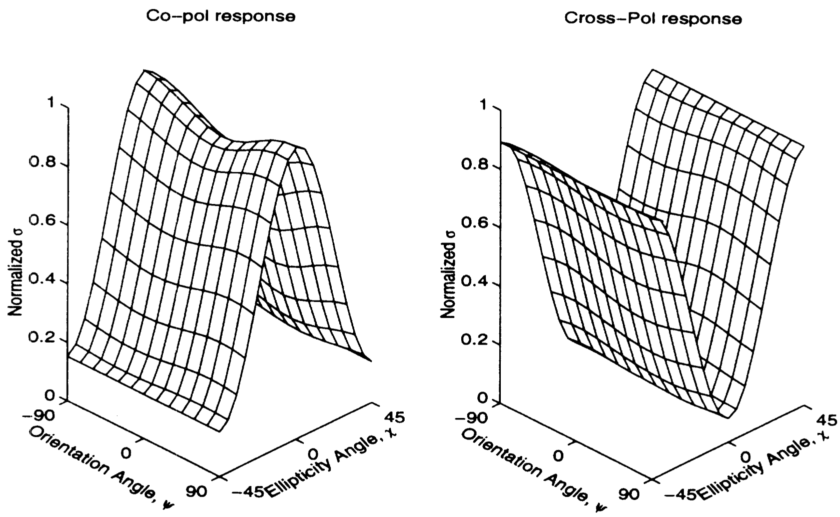
Modified Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0282 \begin{bmatrix} 1.0000 & 0.0891 & -0.0026 & 0.0158 \\ 0.0891 & 1.1020 & 0.0021 & -0.0106 \\ -0.0051 & 0.0042 & 0.9667 & 0.0466 \\ -0.0315 & 0.0212 & -0.0466 & 0.8169 \end{bmatrix}$$

$$\sigma_{vv} = -4.51 \text{ dB} \qquad \sigma_{hh} = -4.08 \text{ dB}$$
$$\sigma_{vh} = -15.01 \text{ dB}$$
$$\chi_d = -10.72 \text{ dB}$$
$$\alpha = 0.85 \qquad \zeta = 2.99^\circ$$

Degree of Polarization:

$$m_v = 0.84 \qquad m_h = 0.85$$
$$m_{45} = 0.85 \qquad m_{135} = 0.85$$
$$m_{lhc} = 0.71 \qquad m_{rhc} = 0.73$$



Target: Weeping Willow
System/Frequency: UMass - 35 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

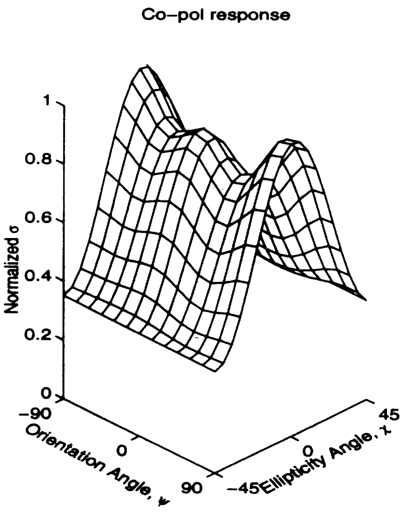
$$\mathbf{L}\,{}^{\circ}_{m} = 0.0015 \begin{bmatrix} 1.0000 & 0.1335 & -0.0290 & 0.0372 \\ 0.1335 & 1.1195 & 0.0210 & -0.0309 \\ -0.0581 & 0.0420 & 0.6895 & -0.0415 \\ -0.0745 & 0.0618 & 0.0415 & 0.4225 \end{bmatrix}$$

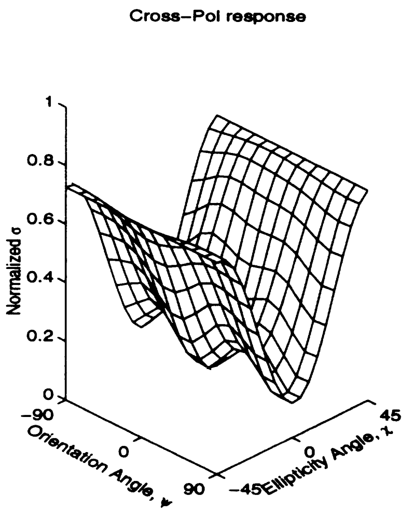
$$\begin{aligned} \sigma_{vv} &= -17.26 \text{ dB} & \sigma_{hh} &= -16.77 \text{ dB} \\ \sigma_{vh} &= -26.01 \text{ dB} \\ \chi_d &= -9.00 \text{ dB} \\ \alpha^{\ddagger} &= 0.53 & \zeta &= -4.27^{\circ} \end{aligned}$$

‡ value may be underestimated (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.77 & m_h &= 0.79 \\ m_{45} &= 0.58 & m_{135} &= 0.58 \\ m_{lhc} &= 0.35 & m_{rhc} &= 0.38 \end{aligned}$$





Target: Weeping Willow
System/Frequency: UMass - 95 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

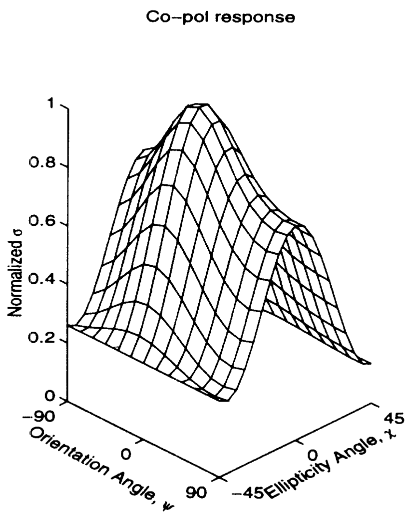
$$\mathbf{L}\,{}^{\circ}_{m} = 1.0000 \begin{bmatrix} 1.0000 & 0.1214 & -0.0446 & 0.0565 \\ 0.1214 & 0.7628 & -0.0120 & -0.0041 \\ -0.0892 & -0.0240 & 0.7464 & -0.0578 \\ -0.1130 & 0.0083 & 0.0578 & 0.5916 \end{bmatrix}$$

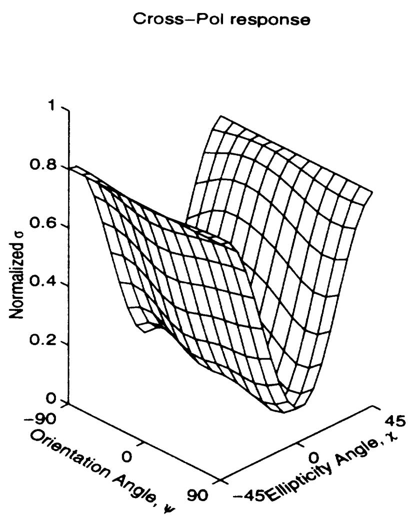
$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -1.18 \text{ dB} \\ \sigma^*_{vh} &= -9.16 \text{ dB} & & \\ \chi_d &= -8.61 \text{ dB} & & \\ \alpha &= 0.77 & \zeta &= -4.94^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.79 & m_h &= 0.73 \\ m_{45} &= 0.73 & m_{135} &= 0.78 \\ m_{lhc} &= 0.55 & m_{rhc} &= 0.68 \end{aligned}$$





Target: Weeping Willow
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

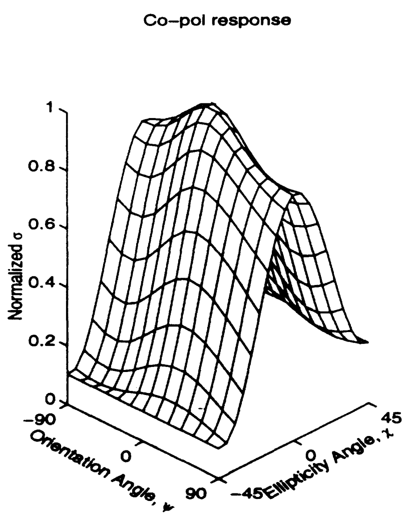
Modified Mueller Matrix:

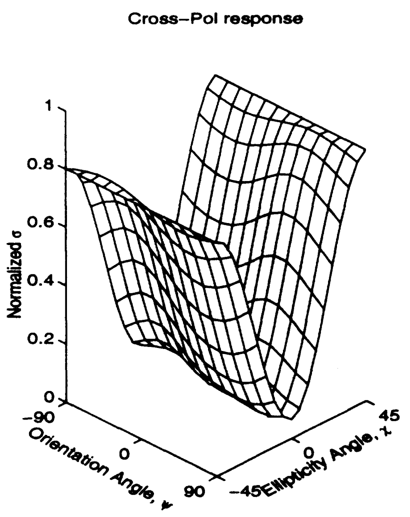
$$\mathbf{L}\,{}^{\circ}_{m} = 0.0018 \begin{bmatrix} 1.0000 & 0.0664 & -0.0130 & -0.0070 \\ 0.0664 & 0.8419 & 0.0008 & -0.0343 \\ -0.0261 & 0.0016 & 0.8108 & 0.1570 \\ 0.0141 & 0.0685 & -0.1570 & 0.6780 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -16.48 \text{ dB} & \sigma_{hh} &= -17.22 \text{ dB} \\ \sigma_{vh} &= -28.25 \text{ dB} & & \\ \chi_d &= -11.42 \text{ dB} & & \\ \alpha &= 0.83 & \zeta &= 11.91^{\circ} \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.88 & m_h &= 0.86 \\ m_{45} &= 0.83 & m_{135} &= 0.85 \\ m_{lhc} &= 0.78 & m_{rhc} &= 0.64 \end{aligned}$$





Target Name: White Pine
1990
System: UMass
Spotsize: 1-2 m (6 dB two-way)

Target Description: Measurement of Pinus strobus (coniferous) between April - June, 1990. Needle shaped leaves, 6-13 cm long and less than 0.55 cm wide.

Data List:

θ_i	freq.	# of expmts.	data no.	page no.
horizontal	225	1	tree.9.1	156
horizontal	225	51	tree.9.2	157

References:
James B. Mead, Philip M. Langlois, Paul S. Chang, Robert E. McIntosh, "Polarimetric Scattering from Natural Surfaces at 225 GHz", IEEE Transactions on Antennas and Propagation, Vol. 39, Num. 9, pp. 1405-1411. Sept, 1991.

Target: White Pine 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

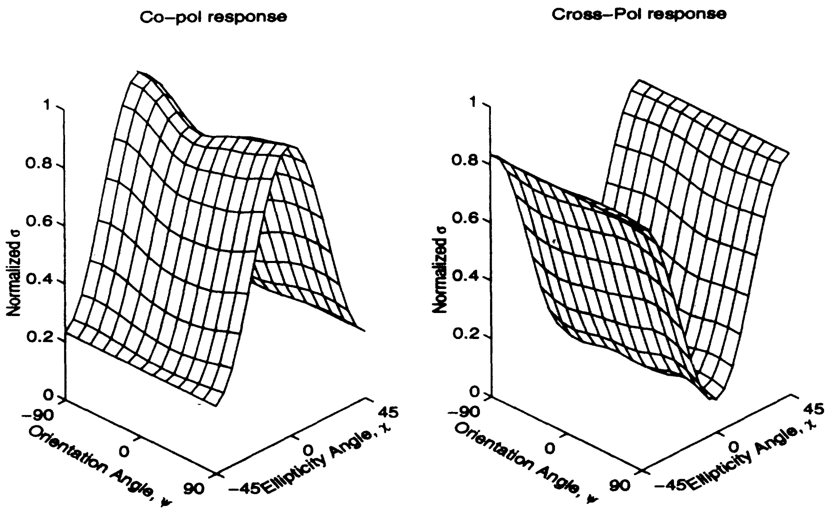
Modified Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0187 \begin{bmatrix} 1.0000 & 0.1251 & 0.0181 & -0.0002 \\ 0.1251 & 1.1070 & -0.0048 & 0.0019 \\ 0.0363 & -0.0096 & 0.9076 & -0.0604 \\ 0.0005 & -0.0039 & 0.0604 & 0.6682 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -6.29 \text{ dB} & \sigma_{hh} &= -5.85 \text{ dB} \\ \sigma_{vh} &= -15.32 \text{ dB} & & \\ \chi_d &= -9.25 \text{ dB} & & \\ \alpha &= 0.75 & \zeta &= -4.38° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.80 \\ m_{45} &= 0.77 & m_{135} &= 0.77 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.57 \end{aligned}$$



Target: White Pine 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

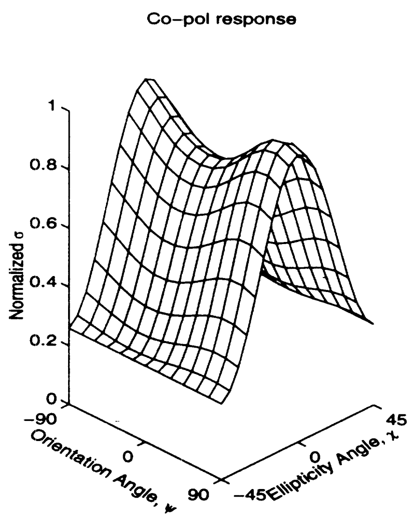
Modified Mueller Matrix:

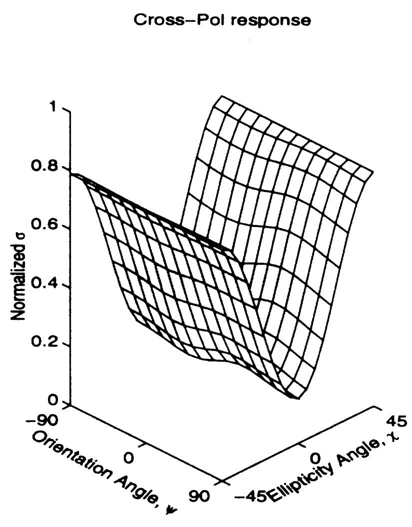
$$\mathbf{L}_m^\circ = 0.0107 \begin{bmatrix} 1.0000 & 0.1831 & 0.0143 & 0.0025 \\ 0.1831 & 1.1709 & 0.0296 & -0.0102 \\ 0.0285 & 0.0592 & 0.8953 & 0.0288 \\ -0.0051 & 0.0204 & -0.0288 & 0.6286 \end{bmatrix}$$

$$\sigma_{vv} = -8.71 \text{ dB} \qquad \sigma_{hh} = -8.03 \text{ dB}$$
$$\sigma_{vh} = -16.09 \text{ dB}$$
$$\chi_d = -7.73 \text{ dB}$$
$$\alpha = 0.70 \qquad \zeta = 2.16°$$

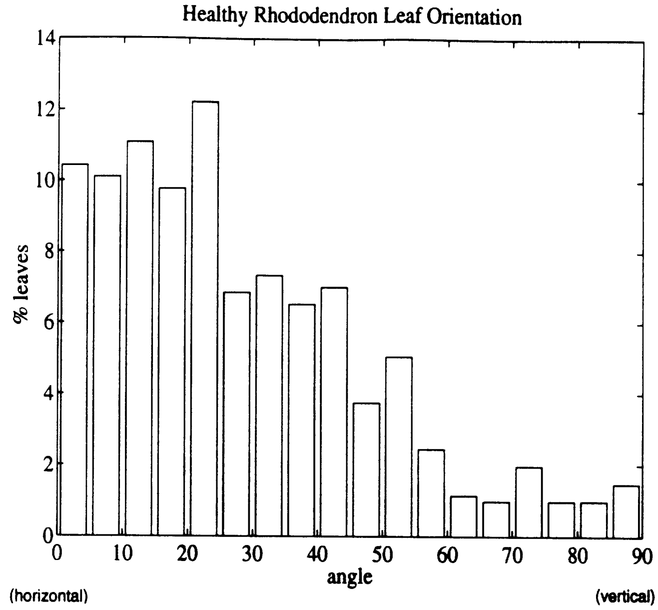
Degree of Polarization:

$$m_v = 0.69 \qquad m_h = 0.73$$
$$m_{45} = 0.72 \qquad m_{135} = 0.70$$
$$m_{lhc} = 0.51 \qquad m_{rhc} = 0.49$$





Target Name: Rhododendron 1991
System: UM



Target Description: Short trunk, long branched planophil. Leaves are prolate shaped with large leaves having the dimensions of 10-11 cm by 3-4 cm and smaller leaves with dimensions of 6-8 cm by 2-3 cm. After June 6, the plant was intentionally deprived of water to study the effects of changing leaf water content and leaf orientation (which became rectophil).

date	leaf water content
5/27	62%
6/1	61%
6/6	60%
6/17	56%
6/18	56%
6/20	53%
6/21	48%

(note: computation of the illumination area for 35 GHz system was uncertain, therefore, these data are normalized to L_{11}. Affected quantities on the following pages are indicated by an asterisk).

References:

Nashashibi, Kuga and Ulaby, "Polarimetric Observations of Trees at 35 and 94 GHz," APS, London, Ontario. June 1990.

Data List:

θ_i	freq.	condition	date	data no.	page no.
10	35	watered	5/27	tree.10.1	160
10	35	watered	6/03	tree.10.2	161
10	35	watered	6/06	tree.10.3	162
15	35	watered	6/03	tree.10.4	163
15	35	watered	6/06	tree.10.5	164
20	35	watered	5/27	tree.10.6	165
20	35	watered	6/03	tree.10.7	166
20	35	watered	6/06	tree.10.8	167
25	35	watered	6/03	tree.10.9	168
30	35	watered	5/27	tree.10.10	169
30	35	watered	6/03	tree.10.11	170
30	35	watered	6/06	tree.10.12	171
40	35	watered	5/27	tree.10.13	172
50	35	watered	5/27	tree.10.14	173
70	35	watered	5/27	tree.10.15	174
90	35	watered	5/27	tree.10.16	175
10	94	watered	5/31	tree.10.17	176
20	94	watered	5/31	tree.10.18	177
30	94	watered	5/31	tree.10.19	178
40	94	watered	5/31	tree.10.20	179
50	94	watered	5/31	tree.10.21	180
60	94	watered	5/31	tree.10.22	181
70	94	watered	5/31	tree.10.23	182
90	94	watered	5/31	tree.10.24	183
20	35	drying	6/18	tree.10.25	184
30	35	drying	6/18	tree.10.26	185
30	35	drying	6/21	tree.10.27	186
50	35	drying	6/17	tree.10.28	187
50	35	drying	6/18	tree.10.29	188
50	35	drying	6/21	tree.10.30	189
70	35	drying	6/18	tree.10.31	190
70	35	drying	6/21	tree.10.32	191
90	35	drying	6/17	tree.10.33	192
90	35	drying	6/18	tree.10.34	193
90	35	drying	6/21	tree.10.35	194

Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 10°
Independent Samples: 99

Normalized Mueller Matrix:

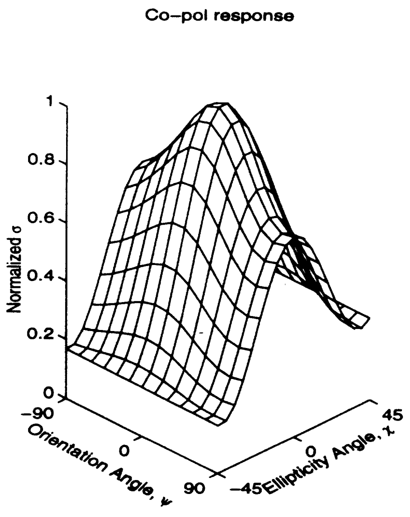
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1012 & -0.0232 & -0.0488 \\ 0.1118 & 0.6834 & -0.0199 & 0.0171 \\ -0.0072 & -0.0373 & 0.6779 & -0.0393 \\ 0.0928 & 0.0011 & 0.0087 & 0.5043 \end{bmatrix}$$

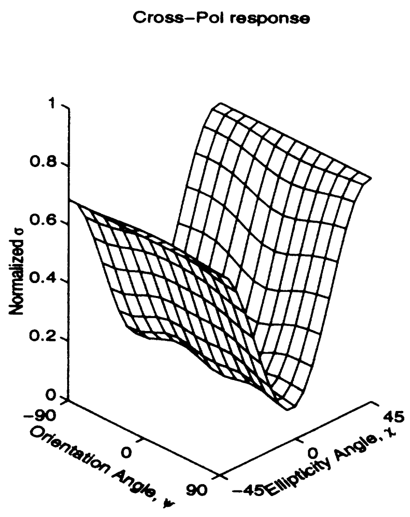
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.65 \text{ dB} \\ \sigma_{vh}^* &= -9.73 \text{ dB} & & \\ \chi_d &= -8.98 \text{ dB} & & \\ \alpha &= 0.72 & \zeta &= -2.32^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.80 & m_h &= 0.74 \\ m_{45} &= 0.75 & m_{135} &= 0.72 \\ m_{lhc} &= 0.61 & m_{rhc} &= 0.52 \end{aligned}$$





Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 10°
Independent Samples: 99

Normalized Mueller Matrix:

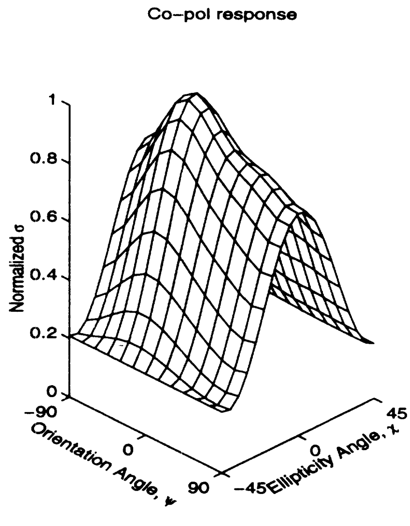
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1502 & -0.0199 & 0.0428 \\ 0.1976 & 0.8292 & -0.0571 & -0.0129 \\ -0.1072 & -0.0112 & 0.8758 & -0.0896 \\ -0.0629 & 0.0543 & 0.0146 & 0.6571 \end{bmatrix}$$

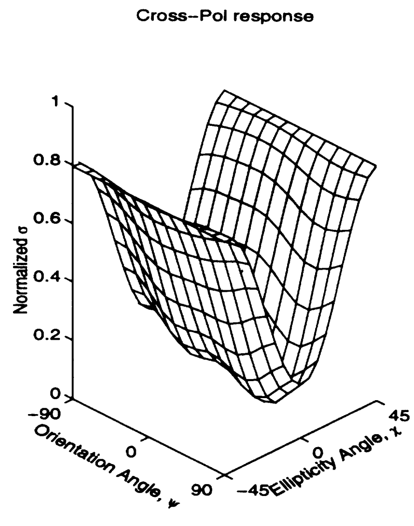
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.81 \text{ dB} \\ \sigma_{vh}^* &= -7.60 \text{ dB} & & \\ \chi_d &= -7.21 \text{ dB} & & \\ \alpha &= 0.84 & \zeta &= -3.89° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.68 & m_h &= 0.70 \\ m_{45} &= 0.81 & m_{135} &= 0.80 \\ m_{lhc} &= 0.61 & m_{rhc} &= 0.63 \end{aligned}$$





Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 10°
Independent Samples: 99

Normalized Mueller Matrix:

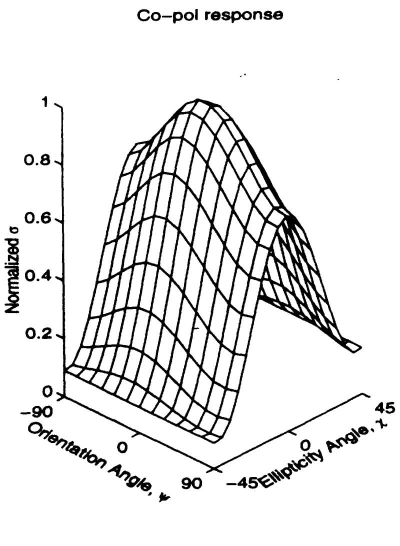
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1004 & -0.0245 & -0.0048 \\ 0.0926 & 0.7429 & -0.0124 & -0.0093 \\ -0.0190 & -0.0133 & 0.7927 & -0.0714 \\ 0.0528 & 0.0086 & 0.0643 & 0.7202 \end{bmatrix}$$

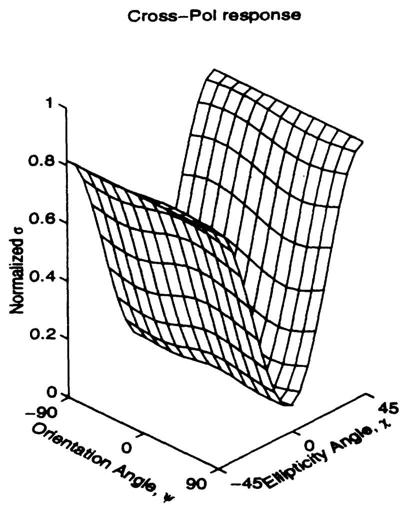
$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -1.29 \text{ dB} \\ \sigma^*_{vh} &= -10.15 \text{ dB} \\ \chi_d &= -9.56 \text{ dB} \\ \alpha &= 0.88 & \zeta &= -5.13° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.76 \\ m_{45} &= 0.85 & m_{135} &= 0.82 \\ m_{lhc} &= 0.81 & m_{rhc} &= 0.72 \end{aligned}$$





Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 15°
Independent Samples: 99

Normalized Mueller Matrix:

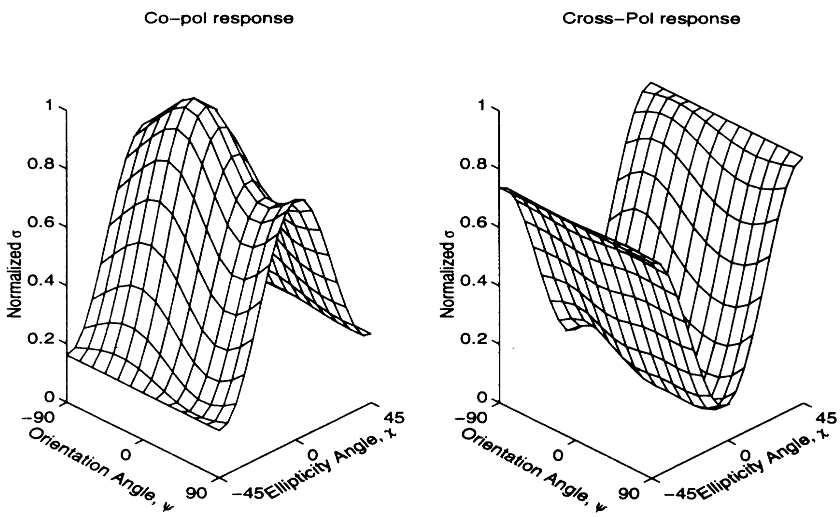
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0897 & -0.0438 & 0.0233 \\ 0.1303 & 0.8738 & -0.0578 & 0.0080 \\ -0.1204 & -0.0608 & 0.7758 & -0.1042 \\ 0.0566 & 0.0373 & 0.0795 & 0.6274 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.59 \text{ dB} \\ \sigma_{vh}^* &= -9.59 \text{ dB} & & \\ \chi_d &= -9.30 \text{ dB} & & \\ \alpha &= 0.76 & \zeta &= -7.46^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.82 \\ m_{45} &= 0.74 & m_{135} &= 0.76 \\ m_{lhc} &= 0.65 & m_{rhc} &= 0.57 \end{aligned}$$



Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 15°
Independent Samples: 99

Normalized Mueller Matrix:

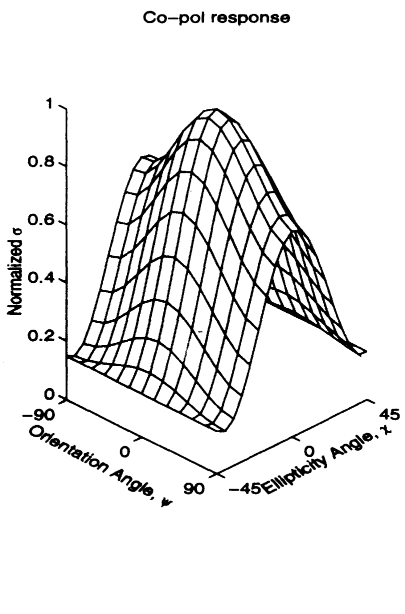
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0662 & 0.0039 & 0.0233 \\ 0.1073 & 0.7043 & 0.0165 & -0.0299 \\ 0.0103 & 0.0191 & 0.7584 & -0.0378 \\ -0.0319 & 0.0437 & 0.0146 & 0.6271 \end{bmatrix}$$

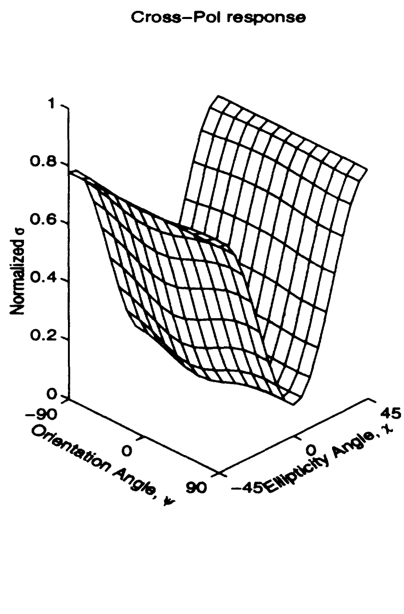
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.52 \text{ dB} \\ \sigma_{vh}^* &= -10.62 \text{ dB} & & \\ \chi_d &= -9.92 \text{ dB} & & \\ \alpha &= 0.83 & \zeta &= -2.16° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.83 \\ m_{45} &= 0.82 & m_{135} &= 0.82 \\ m_{lhc} &= 0.71 & m_{rhc} &= 0.66 \end{aligned}$$





Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

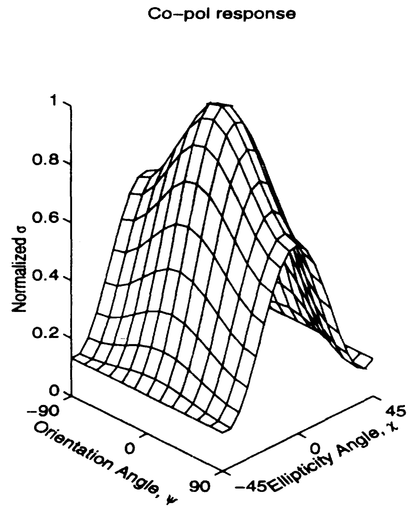
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0646 & -0.0068 & -0.0140 \\ 0.0800 & 0.6500 & -0.0002 & 0.0345 \\ -0.0177 & -0.0044 & 0.7438 & 0.0064 \\ 0.0534 & -0.0455 & -0.0245 & 0.6378 \end{bmatrix}$$

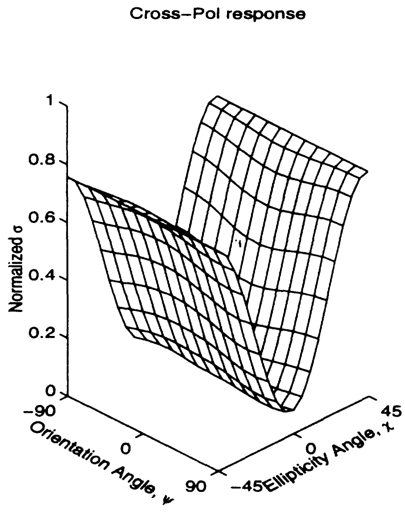
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.87 \text{ dB} \\ \sigma_{vh}^* &= -11.41 \text{ dB} \\ \chi_d &= -10.57 \text{ dB} \\ \alpha &= 0.86 & \zeta &= 1.28° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.82 \\ m_{45} &= 0.84 & m_{135} &= 0.86 \\ m_{lhc} &= 0.71 & m_{rhc} &= 0.76 \end{aligned}$$





Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

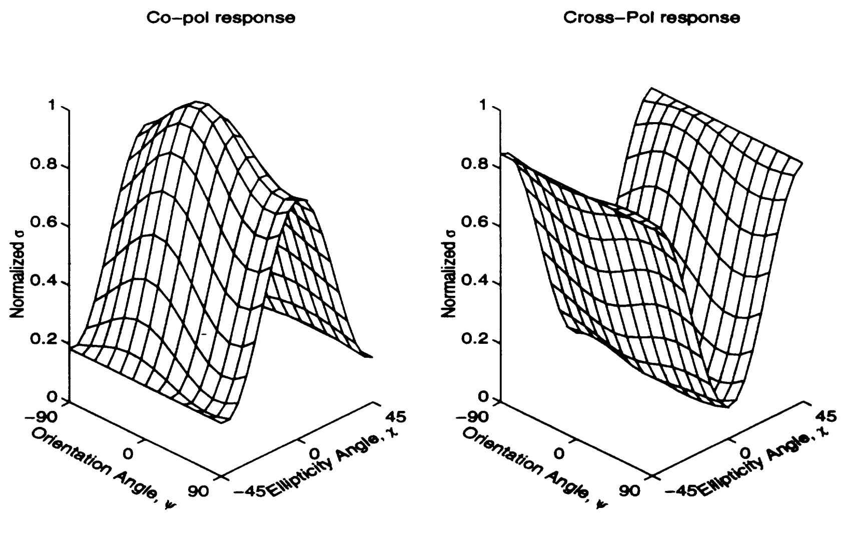
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0980 & -0.0132 & 0.0238 \\ 0.1109 & 0.8367 & -0.0464 & -0.0255 \\ -0.0574 & -0.0341 & 0.7944 & -0.1425 \\ -0.0543 & 0.0228 & 0.0994 & 0.6784 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.77 \text{ dB} \\ \sigma_{vh}^* &= -9.81 \text{ dB} & & \\ \chi_d &= -9.44 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= -9.33^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.80 & m_h &= 0.79 \\ m_{45} &= 0.79 & m_{135} &= 0.78 \\ m_{lhc} &= 0.69 & m_{rhc} &= 0.68 \end{aligned}$$



Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0773 & -0.0630 & 0.0296 \\ 0.0884 & 0.7817 & -0.0612 & 0.0003 \\ -0.1104 & -0.1078 & 0.8134 & -0.0890 \\ -0.0543 & 0.0245 & 0.0571 & 0.7162 \end{bmatrix}$$

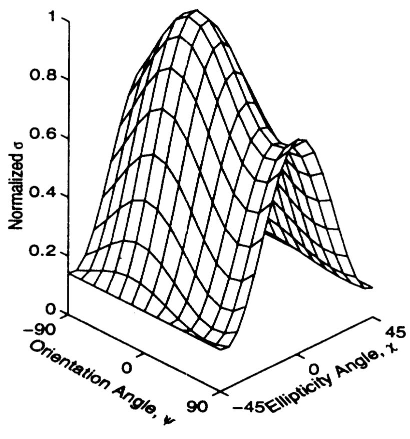
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.07 \text{ dB} \\ \sigma_{vh}^* &= -10.82 \text{ dB} & & \\ \chi_d &= -10.32 \text{ dB} & & \\ \alpha &= 0.87 & \zeta &= -5.45^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

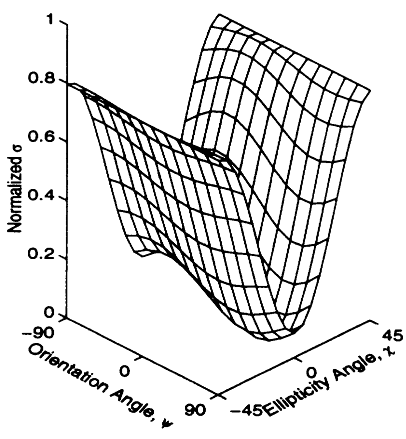
Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.83 \\ m_{45} &= 0.84 & m_{135} &= 0.85 \\ m_{lhc} &= 0.74 & m_{rhc} &= 0.78 \end{aligned}$$

Co-pol response



Cross-Pol response



Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 25°
Independent Samples: 99

Normalized Mueller Matrix:

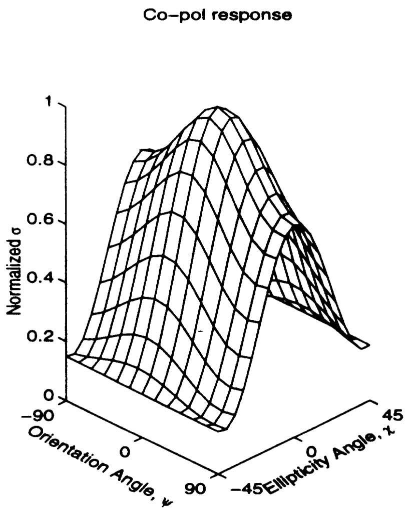
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0641 & -0.0126 & 0.0112 \\ 0.0965 & 0.7238 & 0.0154 & -0.0101 \\ 0.0243 & -0.0138 & 0.7348 & -0.1212 \\ 0.0056 & 0.0322 & 0.0753 & 0.6054 \end{bmatrix}$$

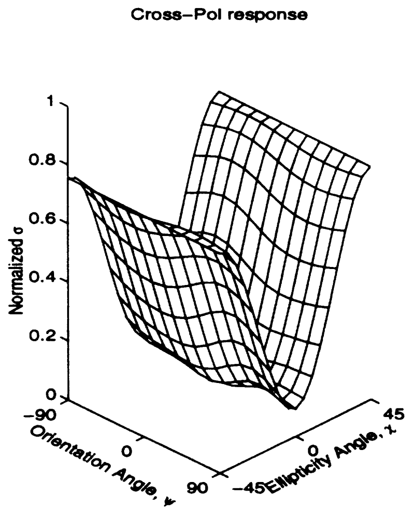
$$\sigma_{vv}^* = 0.00 \text{ dB} \qquad \sigma_{hh}^* = -1.40 \text{ dB}$$
$$\sigma_{vh}^* = -10.95 \text{ dB}$$
$$\chi_d = -10.31 \text{ dB}$$
$$\alpha = 0.80 \qquad \zeta = -8.34^\circ$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$m_v = 0.82 \qquad m_h = 0.84$$
$$m_{45} = 0.80 \qquad m_{135} = 0.80$$
$$m_{lhc} = 0.69 \qquad m_{rhc} = 0.65$$





Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

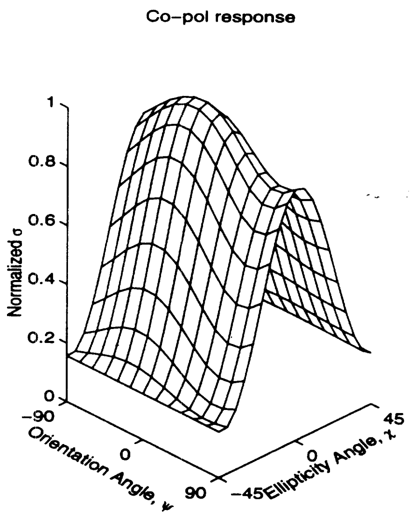
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0838 & -0.0334 & 0.0189 \\ 0.1020 & 0.8699 & -0.0308 & -0.0259 \\ -0.0376 & -0.0667 & 0.8191 & -0.0916 \\ -0.0397 & 0.0535 & 0.0640 & 0.6915 \end{bmatrix}$$

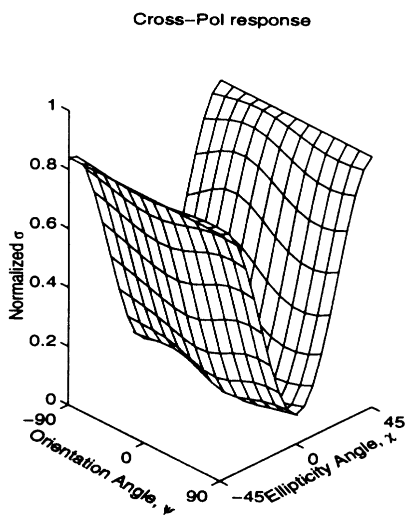
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.61 \text{ dB} \\ \sigma_{vh}^* &= -10.32 \text{ dB} \\ \chi_d &= -10.03 \text{ dB} \\ \alpha &= 0.81 & \zeta &= -5.88° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.83 \\ m_{45} &= 0.80 & m_{135} &= 0.80 \\ m_{lhc} &= 0.71 & m_{rhc} &= 0.66 \end{aligned}$$





Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

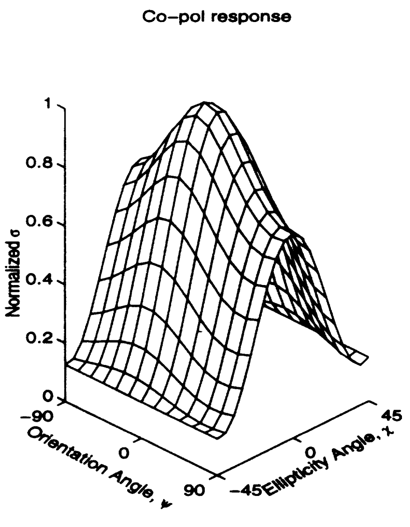
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0571 & -0.0169 & -0.0070 \\ 0.0913 & 0.7110 & -0.0220 & 0.0242 \\ -0.0645 & -0.0160 & 0.7628 & -0.0841 \\ 0.0642 & -0.0316 & 0.0234 & 0.6500 \end{bmatrix}$$

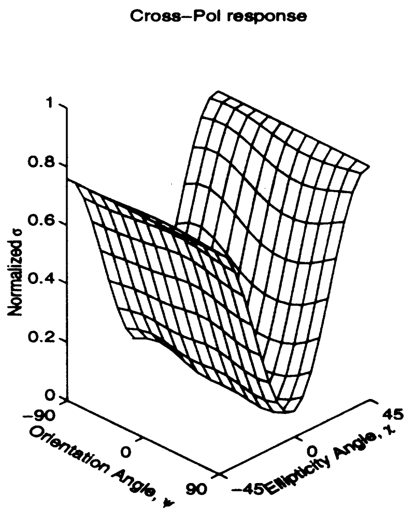
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.48 \text{ dB} \\ \sigma_{vh}^* &= -11.30 \text{ dB} & & \\ \chi_d &= -10.62 \text{ dB} & & \\ \alpha &= 0.84 & \zeta &= -4.35^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.84 & m_h &= 0.85 \\ m_{45} &= 0.83 & m_{135} &= 0.84 \\ m_{lhc} &= 0.72 & m_{rhc} &= 0.72 \end{aligned}$$





Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

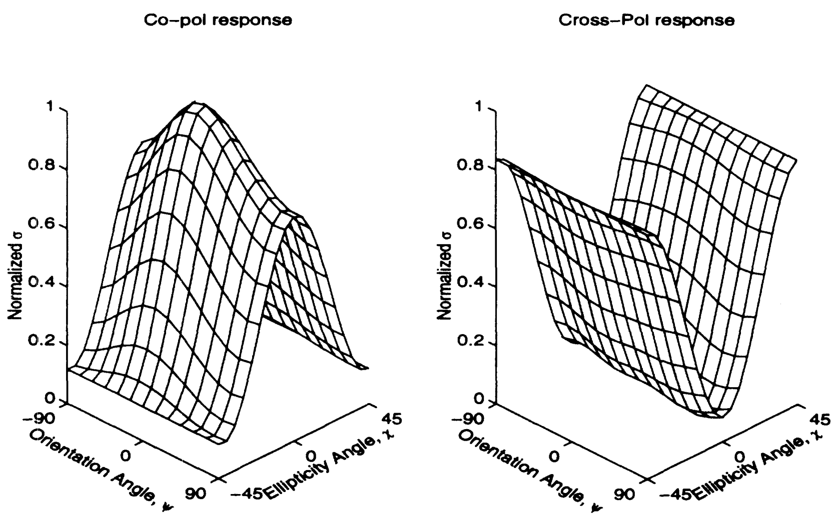
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0853 & -0.0412 & 0.0125 \\ 0.0850 & 0.7866 & -0.0304 & -0.0170 \\ -0.0547 & -0.0208 & 0.8324 & -0.0588 \\ -0.0397 & 0.0403 & 0.0037 & 0.7341 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.04 \text{ dB} \\ \sigma_{vh}^* &= -10.70 \text{ dB} & & \\ \chi_d &= -10.21 \text{ dB} & & \\ \alpha &= 0.88 & \zeta &= -2.28^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.81 \\ m_{45} &= 0.88 & m_{135} &= 0.84 \\ m_{lhc} &= 0.77 & m_{rhc} &= 0.75 \end{aligned}$$



Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

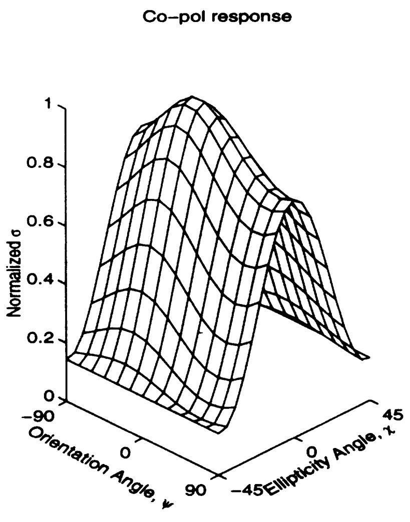
$$\mathbf{L}_m^{\circ} = 1.0000 \begin{bmatrix} 1.0000 & 0.0676 & -0.0275 & -0.0130 \\ 0.1064 & 0.8370 & -0.0278 & -0.0018 \\ -0.0677 & -0.0381 & 0.8384 & -0.1215 \\ -0.0030 & -0.0026 & 0.0782 & 0.7073 \end{bmatrix}$$

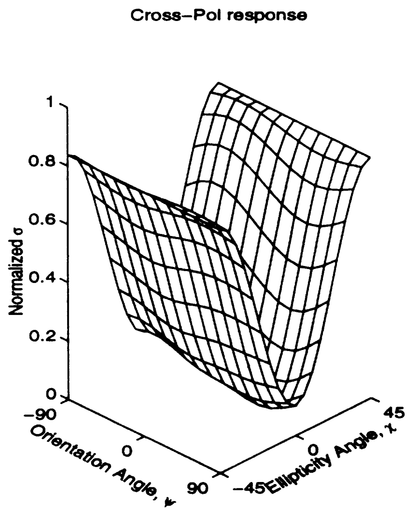
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.77 \text{ dB} \\ \sigma_{vh}^* &= -10.60 \text{ dB} & & \\ \chi_d &= -10.23 \text{ dB} & & \\ \alpha &= 0.85 & \zeta &= -7.36^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.85 \\ m_{45} &= 0.83 & m_{135} &= 0.85 \\ m_{lhc} &= 0.73 & m_{rhc} &= 0.70 \end{aligned}$$





Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

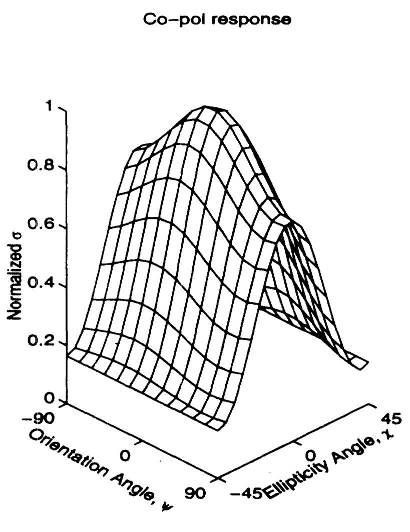
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0822 & -0.0127 & -0.0343 \\ 0.1037 & 0.7556 & -0.0194 & 0.0237 \\ -0.0174 & -0.0160 & 0.7807 & -0.0620 \\ 0.0511 & -0.0770 & 0.0448 & 0.6636 \end{bmatrix}$$

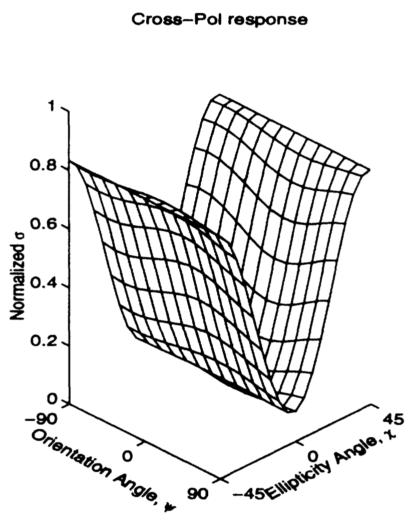
$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -1.22 \text{ dB} \\ \sigma^*_{vh} &= -10.32 \text{ dB} \\ \chi_d &= -9.75 \text{ dB} \\ \alpha &= 0.83 & \zeta &= -4.23° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.81 \\ m_{45} &= 0.82 & m_{135} &= 0.80 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

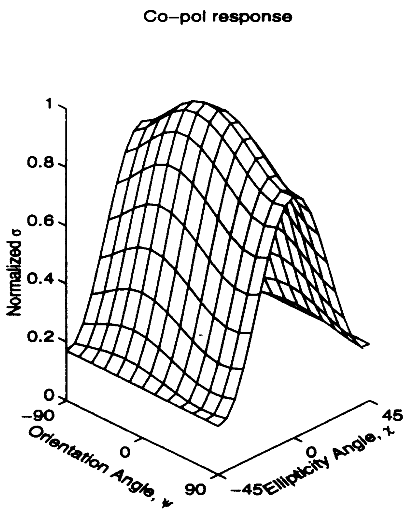
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1120 & -0.0111 & -0.0017 \\ 0.1363 & 0.8326 & -0.0116 & 0.0015 \\ -0.0213 & -0.0242 & 0.8103 & -0.0902 \\ 0.0312 & -0.0081 & 0.0640 & 0.6770 \end{bmatrix}$$

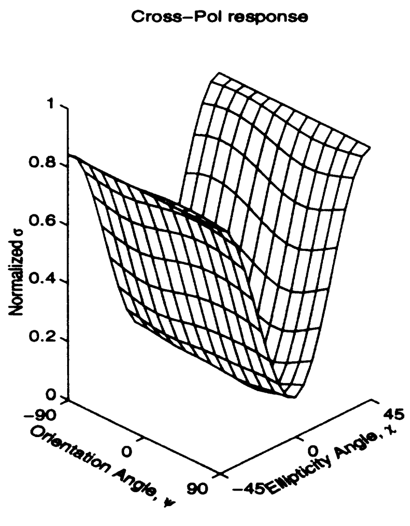
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.80 \text{ dB} \\ \sigma_{vh}^* &= -9.06 \text{ dB} & & \\ \chi_d &= -8.68 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= -5.92° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.76 & m_h &= 0.76 \\ m_{45} &= 0.78 & m_{135} &= 0.79 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.65 \end{aligned}$$





Target: Rhododendron - 5/27/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

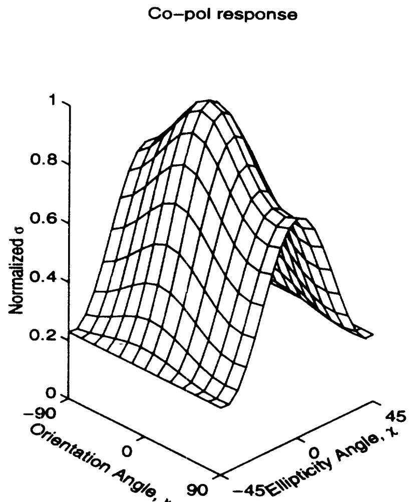
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1136 & -0.0375 & 0.0209 \\ 0.1599 & 0.7661 & -0.0138 & 0.0150 \\ -0.0610 & -0.0462 & 0.7075 & -0.0030 \\ -0.0009 & 0.0185 & -0.0199 & 0.5525 \end{bmatrix}$$

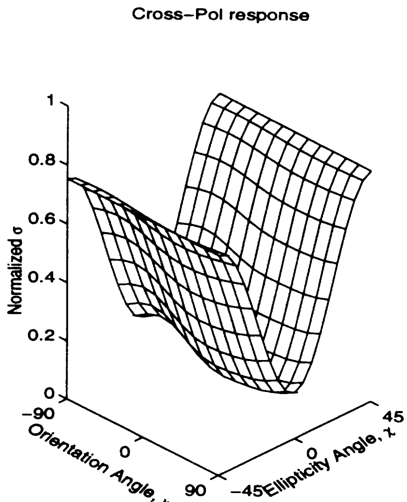
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.16 \text{ dB} \\ \sigma_{vh}^* &= -8.64 \text{ dB} & & \\ \chi_d &= -8.10 \text{ dB} & & \\ \alpha &= 0.72 & \zeta &= 0.77^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.73 & m_h &= 0.74 \\ m_{45} &= 0.68 & m_{135} &= 0.72 \\ m_{lhc} &= 0.54 & m_{rhc} &= 0.56 \end{aligned}$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 10°
Independent Samples: 99

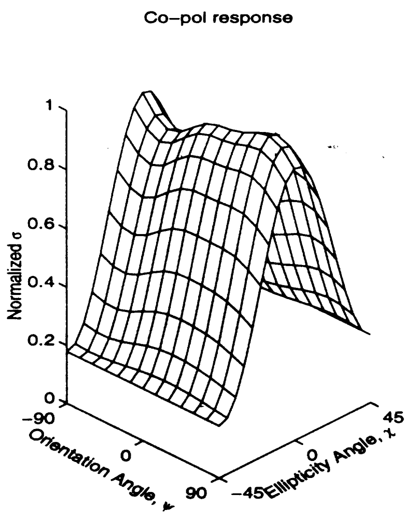
Normalized Mueller Matrix:

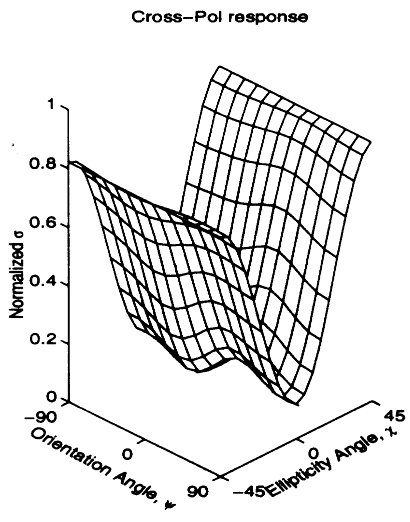
$$\mathbf{L}_m^\circ = 0.5383 \begin{bmatrix} 1.0000 & 0.1342 & 0.0215 & 0.0329 \\ 0.1248 & 0.9812 & 0.0169 & -0.0215 \\ 0.0056 & 0.1076 & 0.8322 & -0.0010 \\ -0.0065 & 0.0708 & 0.0295 & 0.6842 \end{bmatrix}$$

$$\sigma_{vv} = 8.30 \text{ dB} \qquad \sigma_{hh} = 8.22 \text{ dB}$$
$$\sigma_{vh} = -0.57 \text{ dB}$$
$$\chi_d = -8.84 \text{ dB}$$
$$\alpha = 0.77 \qquad \zeta = -1.15°$$

Degree of Polarization:

$$m_v = 0.78 \qquad m_h = 0.77$$
$$m_{45} = 0.77 \qquad m_{135} = 0.72$$
$$m_{lhc} = 0.64 \qquad m_{rhc} = 0.59$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 99

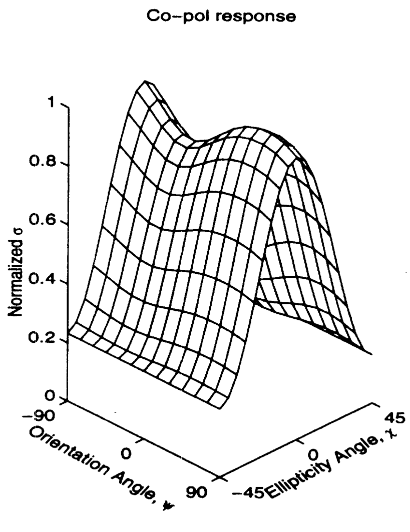
Normalized Mueller Matrix:

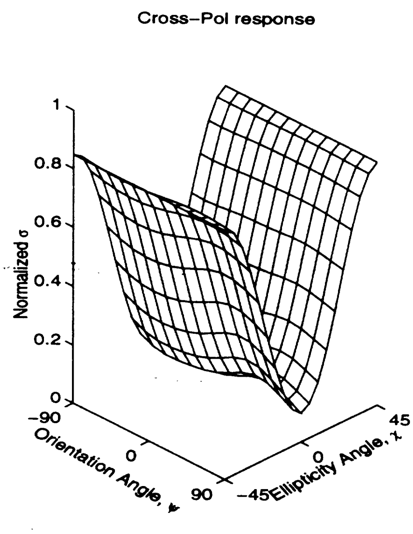
$$\mathbf{L}_m^\circ = 0.5932 \begin{bmatrix} 1.0000 & 0.1116 & 0.0276 & 0.0372 \\ 0.1092 & 1.0573 & 0.0578 & 0.0158 \\ 0.0781 & 0.0437 & 0.8850 & -0.0263 \\ -0.0317 & -0.0153 & 0.0399 & 0.7017 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 8.72 \text{ dB} & \sigma_{hh} &= 8.97 \text{ dB} \\ \sigma_{vh} &= -0.85 \text{ dB} & & \\ \chi_d &= -9.69 \text{ dB} & & \\ \alpha &= 0.77 & \zeta &= -2.39^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.81 \\ m_{45} &= 0.77 & m_{135} &= 0.78 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.67 \end{aligned}$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 30°
Independent Samples: 99

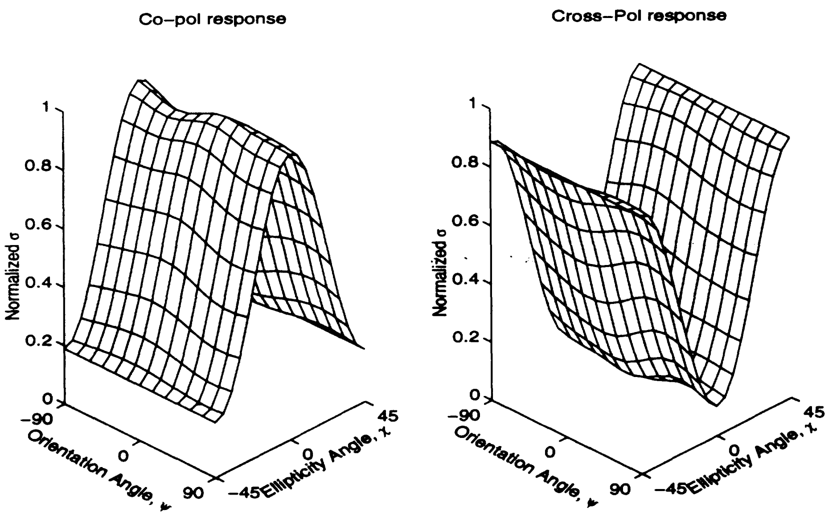
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.6141 \begin{bmatrix} 1.0000 & 0.0794 & 0.0035 & 0.0123 \\ 0.1016 & 0.9870 & 0.0203 & 0.0037 \\ 0.0304 & 0.0053 & 0.8617 & -0.0473 \\ -0.0438 & 0.0415 & 0.0897 & 0.7121 \end{bmatrix}$$

$\sigma_{vv} = 8.87$ dB $\qquad \sigma_{hh} = 8.82$ dB
$\sigma_{vh} = -1.56$ dB
$\chi_d = -10.41$ dB
$\alpha = 0.80 \qquad \zeta = -4.98°$

Degree of Polarization:

$m_v = 0.82 \qquad m_h = 0.85$
$m_{45} = 0.80 \qquad m_{135} = 0.80$
$m_{lhc} = 0.65 \qquad m_{rhc} = 0.67$



Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 40°
Independent Samples: 99

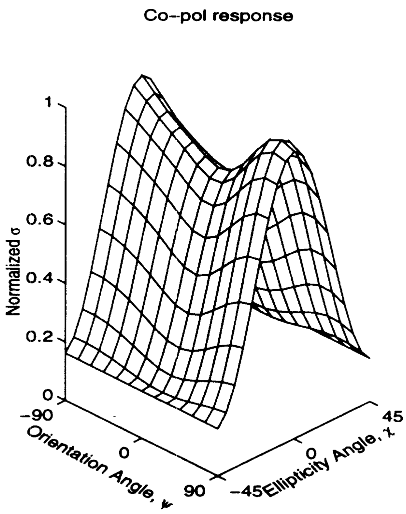
Normalized Mueller Matrix:

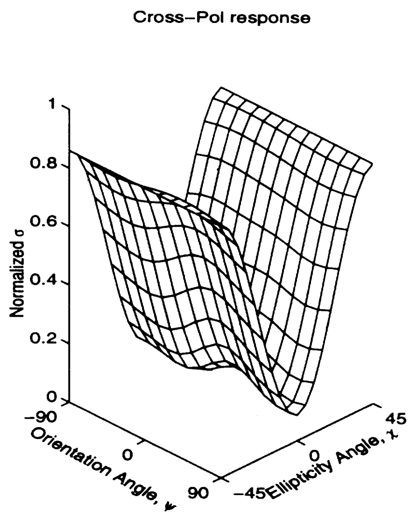
$$\mathbf{L}_m^\circ = 0.4939 \begin{bmatrix} 1.0000 & 0.1542 & -0.0025 & -0.0260 \\ 0.1086 & 1.2305 & 0.0085 & -0.0068 \\ -0.0146 & 0.0729 & 0.9985 & -0.0720 \\ -0.0053 & -0.0285 & 0.1147 & 0.8584 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 7.93 \text{ dB} & \sigma_{hh} &= 8.83 \text{ dB} \\ \sigma_{vh} &= -0.89 \text{ dB} & & \\ \chi_d &= -9.29 \text{ dB} & & \\ \alpha &= 0.84 & \zeta &= -5.74° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.80 & m_h &= 0.78 \\ m_{45} &= 0.83 & m_{135} &= 0.79 \\ m_{lhc} &= 0.70 & m_{rhc} &= 0.69 \end{aligned}$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

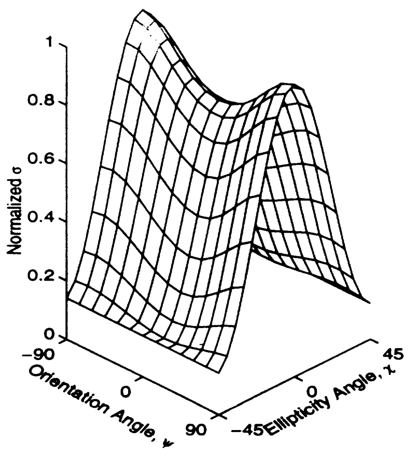
$$\mathbf{L}_m^\circ = 0.4689 \begin{bmatrix} 1.0000 & 0.1059 & 0.0076 & -0.0262 \\ 0.0748 & 1.2224 & -0.0180 & 0.0083 \\ -0.0056 & 0.0040 & 0.9760 & -0.0771 \\ 0.0130 & -0.0454 & 0.0976 & 0.8800 \end{bmatrix}$$

$$\sigma_{vv} = 7.70 \text{ dB} \qquad \sigma_{hh} = 8.57 \text{ dB}$$
$$\sigma_{vh} = -2.74 \text{ dB}$$
$$\chi_d = -10.90 \text{ dB}$$
$$\alpha = 0.84 \qquad \zeta = -5.38°$$

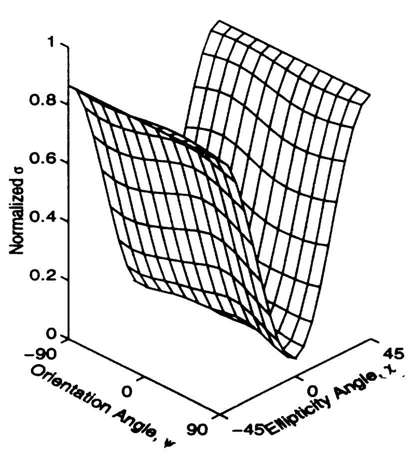
Degree of Polarization:

$$m_v = 0.86 \qquad m_h = 0.84$$
$$m_{45} = 0.82 \qquad m_{135} = 0.82$$
$$m_{lhc} = 0.74 \qquad m_{rhc} = 0.74$$

Co–pol response



Cross–Pol response



Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

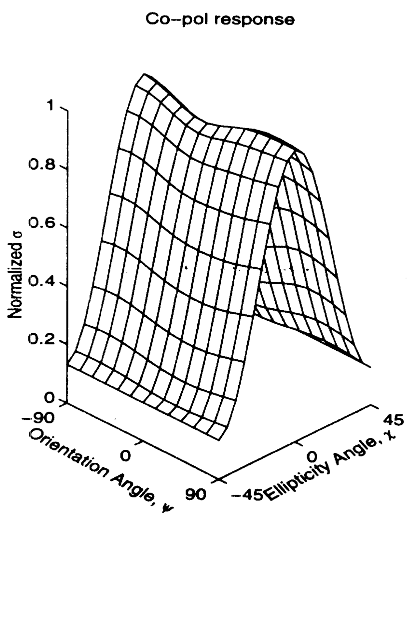
Normalized Mueller Matrix:

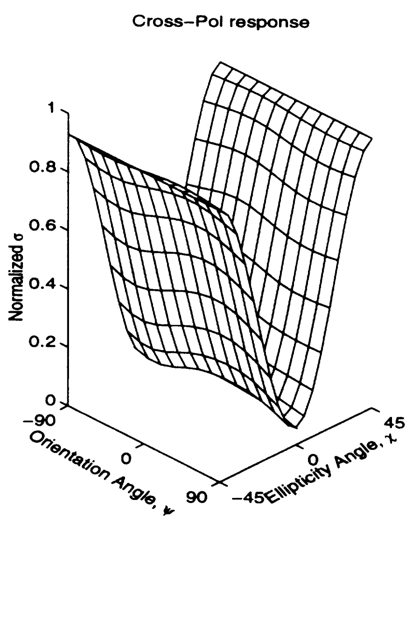
$$\mathbf{L}_m^\circ = 0.4127 \begin{bmatrix} 1.0000 & 0.1080 & 0.0083 & -0.0088 \\ 0.0610 & 1.0510 & 0.0080 & 0.0043 \\ 0.0295 & 0.0037 & 0.9390 & -0.0554 \\ 0.0006 & -0.0066 & 0.0739 & 0.8358 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 7.15 \text{ dB} & \sigma_{hh} &= 7.36 \text{ dB} \\ \sigma_{vh} &= -3.58 \text{ dB} \\ \chi_d &= -10.84 \text{ dB} \\ \alpha &= 0.87 & \zeta &= -4.17^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.89 & m_h &= 0.81 \\ m_{45} &= 0.85 & m_{135} &= 0.85 \\ m_{lhc} &= 0.75 & m_{rhc} &= 0.76 \end{aligned}$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

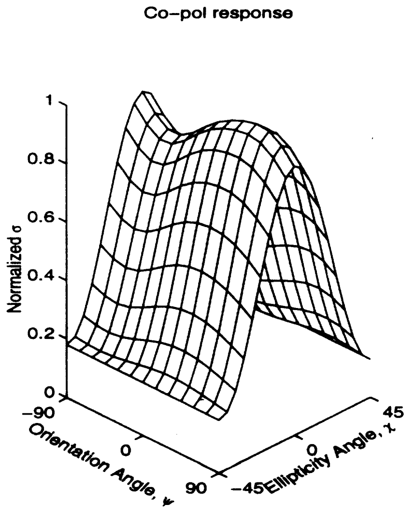
Normalized Mueller Matrix:

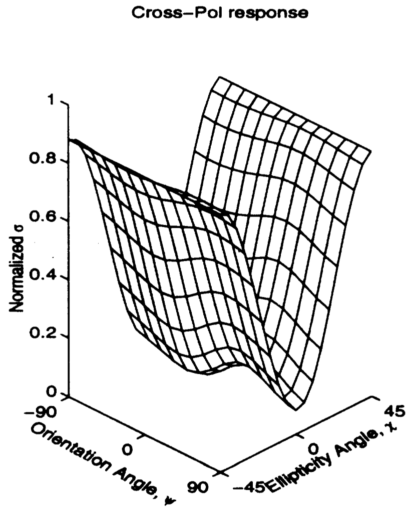
$$\mathbf{L}_m^\circ = 0.3684 \begin{bmatrix} 1.0000 & 0.0922 & 0.0412 & 0.0237 \\ 0.0859 & 0.9749 & 0.0219 & -0.0136 \\ 0.0446 & 0.1007 & 0.8685 & -0.0121 \\ -0.0624 & 0.0131 & 0.0055 & 0.7488 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 6.66 \text{ dB} & \sigma_{hh} &= 6.55 \text{ dB} \\ \sigma_{vh} &= -3.85 \text{ dB} & & \\ \chi_d &= -10.45 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= -0.62^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.84 & m_h &= 0.83 \\ m_{45} &= 0.83 & m_{135} &= 0.79 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.73 \end{aligned}$$





Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

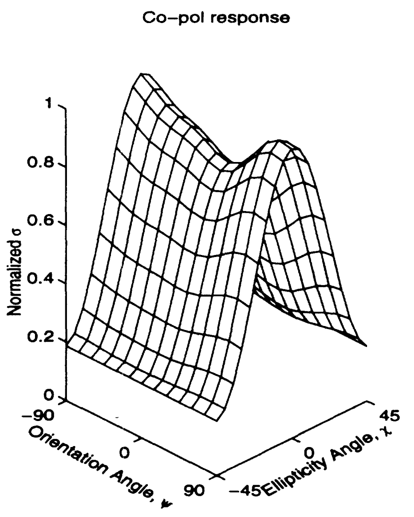
Normalized Mueller Matrix:

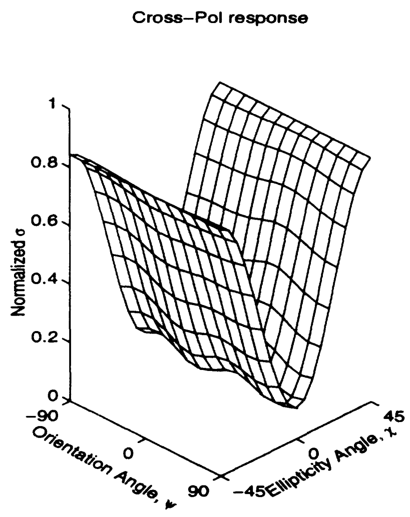
$$\mathbf{L}_m^\circ = 0.1937 \begin{bmatrix} 1.0000 & 0.1236 & -0.0079 & 0.0215 \\ 0.1245 & 1.1673 & -0.0027 & -0.0319 \\ -0.0499 & 0.0558 & 0.9347 & 0.0241 \\ -0.0325 & 0.0267 & -0.0186 & 0.7682 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 3.86 \text{ dB} & \sigma_{hh} &= 4.54 \text{ dB} \\ \sigma_{vh} &= -5.20 \text{ dB} \\ \chi_d &= -9.41 \text{ dB} \\ \alpha &= 0.79 & \zeta &= 1.44^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.81 \\ m_{45} &= 0.79 & m_{135} &= 0.77 \\ m_{lhc} &= 0.64 & m_{rhc} &= 0.64 \end{aligned}$$





Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

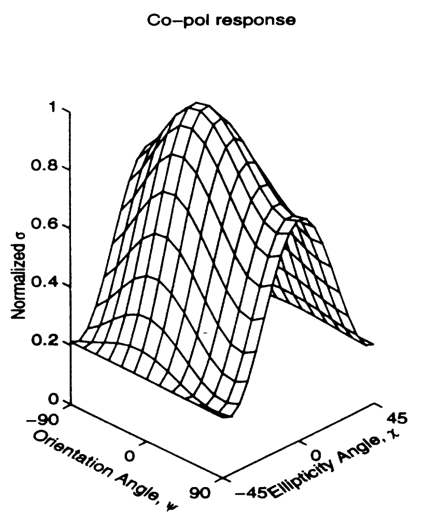
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1199 & -0.0303 & 0.0447 \\ 0.1401 & 0.7699 & -0.0361 & -0.0143 \\ -0.0567 & -0.0514 & 0.7740 & -0.0973 \\ -0.0542 & 0.0568 & 0.0679 & 0.5955 \end{bmatrix}$$

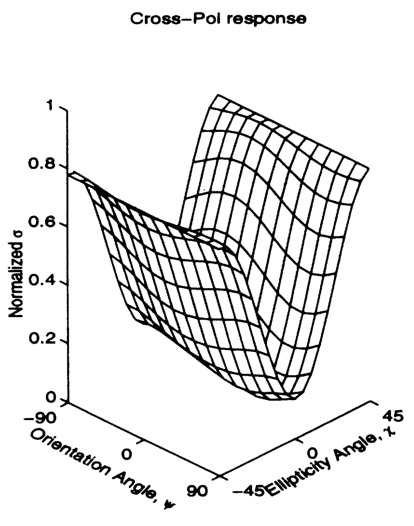
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.14 \text{ dB} \\ \sigma_{vh}^* &= -8.86 \text{ dB} & & \\ \chi_d &= -8.33 \text{ dB} & & \\ \alpha &= 0.79 & \zeta &= -6.88° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.76 & m_h &= 0.74 \\ m_{45} &= 0.77 & m_{135} &= 0.77 \\ m_{lhc} &= 0.61 & m_{rhc} &= 0.61 \end{aligned}$$





Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

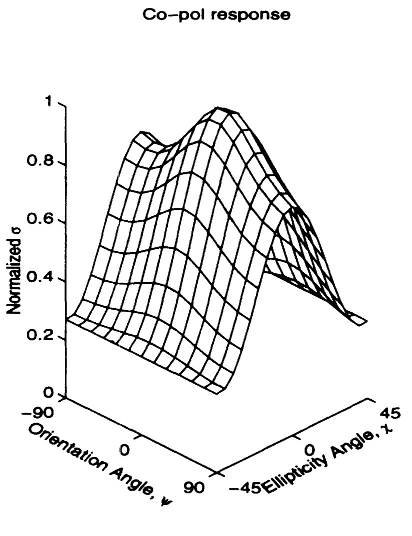
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1402 & -0.0199 & 0.0193 \\ 0.1446 & 0.7896 & 0.0138 & 0.0192 \\ 0.0627 & 0.0317 & 0.6906 & -0.0446 \\ 0.0226 & -0.0088 & 0.0442 & 0.4974 \end{bmatrix}$$

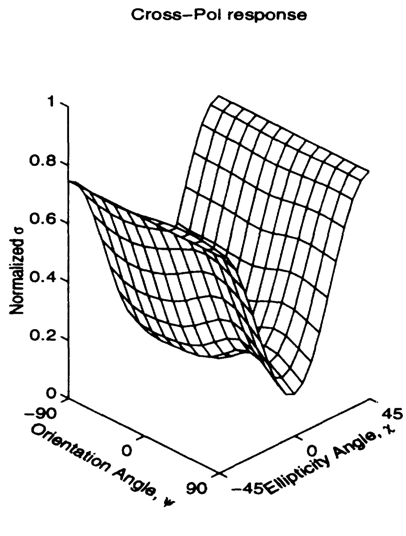
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.03 \text{ dB} \\ \sigma_{vh}^* &= -8.46 \text{ dB} & & \\ \chi_d &= -7.98 \text{ dB} & & \\ \alpha &= 0.67 & \zeta &= -4.27^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.75 & m_h &= 0.70 \\ m_{45} &= 0.72 & m_{135} &= 0.63 \\ m_{lhc} &= 0.48 & m_{rhc} &= 0.51 \end{aligned}$$





Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

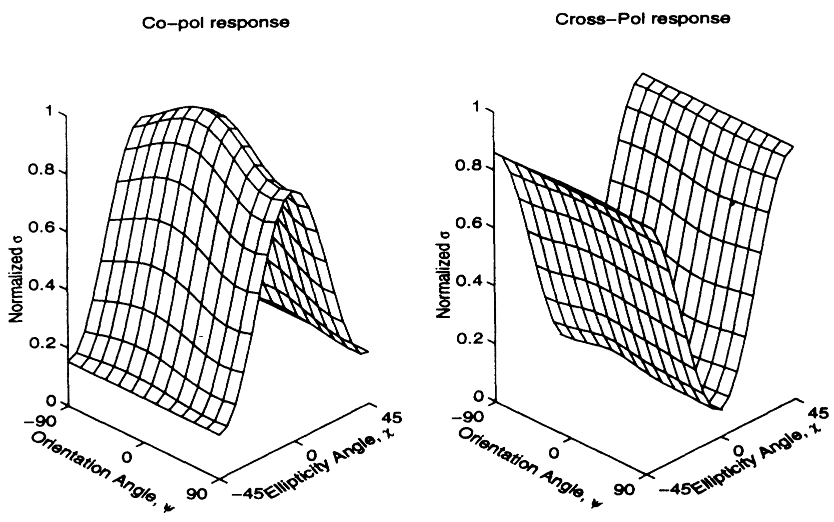
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1050 & -0.0109 & -0.0289 \\ 0.0948 & 0.8674 & -0.0283 & 0.0150 \\ -0.0203 & -0.0290 & 0.8226 & -0.0335 \\ 0.0214 & -0.0048 & -0.0010 & 0.7033 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.62 \text{ dB} \\ \sigma_{vh}^* &= -10.00 \text{ dB} & & \\ \chi_d &= -9.71 \text{ dB} & & \\ \alpha &= 0.82 & \zeta &= -1.22^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.78 \\ m_{45} &= 0.81 & m_{135} &= 0.79 \\ m_{lhc} &= 0.70 & m_{rhc} &= 0.67 \end{aligned}$$



Target: Rhododendron - 6/17/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

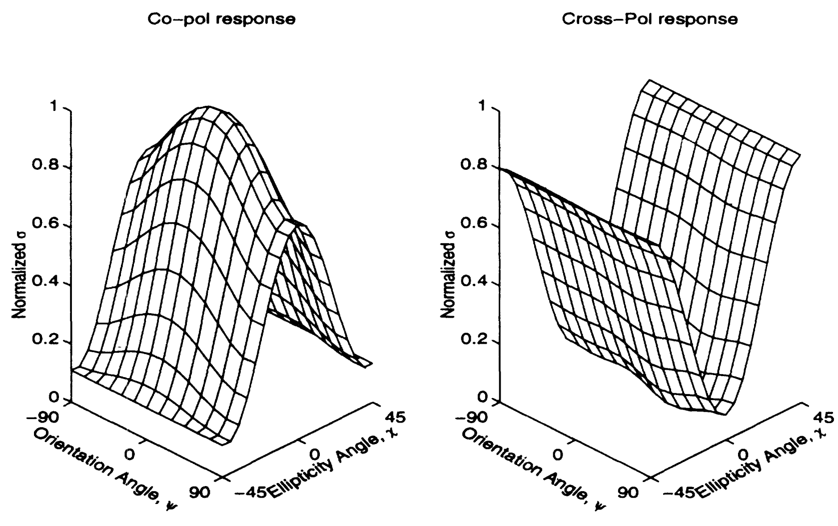
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0725 & -0.0234 & 0.0120 \\ 0.0854 & 0.7385 & 0.0054 & 0.0107 \\ -0.0003 & -0.0521 & 0.8277 & -0.0375 \\ 0.0111 & 0.0248 & -0.0291 & 0.7056 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.32 \text{ dB} \\ \sigma_{vh}^* &= -11.03 \text{ dB} & & \\ \chi_d &= -10.42 \text{ dB} & & \\ \alpha &= 0.89 & \zeta &= -0.31^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.84 & m_h &= 0.82 \\ m_{45} &= 0.87 & m_{135} &= 0.90 \\ m_{lhc} &= 0.76 & m_{rhc} &= 0.75 \end{aligned}$$



Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

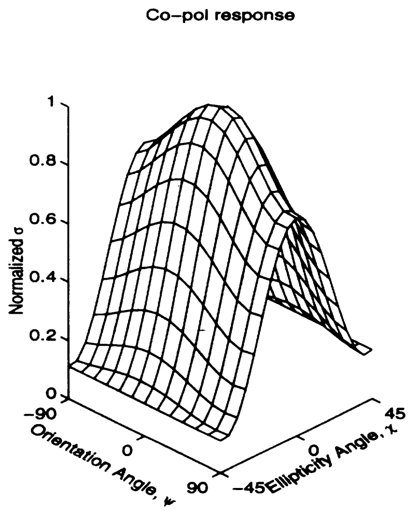
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0829 & -0.0188 & -0.0093 \\ 0.0934 & 0.7488 & -0.0012 & 0.0229 \\ 0.0075 & -0.0305 & 0.7959 & -0.0586 \\ 0.0464 & 0.0166 & 0.0215 & 0.6823 \end{bmatrix}$$

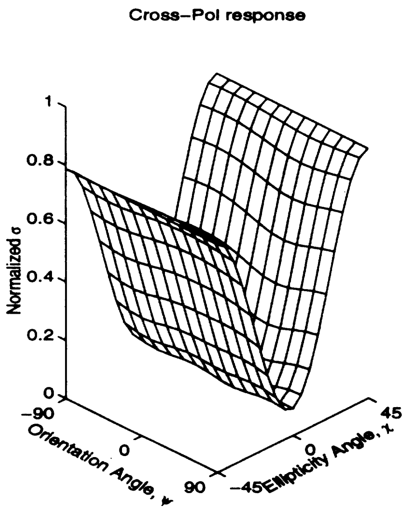
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.26 \text{ dB} \\ \sigma_{vh}^* &= -10.55 \text{ dB} & & \\ \chi_d &= -9.97 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= -3.10^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.80 \\ m_{45} &= 0.84 & m_{135} &= 0.83 \\ m_{lhc} &= 0.74 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

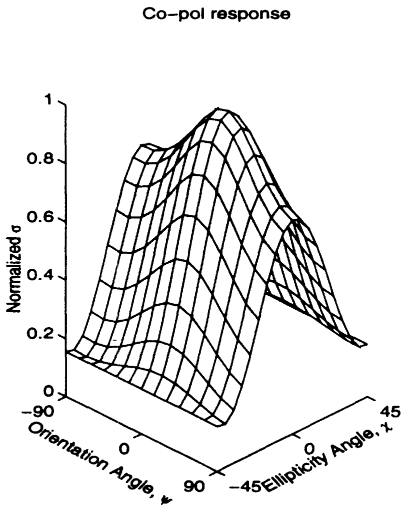
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0876 & 0.0226 & 0.0196 \\ 0.1056 & 0.7448 & -0.0011 & 0.0080 \\ 0.0595 & 0.0210 & 0.7547 & 0.0211 \\ -0.0158 & 0.0558 & -0.0511 & 0.6283 \end{bmatrix}$$

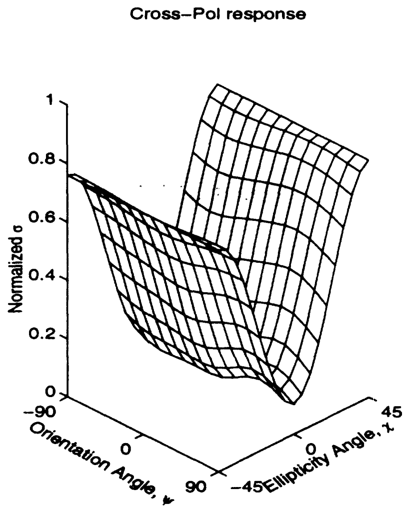
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.28 \text{ dB} \\ \sigma_{vh}^* &= -10.15 \text{ dB} \\ \chi_d &= -9.56 \text{ dB} \\ \alpha &= 0.80 & \zeta &= 2.99° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.79 \\ m_{45} &= 0.82 & m_{135} &= 0.76 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.66 \end{aligned}$$





Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

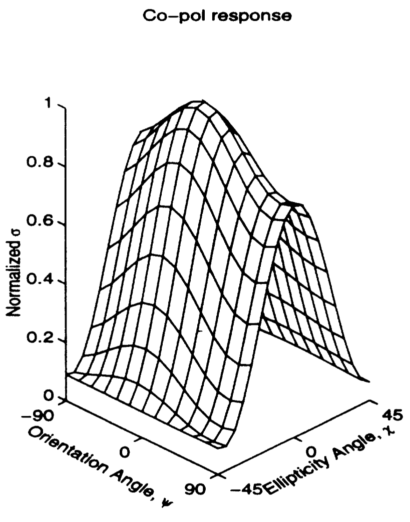
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0405 & -0.0177 & 0.0421 \\ 0.0449 & 0.8023 & -0.0267 & -0.0202 \\ -0.0409 & -0.0412 & 0.8448 & -0.0870 \\ -0.0740 & 0.0576 & 0.0455 & 0.7890 \end{bmatrix}$$

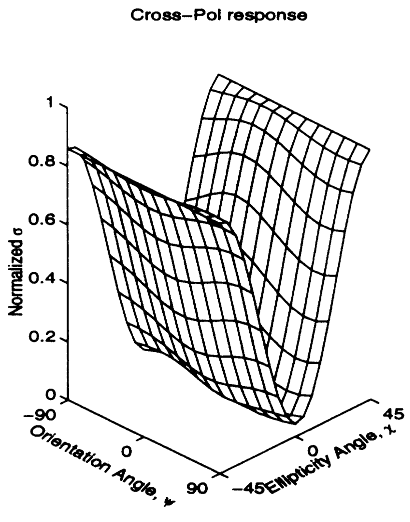
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.96 \text{ dB} \\ \sigma_{vh}^* &= -13.69 \text{ dB} & & \\ \chi_d &= -13.24 \text{ dB} & & \\ \alpha &= 0.91 & \zeta &= -4.64° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.92 & m_h &= 0.91 \\ m_{45} &= 0.90 & m_{135} &= 0.90 \\ m_{lhc} &= 0.84 & m_{rhc} &= 0.87 \end{aligned}$$





Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

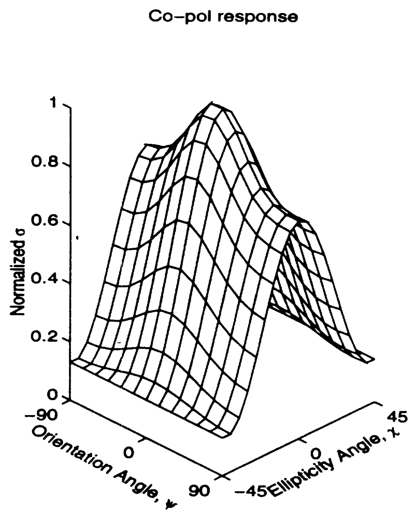
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0433 & -0.0058 & -0.0001 \\ 0.0563 & 0.7480 & -0.0207 & 0.0073 \\ -0.0516 & 0.0051 & 0.7265 & 0.0236 \\ -0.0030 & 0.0220 & -0.0322 & 0.6478 \end{bmatrix}$$

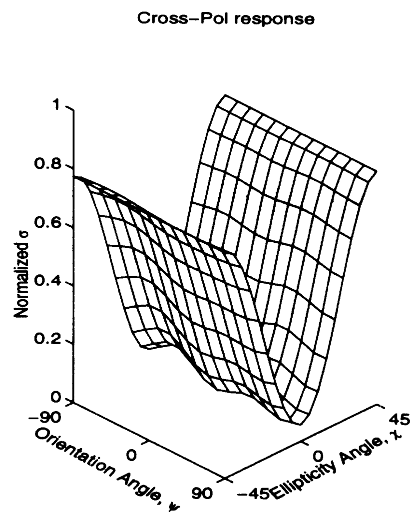
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.26 \text{ dB} \\ \sigma_{vh}^* &= -13.03 \text{ dB} & & \\ \chi_d &= -12.44 \text{ dB} & & \\ \alpha &= 0.80 & \zeta &= 2.33° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.89 & m_h &= 0.89 \\ m_{45} &= 0.80 & m_{135} &= 0.80 \\ m_{lhc} &= 0.72 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Rhododendron - 6/17/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0641 & -0.0126 & -0.0064 \\ 0.0750 & 0.6862 & -0.0037 & 0.0025 \\ -0.0143 & 0.0154 & 0.7369 & -0.0154 \\ 0.0146 & -0.0065 & -0.0004 & 0.6336 \end{bmatrix}$$

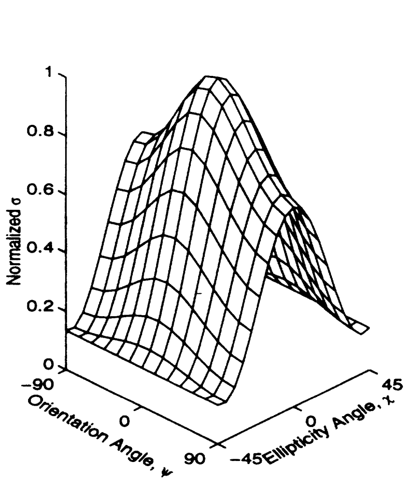
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.64 \text{ dB} \\ \sigma_{vh}^* &= -11.58 \text{ dB} & & \\ \chi_d &= -10.83 \text{ dB} & & \\ \alpha &= 0.83 & \zeta &= -0.63° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

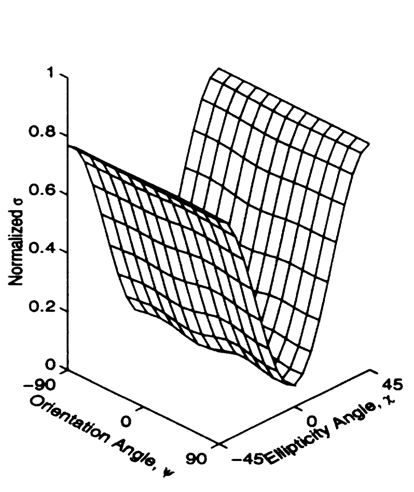
Degree of Polarization:

$$\begin{aligned} m_v &= 0.86 & m_h &= 0.83 \\ m_{45} &= 0.84 & m_{135} &= 0.81 \\ m_{lhc} &= 0.72 & m_{rhc} &= 0.71 \end{aligned}$$

Co–pol response



Cross–Pol response



Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

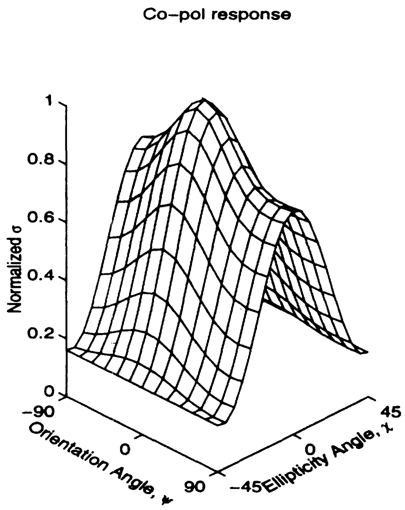
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0613 & -0.0234 & 0.0371 \\ 0.0821 & 0.7831 & -0.0231 & -0.0066 \\ -0.0833 & -0.0082 & 0.7539 & -0.0271 \\ -0.0301 & 0.0388 & 0.0006 & 0.6446 \end{bmatrix}$$

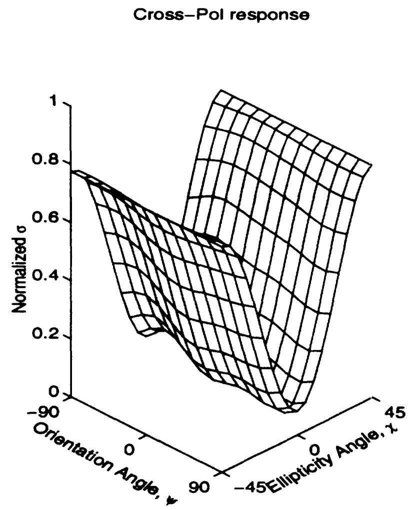
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.06 \text{ dB} \\ \sigma_{vh}^* &= -11.44 \text{ dB} & & \\ \chi_d &= -10.94 \text{ dB} & & \\ \alpha &= 0.79 & \zeta &= -1.13^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.85 & m_h &= 0.86 \\ m_{45} &= 0.78 & m_{135} &= 0.80 \\ m_{lhc} &= 0.67 & m_{rhc} &= 0.69 \end{aligned}$$





Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

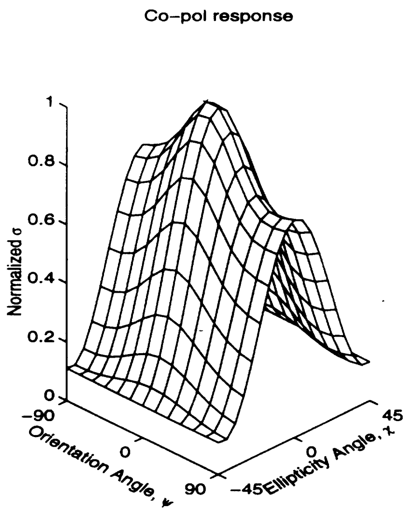
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0311 & -0.0202 & 0.0102 \\ 0.0442 & 0.7452 & -0.0200 & -0.0022 \\ -0.0509 & -0.0205 & 0.7121 & 0.0492 \\ -0.0024 & 0.0284 & -0.0753 & 0.6666 \end{bmatrix}$$

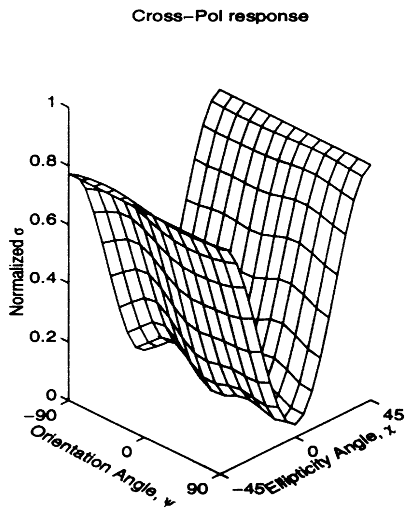
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.28 \text{ dB} \\ \sigma_{vh}^* &= -14.24 \text{ dB} & & \\ \chi_d &= -13.65 \text{ dB} & & \\ \alpha &= 0.80 & \zeta &= 5.16° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.92 & m_h &= 0.92 \\ m_{45} &= 0.79 & m_{135} &= 0.80 \\ m_{lhc} &= 0.75 & m_{rhc} &= 0.74 \end{aligned}$$





Target Name: Spirea 1991
System: UM

Target Description: Bushy, dense-leafed planophil. Leaves are 0.5-1 cm by 1-2 cm, with approximately 68% water content.

(note: computation of the illumination area for 35 GHz system was uncertain, therefore, these data are normalized to L_{11}. Affected quantities on the following pages are indicated by an asterisk).

References:

Nashashibi, Kuga and Ulaby, "Polarimetric Observations of Trees at 35 and 94 GHz," APS, London, Ontario. June 1990.

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	w/leaves	tree.11.1	197
30	35	w/leaves	tree.11.2	198
40	35	w/leaves	tree.11.3	199
50	35	w/leaves	tree.11.4	200
60	35	w/leaves	tree.11.5	201
70	35	w/leaves	tree.11.6	202
90	35	w/leaves	tree.11.7	203
50	94	w/leaves	tree.11.8	204
60	94	w/leaves	tree.11.9	205
70	94	w/leaves	tree.11.10	206
90	94	w/leaves	tree.11.11	207
60	35	defoliated	tree.11.12	208
70	35	defoliated	tree.11.13	209
90	35	defoliated	tree.11.14	210
60	94	defoliated	tree.11.15	211
70	94	defoliated	tree.11.16	212
90	94	defoliated	tree.11.17	213

Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

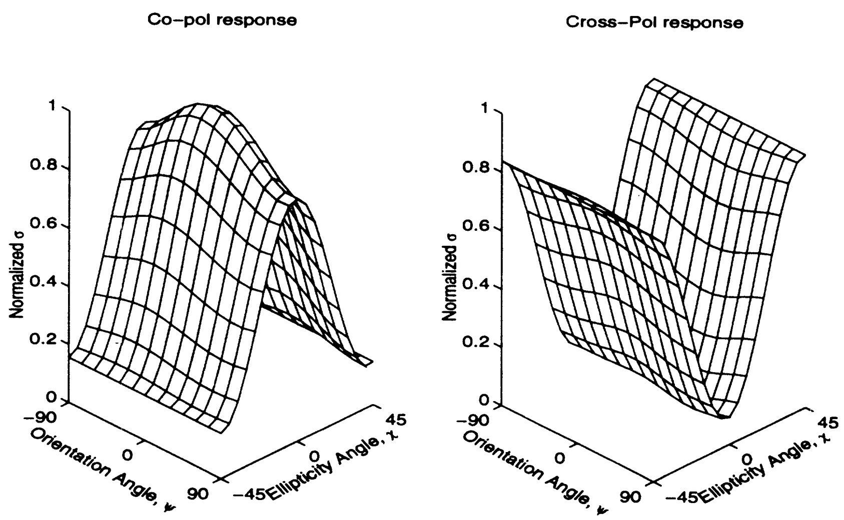
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0840 & -0.0127 & -0.0008 \\ 0.0942 & 0.8388 & -0.0102 & 0.0343 \\ -0.0200 & -0.0184 & 0.8491 & -0.0321 \\ 0.0581 & -0.0486 & 0.0112 & 0.7045 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.76 \text{ dB} \\ \sigma_{vh}^* &= -10.50 \text{ dB} & & \\ \chi_d &= -10.14 \text{ dB} & & \\ \alpha &= 0.85 & \zeta &= -1.60^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.82 \\ m_{45} &= 0.85 & m_{135} &= 0.85 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.73 \end{aligned}$$



Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

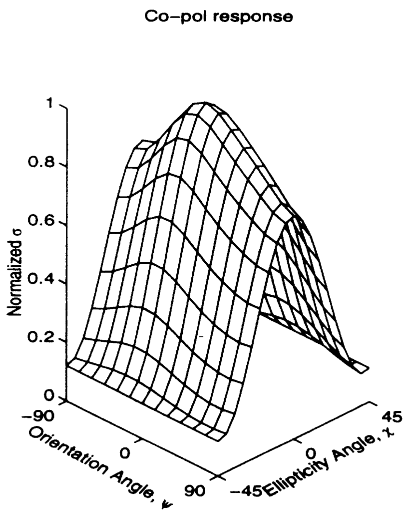
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0819 & -0.0083 & -0.0164 \\ 0.0920 & 0.7746 & -0.0197 & 0.0199 \\ -0.0512 & 0.0221 & 0.8327 & -0.0848 \\ 0.0385 & -0.0429 & 0.0237 & 0.7369 \end{bmatrix}$$

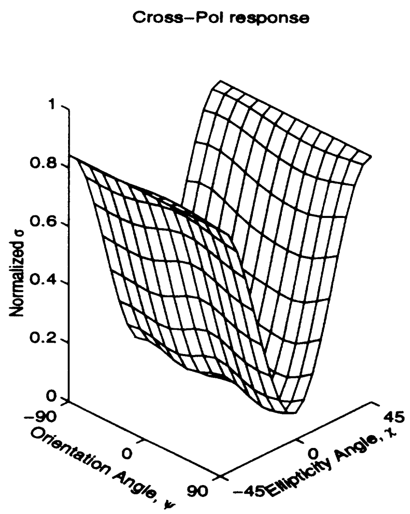
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.11 \text{ dB} \\ \sigma_{vh}^* &= -10.61 \text{ dB} & & \\ \chi_d &= -10.09 \text{ dB} & & \\ \alpha &= 0.89 & \zeta &= -3.96^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.83 & m_h &= 0.81 \\ m_{45} &= 0.87 & m_{135} &= 0.85 \\ m_{lhc} &= 0.76 & m_{rhc} &= 0.78 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

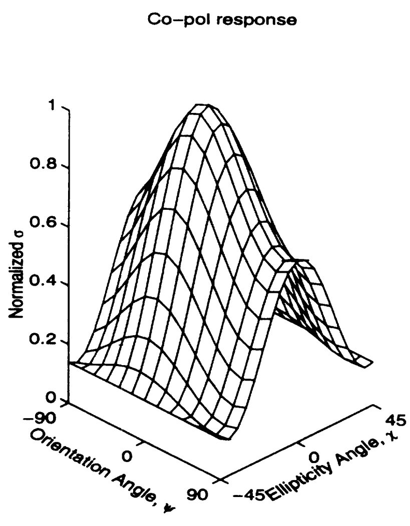
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0626 & -0.0467 & 0.0296 \\ 0.1011 & 0.6433 & -0.0428 & 0.0075 \\ -0.1086 & -0.0694 & 0.7515 & -0.0476 \\ -0.0140 & 0.0395 & 0.0011 & 0.6077 \end{bmatrix}$$

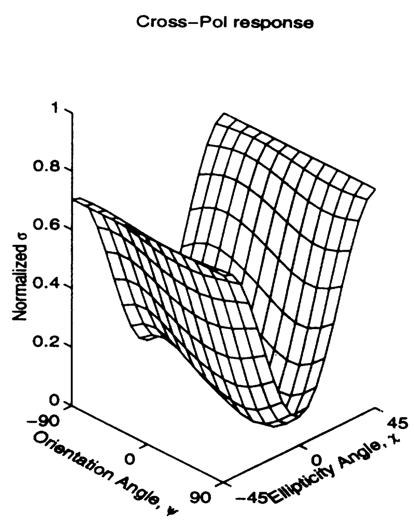
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.92 \text{ dB} \\ \sigma_{vh}^* &= -10.87 \text{ dB} & & \\ \chi_d &= -10.02 \text{ dB} & & \\ \alpha &= 0.85 & \zeta &= -2.05° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.83 \\ m_{45} &= 0.84 & m_{135} &= 0.86 \\ m_{lhc} &= 0.70 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

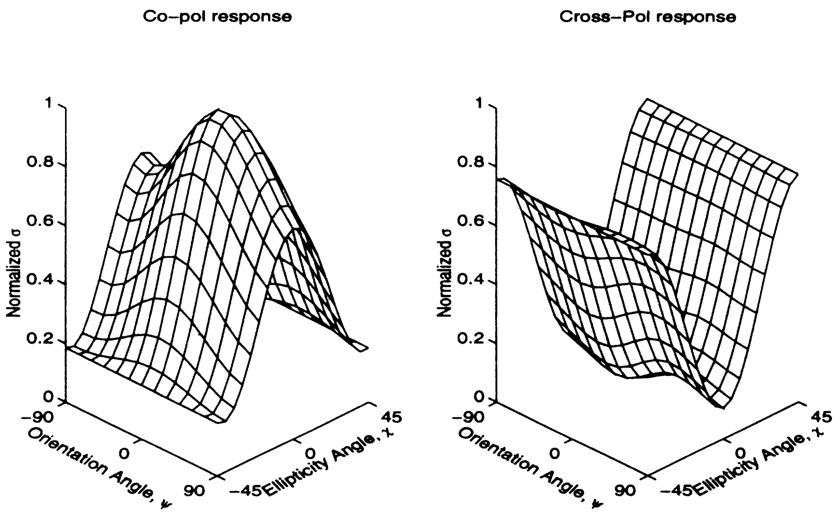
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.0844 & 0.0191 & 0.0249 \\ 0.1075 & 0.7219 & 0.0308 & -0.0072 \\ 0.0393 & 0.0621 & 0.7451 & -0.0461 \\ -0.0157 & 0.0243 & 0.0403 & 0.5843 \end{bmatrix}$$

$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -1.42 \text{ dB} \\ \sigma^*_{vh} &= -10.18 \text{ dB} & & \\ \chi_d &= -9.53 \text{ dB} & & \\ \alpha &= 0.78 & \zeta &= -3.72° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.80 \\ m_{45} &= 0.80 & m_{135} &= 0.78 \\ m_{lhc} &= 0.63 & m_{rhc} &= 0.63 \end{aligned}$$



Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

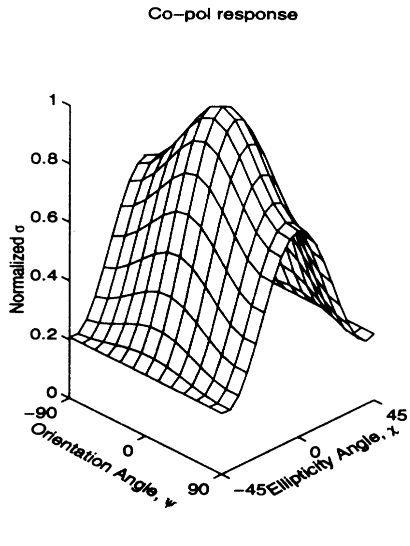
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1113 & -0.0145 & 0.0013 \\ 0.1181 & 0.7032 & 0.0019 & 0.0106 \\ 0.0074 & -0.0169 & 0.7083 & -0.0194 \\ 0.0335 & -0.0097 & 0.0225 & 0.5309 \end{bmatrix}$$

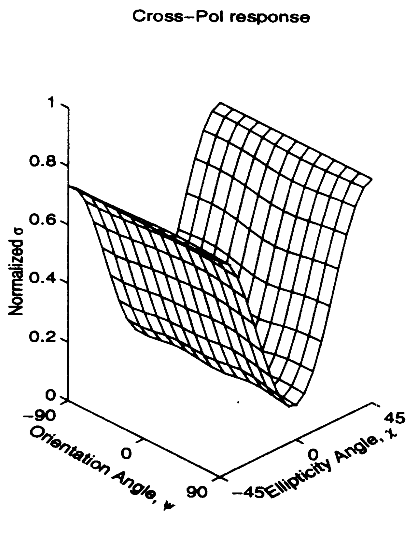
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.53 \text{ dB} \\ \sigma_{vh}^* &= -9.41 \text{ dB} & & \\ \chi_d &= -8.71 \text{ dB} & & \\ \alpha &= 0.74 & \zeta &= -1.94° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.79 & m_h &= 0.73 \\ m_{45} &= 0.75 & m_{135} &= 0.75 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.57 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

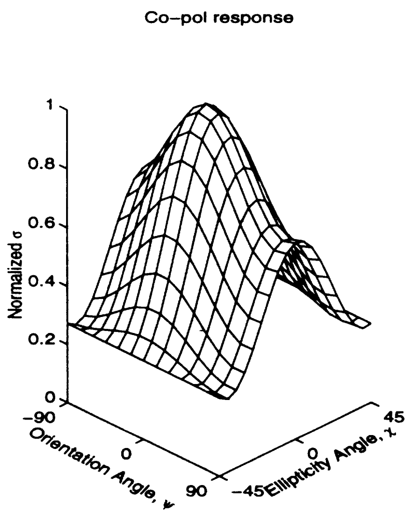
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1234 & -0.0406 & 0.0240 \\ 0.1776 & 0.6840 & -0.0175 & -0.0245 \\ -0.0495 & -0.0568 & 0.6826 & -0.0036 \\ -0.0314 & 0.0305 & -0.0351 & 0.4419 \end{bmatrix}$$

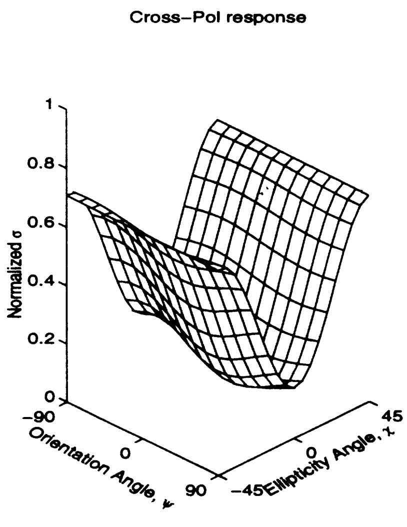
$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -1.65 \text{ dB} \\ \sigma^*_{vh} &= -8.22 \text{ dB} & & \\ \chi_d &= -7.48 \text{ dB} & & \\ \alpha &= 0.68 & \zeta &= 1.60^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.70 & m_h &= 0.70 \\ m_{45} &= 0.68 & m_{135} &= 0.72 \\ m_{lhc} &= 0.48 & m_{rhc} &= 0.46 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

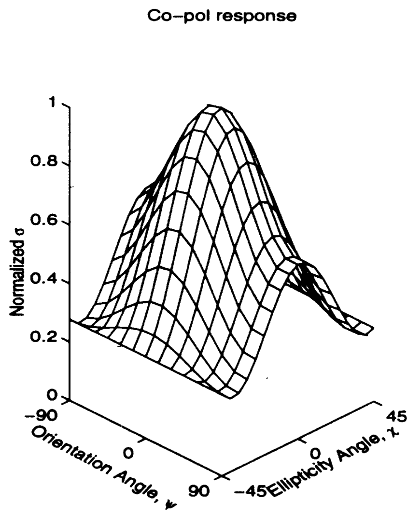
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1289 & -0.0189 & 0.0314 \\ 0.1708 & 0.5968 & -0.0214 & -0.0221 \\ -0.0241 & -0.0414 & 0.6280 & -0.0105 \\ -0.0464 & 0.0245 & -0.0155 & 0.4188 \end{bmatrix}$$

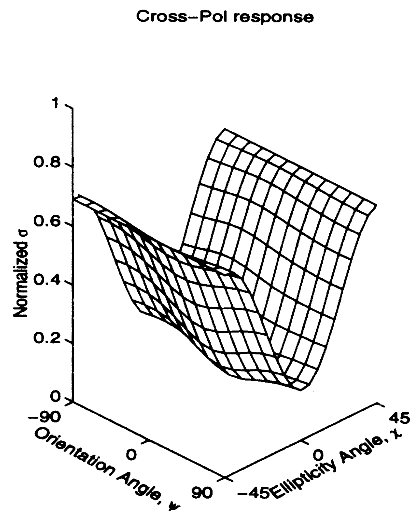
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -2.24 \text{ dB} \\ \sigma_{vh}^* &= -8.24 \text{ dB} & & \\ \chi_d &= -7.27 \text{ dB} & & \\ \alpha &= 0.68 & \zeta &= 0.28^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.71 & m_h &= 0.65 \\ m_{45} &= 0.69 & m_{135} &= 0.69 \\ m_{lhc} &= 0.49 & m_{rhc} &= 0.48 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 50°
Independent Samples: 99

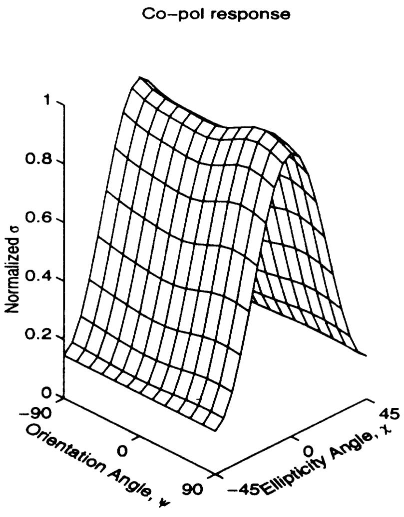
Normalized Mueller Matrix:

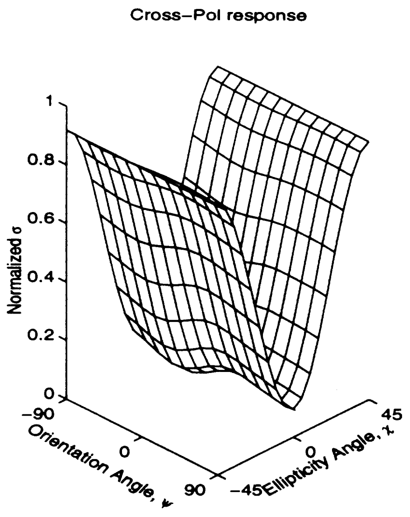
$$\mathbf{L}_m^\circ = 0.3876 \begin{bmatrix} 1.0000 & 0.1049 & 0.0029 & -0.0353 \\ 0.1022 & 1.0384 & -0.0184 & -0.0039 \\ 0.0135 & 0.0558 & 0.9457 & -0.0053 \\ -0.0009 & -0.0184 & 0.0127 & 0.8090 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 6.88 \text{ dB} & \sigma_{hh} &= 7.04 \text{ dB} \\ \sigma_{vh} &= -2.97 \text{ dB} & & \\ \chi_d &= -9.93 \text{ dB} & & \\ \alpha &= 0.86 & \zeta &= -0.59^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.81 & m_h &= 0.82 \\ m_{45} &= 0.89 & m_{135} &= 0.80 \\ m_{lhc} &= 0.74 & m_{rhc} &= 0.71 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

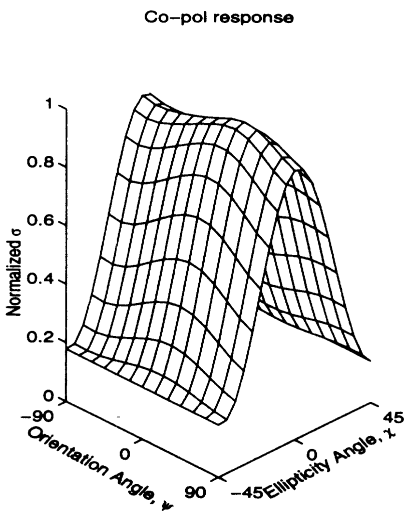
Normalized Mueller Matrix:

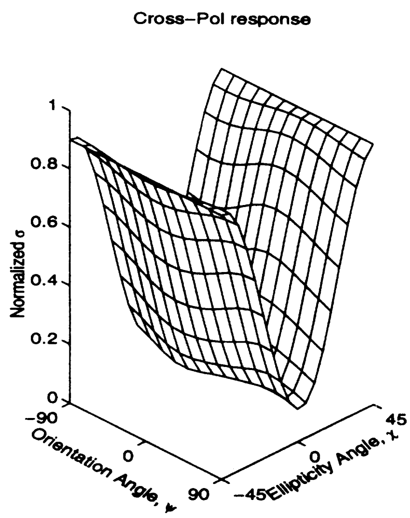
$$\mathbf{L}_m^\circ = 0.3154 \begin{bmatrix} 1.0000 & 0.1088 & 0.0247 & 0.0492 \\ 0.1149 & 0.9478 & -0.0167 & -0.0226 \\ 0.0269 & 0.0434 & 0.8898 & 0.0130 \\ -0.0875 & 0.0626 & -0.0233 & 0.7568 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 5.98 \text{ dB} & \sigma_{hh} &= 5.75 \text{ dB} \\ \sigma_{vh} &= -3.53 \text{ dB} \\ \chi_d &= -9.40 \text{ dB} \\ \alpha &= 0.85 & \zeta &= 1.26° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.80 & m_h &= 0.80 \\ m_{45} &= 0.85 & m_{135} &= 0.79 \\ m_{lhc} &= 0.68 & m_{rhc} &= 0.73 \end{aligned}$$





Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

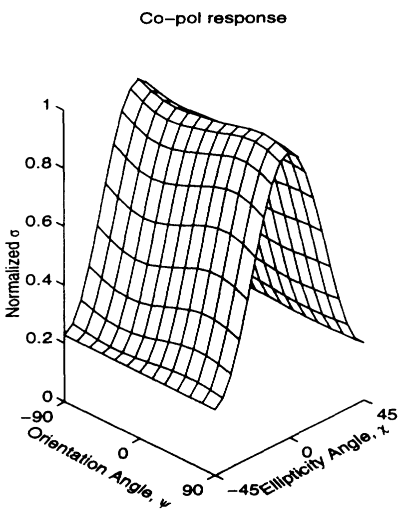
Normalized Mueller Matrix:

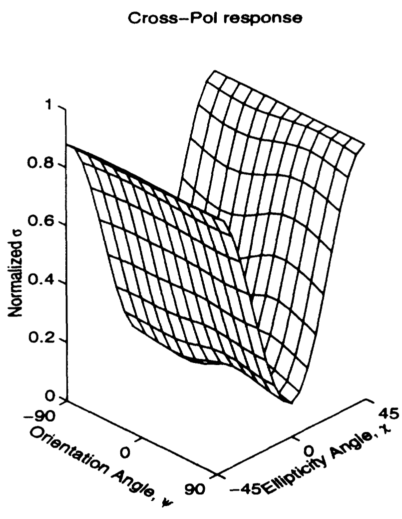
$$\mathbf{L}_m^\circ = 0.2543 \begin{bmatrix} 1.0000 & 0.1285 & -0.0048 & 0.0107 \\ 0.1208 & 1.0161 & -0.0085 & 0.0167 \\ 0.0180 & 0.0432 & 0.8798 & 0.0439 \\ -0.0054 & -0.0137 & -0.0652 & 0.6927 \end{bmatrix}$$

$$\sigma_{vv} = 5.05 \text{ dB} \qquad \sigma_{hh} = 5.11 \text{ dB}$$
$$\sigma_{vh} = -4.00 \text{ dB}$$
$$\chi_d = -9.08 \text{ dB}$$
$$\alpha = 0.78 \qquad \zeta = 3.97°$$

Degree of Polarization:

$$m_v = 0.78 \qquad m_h = 0.78$$
$$m_{45} = 0.82 \qquad m_{135} = 0.74$$
$$m_{lhc} = 0.59 \qquad m_{rhc} = 0.64$$





Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

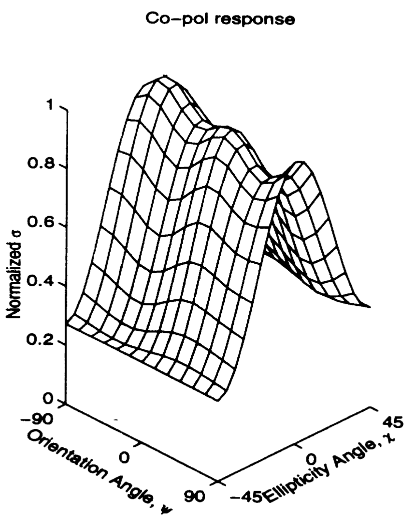
Normalized Mueller Matrix:

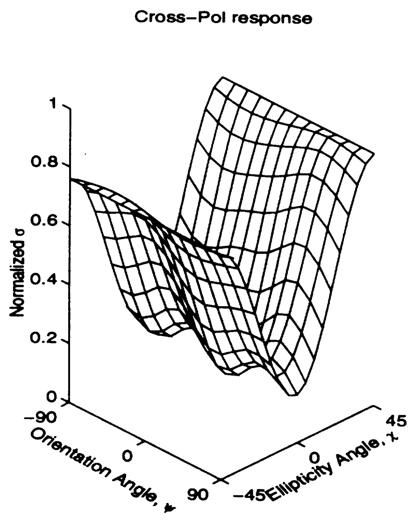
$$\mathbf{L}_m^\circ = 0.2044 \begin{bmatrix} 1.0000 & 0.1669 & -0.0420 & -0.0325 \\ 0.1703 & 1.0097 & -0.0498 & 0.0653 \\ 0.0833 & -0.1008 & 0.7479 & 0.1206 \\ 0.0143 & 0.0707 & -0.1535 & 0.5304 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 4.10 \text{ dB} & \sigma_{hh} &= 4.14 \text{ dB} \\ \sigma_{vh} &= -3.63 \text{ dB} & & \\ \chi_d &= -7.75 \text{ dB} & & \\ \alpha &= 0.65 & \zeta &= 12.10^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.71 & m_h &= 0.72 \\ m_{45} &= 0.69 & m_{135} &= 0.62 \\ m_{lhc} &= 0.49 & m_{rhc} &= 0.45 \end{aligned}$$





Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

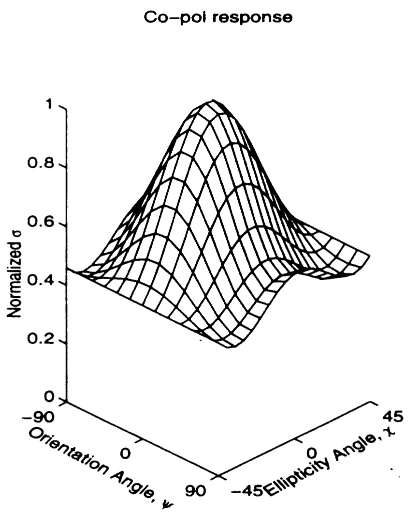
$$\mathbf{L}_m^{\circ} = 1.0000 \begin{bmatrix} 1.0000 & 0.2670 & -0.0485 & 0.0222 \\ 0.2944 & 0.5755 & -0.0558 & -0.0172 \\ -0.0704 & -0.0787 & 0.4856 & 0.0382 \\ 0.0152 & 0.0271 & -0.0954 & 0.0949 \end{bmatrix}$$

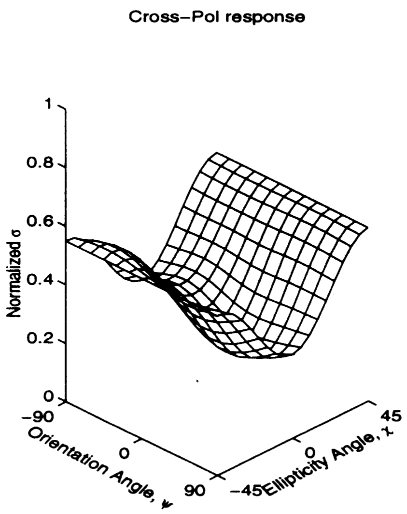
$$\begin{aligned} \sigma_{vv}^{*} &= 0.00 \text{ dB} & \sigma_{hh}^{*} &= -2.40 \text{ dB} \\ \sigma_{vh}^{*} &= -5.52 \text{ dB} & & \\ \chi_d &= -4.48 \text{ dB} & & \\ \alpha &= 0.39 & \zeta &= 12.96° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.55 & m_h &= 0.38 \\ m_{45} &= 0.48 & m_{135} &= 0.51 \\ m_{lhc} &= 0.25 & m_{rhc} &= 0.20 \end{aligned}$$





Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

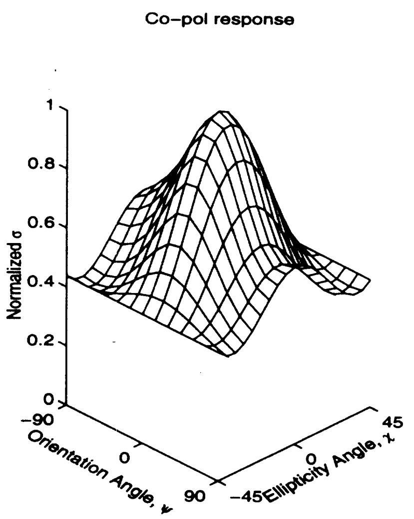
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.1860 & 0.0004 & 0.0161 \\ 0.2625 & 0.6001 & -0.0393 & -0.0035 \\ 0.0371 & -0.0387 & 0.4808 & 0.1157 \\ -0.0072 & 0.0062 & -0.1129 & 0.1561 \end{bmatrix}$$

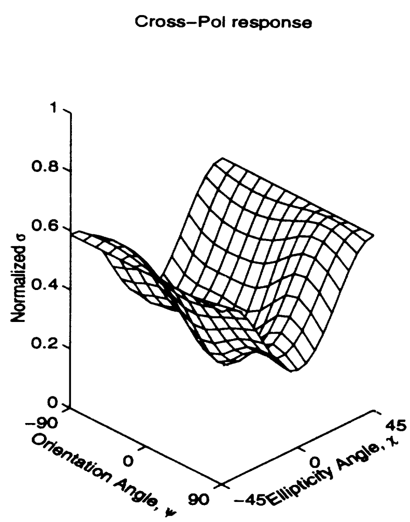
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -2.22 \text{ dB} \\ \sigma_{vh}^* &= -6.49 \text{ dB} \\ \chi_d &= -5.52 \text{ dB} \\ \alpha &= 0.44 & \zeta &= 19.75° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.58 & m_h &= 0.53 \\ m_{45} &= 0.54 & m_{135} &= 0.48 \\ m_{lhc} &= 0.26 & m_{rhc} &= 0.24 \end{aligned}$$





Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

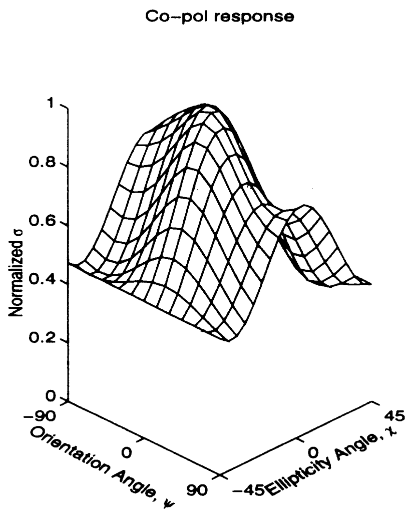
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.2245 & -0.0465 & 0.0552 \\ 0.2398 & 0.7928 & -0.0341 & -0.0259 \\ -0.0224 & -0.0495 & 0.5934 & 0.2166 \\ -0.1200 & 0.0620 & -0.2008 & 0.2488 \end{bmatrix}$$

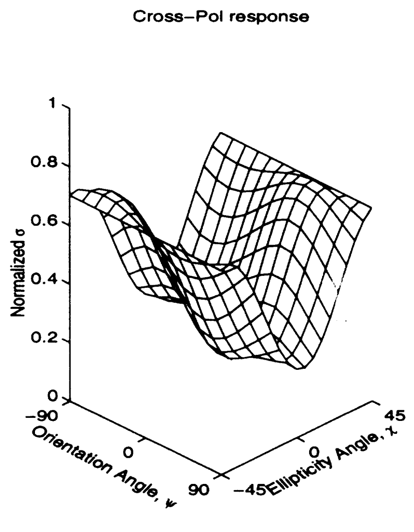
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.01 \text{ dB} \\ \sigma_{vh}^* &= -6.34 \text{ dB} & & \\ \chi_d &= -5.87 \text{ dB} & & \\ \alpha &= 0.53 & \zeta &= 26.36° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.62 & m_h &= 0.56 \\ m_{45} &= 0.58 & m_{135} &= 0.55 \\ m_{lhc} &= 0.29 & m_{rhc} &= 0.34 \end{aligned}$$





Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

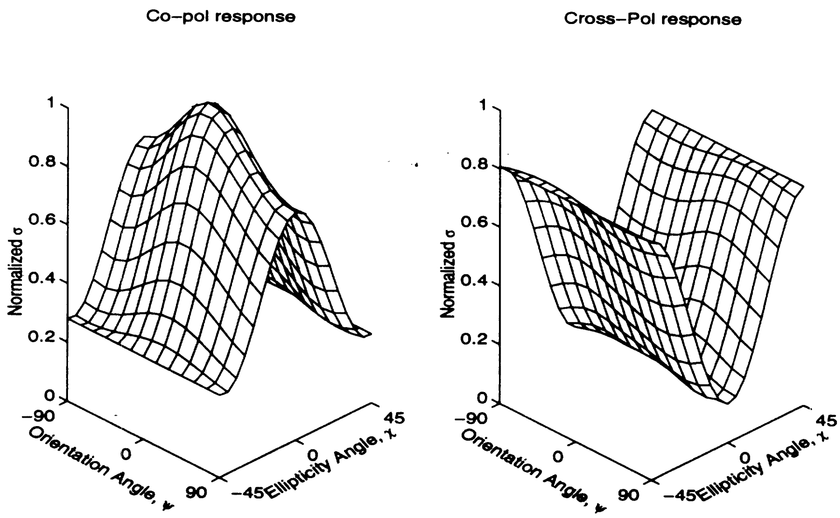
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.1463 \begin{bmatrix} 1.0000 & 0.1671 & -0.0193 & 0.0074 \\ 0.1329 & 0.7801 & -0.0324 & -0.0212 \\ -0.0375 & 0.0067 & 0.7244 & 0.1053 \\ -0.0388 & -0.0152 & -0.0928 & 0.5236 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 2.64 \text{ dB} & \sigma_{hh} &= 1.57 \text{ dB} \\ \sigma_{vh} &= -5.59 \text{ dB} \\ \chi_d &= -7.73 \text{ dB} \\ \alpha &= 0.72 & \zeta &= 9.02° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.77 & m_h &= 0.65 \\ m_{45} &= 0.74 & m_{135} &= 0.69 \\ m_{lhc} &= 0.51 & m_{rhc} &= 0.54 \end{aligned}$$



Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

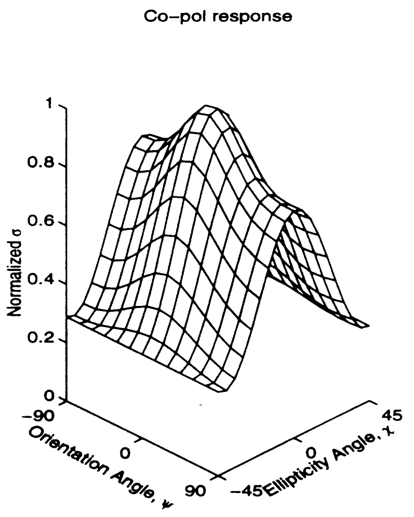
Normalized Mueller Matrix:

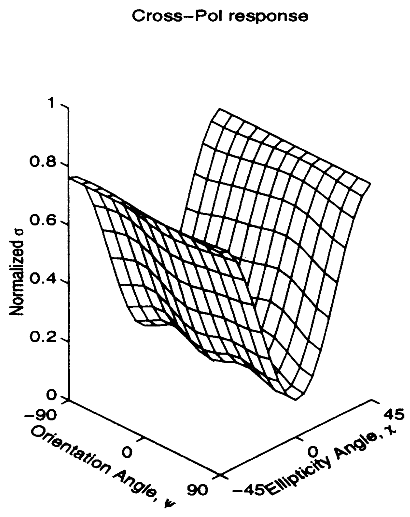
$$\mathbf{L}_m^\circ = 0.1356 \begin{bmatrix} 1.0000 & 0.1419 & 0.0009 & 0.0226 \\ 0.1279 & 0.7784 & -0.0297 & -0.0133 \\ -0.0353 & 0.0141 & 0.6663 & 0.0318 \\ -0.0551 & 0.0284 & -0.0398 & 0.4797 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 2.32 \text{ dB} & \sigma_{hh} &= 1.23 \text{ dB} \\ \sigma_{vh} &= -6.38 \text{ dB} & & \\ \chi_d &= -8.19 \text{ dB} & & \\ \alpha &= 0.65 & \zeta &= 3.58^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.78 & m_h &= 0.69 \\ m_{45} &= 0.68 & m_{135} &= 0.65 \\ m_{lhc} &= 0.48 & m_{rhc} &= 0.49 \end{aligned}$$





Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

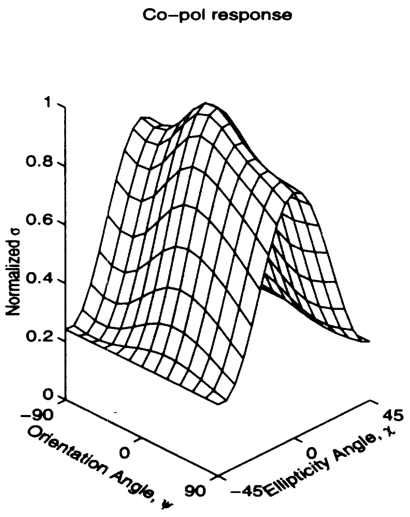
Normalized Mueller Matrix:

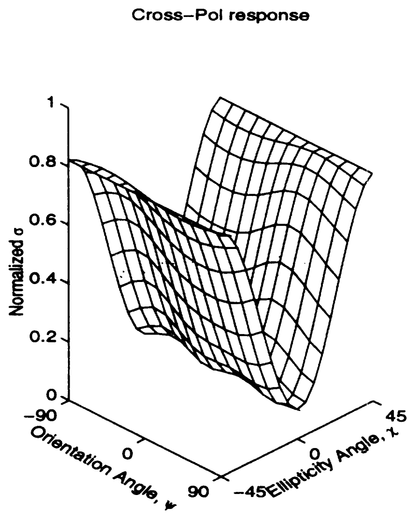
$$\mathbf{L}_m^\circ = 0.3367 \begin{bmatrix} 1.0000 & 0.1050 & -0.0009 & 0.0056 \\ 0.0994 & 0.8383 & 0.0070 & -0.0081 \\ -0.0289 & 0.0316 & 0.7545 & 0.1268 \\ -0.0595 & 0.0168 & -0.1096 & 0.5796 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 6.26 \text{ dB} & \sigma_{hh} &= 5.50 \text{ dB} \\ \sigma_{vh} &= -3.64 \text{ dB} & & \\ \chi_d &= -9.54 \text{ dB} & & \\ \alpha &= 0.74 & \zeta &= 10.05^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.82 & m_h &= 0.78 \\ m_{45} &= 0.75 & m_{135} &= 0.75 \\ m_{lhc} &= 0.57 & m_{rhc} &= 0.60 \end{aligned}$$





Target Name: Spruce 1991
System: UM

Target Description: Young spruce, approximately 1 m in diameter and 1 m tall. Needles on young, small branches are 1-2 cm long, on mature branches, needles are 2-4 cm long.

(note: computation of the illumination area for 35 GHz system was uncertain, therefore, these data are normalized to L_{11}. Affected quantities on the following pages are indicated by an asterisk).

References:

Nashashibi, Kuga and Ulaby, "Polarimetric Observations of Trees at 35 and 94 GHz," APS, London, Ontario. June 1990.

Data List:

θ_i	freq.	condition	data no.	page no.
20	35	w/leaves	tree.12.1	216
30	35	w/leaves	tree.12.2	217
40	35	w/leaves	tree.12.3	218
50	35	w/leaves	tree.12.4	219
60	35	w/leaves	tree.12.5	220
70	35	w/leaves	tree.12.6	221
90	35	w/leaves	tree.12.7	222
25	94	w/leaves	tree.12.8	223
30	94	w/leaves	tree.12.9	224
40	94	w/leaves	tree.12.10	225
50	94	w/leaves	tree.12.11	226
60	94	w/leaves	tree.12.12	227
70	94	w/leaves	tree.12.13	228
90	94	w/leaves	tree.12.14	229

Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

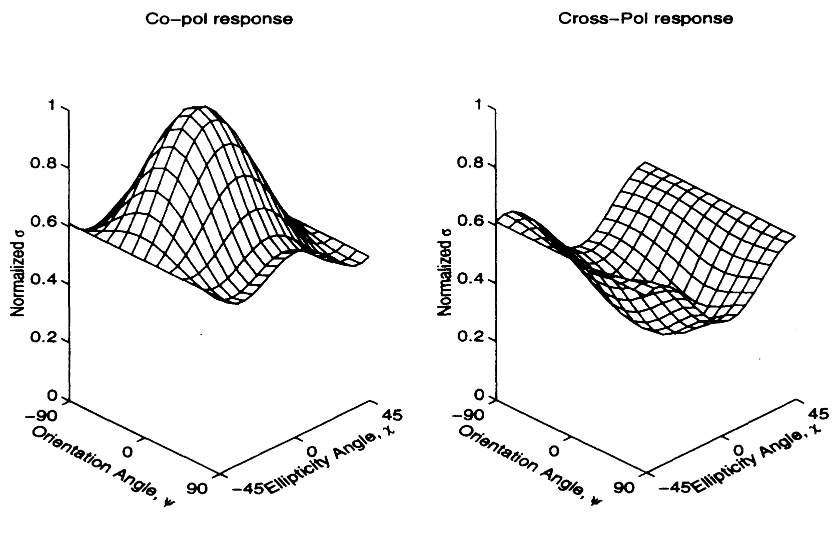
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.2907 & -0.0468 & 0.0449 \\ 0.4072 & 0.6593 & -0.0688 & 0.0187 \\ -0.0635 & -0.0639 & 0.5047 & -0.0376 \\ -0.0973 & 0.0100 & -0.0006 & 0.0354 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.81 \text{ dB} \\ \sigma_{vh}^* &= -4.57 \text{ dB} & & \\ \chi_d &= -3.76 \text{ dB} & & \\ \alpha &= 0.33 & \zeta &= -3.91° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.43 & m_h &= 0.39 \\ m_{45} &= 0.44 & m_{135} &= 0.45 \\ m_{lhc} &= 0.14 & m_{rhc} &= 0.11 \end{aligned}$$



Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

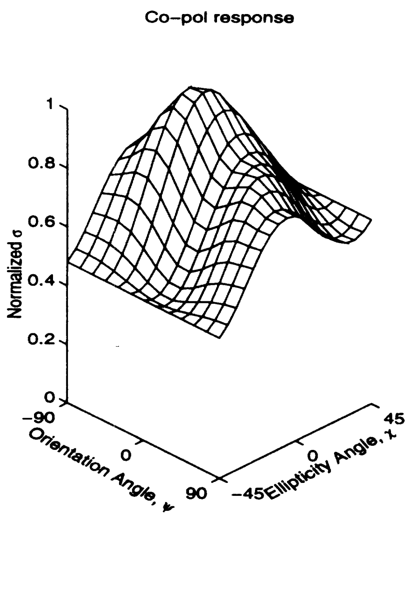
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.3331 & -0.0879 & -0.0776 \\ 0.5603 & 0.9160 & -0.0294 & 0.0869 \\ -0.0781 & -0.0513 & 0.7732 & 0.0371 \\ 0.2448 & -0.0653 & -0.0453 & 0.0812 \end{bmatrix}$$

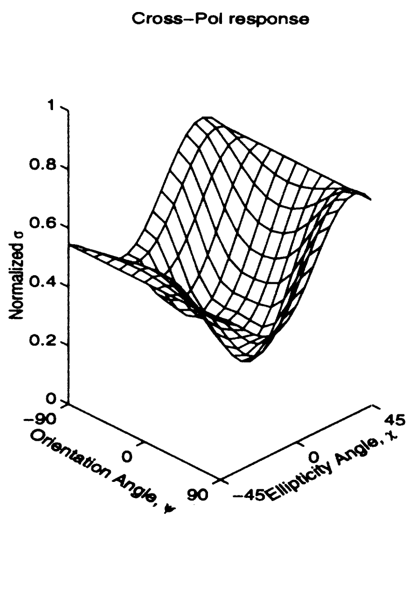
$$\begin{aligned} \sigma^*_{vv} &= 0.00 \text{ dB} & \sigma^*_{hh} &= -0.38 \text{ dB} \\ \sigma^*_{vh} &= -3.50 \text{ dB} & & \\ \chi_d &= -3.31 \text{ dB} & & \\ \alpha &= 0.45 & \zeta &= 5.51^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.33 & m_h &= 0.47 \\ m_{45} &= 0.56 & m_{135} &= 0.56 \\ m_{lhc} &= 0.21 & m_{rhc} &= 0.10 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

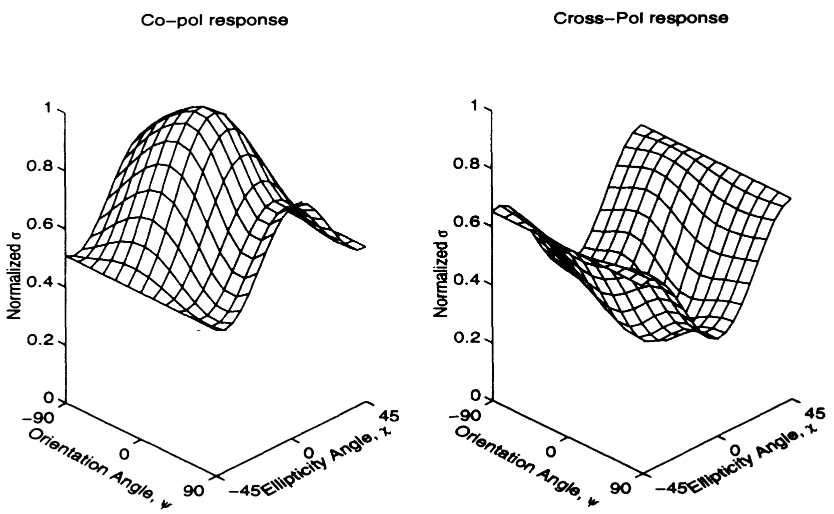
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.2482 & -0.0224 & 0.0364 \\ 0.3381 & 0.7974 & -0.0504 & -0.0223 \\ -0.0204 & -0.0755 & 0.5569 & -0.0764 \\ -0.0229 & 0.0559 & 0.0441 & 0.1518 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.98 \text{ dB} \\ \sigma_{vh}^* &= -5.33 \text{ dB} & & \\ \chi_d &= -4.87 \text{ dB} & & \\ \alpha &= 0.40 & \zeta &= -9.65^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.50 & m_h &= 0.53 \\ m_{45} &= 0.46 & m_{135} &= 0.48 \\ m_{lhc} &= 0.20 & m_{rhc} &= 0.12 \end{aligned}$$



Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

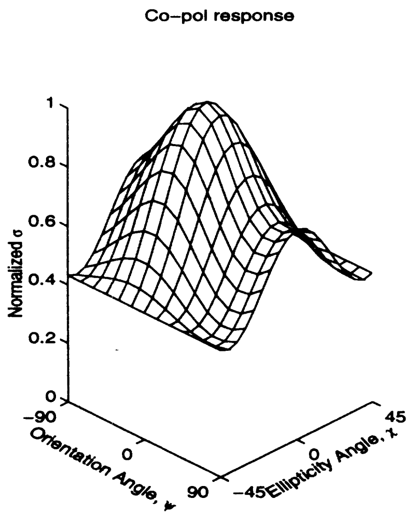
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.2261 & -0.0645 & 0.0029 \\ 0.2605 & 0.7320 & -0.0096 & -0.0041 \\ -0.0733 & -0.0727 & 0.5591 & -0.0653 \\ -0.0055 & 0.0125 & 0.0635 & 0.2141 \end{bmatrix}$$

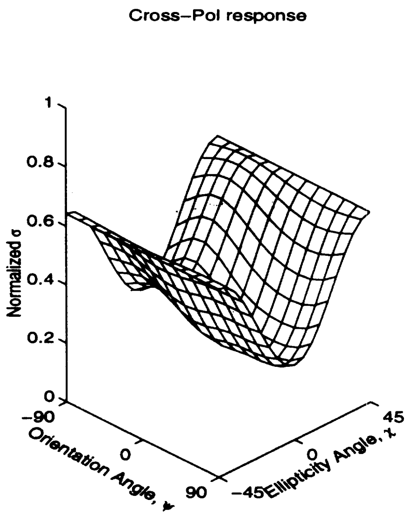
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.36 \text{ dB} \\ \sigma_{vh}^* &= -6.14 \text{ dB} \\ \chi_d &= -5.51 \text{ dB} \\ \alpha &= 0.46 & \zeta &= -9.46^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.59 & m_h &= 0.53 \\ m_{45} &= 0.48 & m_{135} &= 0.56 \\ m_{lhc} &= 0.26 & m_{rhc} &= 0.21 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

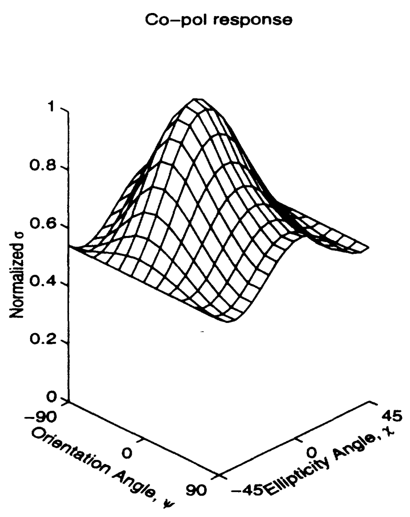
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.3082 & -0.0716 & 0.0446 \\ 0.4071 & 0.7366 & -0.0429 & -0.0100 \\ -0.1221 & -0.0348 & 0.5973 & 0.0122 \\ -0.0445 & 0.0535 & -0.0255 & 0.0660 \end{bmatrix}$$

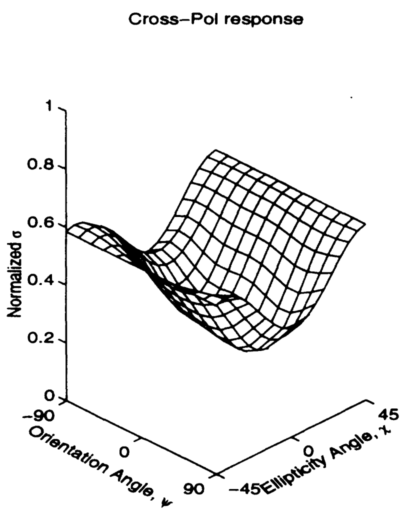
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.33 \text{ dB} \\ \sigma_{vh}^* &= -4.47 \text{ dB} & & \\ \chi_d &= -3.85 \text{ dB} & & \\ \alpha &= 0.39 & \zeta &= 3.25° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.43 & m_h &= 0.41 \\ m_{45} &= 0.47 & m_{135} &= 0.51 \\ m_{lhc} &= 0.13 & m_{rhc} &= 0.09 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

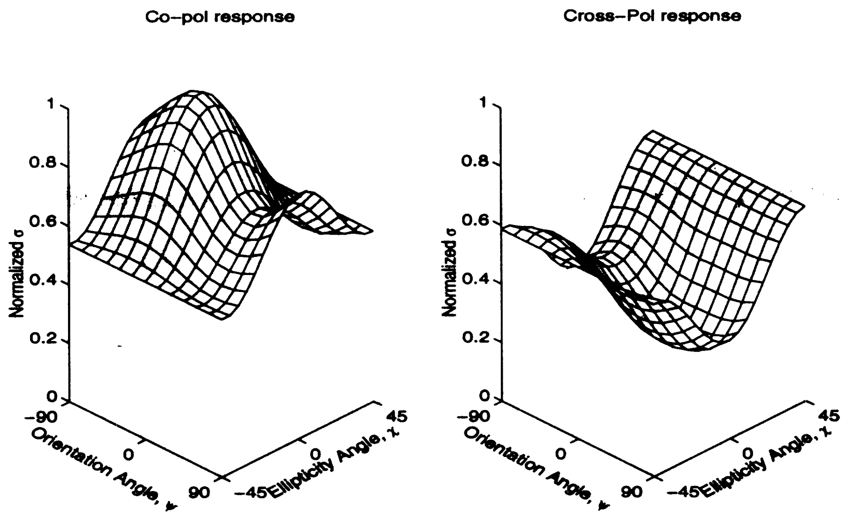
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.3049 & -0.0742 & 0.0292 \\ 0.3645 & 0.9050 & -0.0621 & 0.0062 \\ -0.1241 & -0.0865 & 0.5653 & 0.0460 \\ 0.0184 & 0.0463 & -0.0679 & 0.0706 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -0.43 \text{ dB} \\ \sigma_{vh}^* &= -4.75 \text{ dB} & & \\ \chi_d &= -4.54 \text{ dB} & & \\ \alpha &= 0.34 & \zeta &= 10.16° \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.47 & m_h &= 0.50 \\ m_{45} &= 0.40 & m_{135} &= 0.48 \\ m_{lhc} &= 0.09 & m_{rhc} &= 0.12 \end{aligned}$$



Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

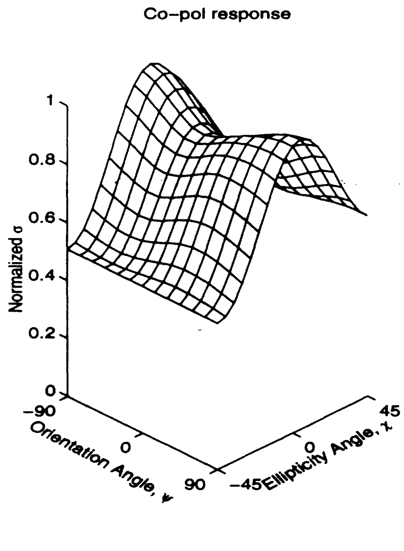
$$\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix} 1.0000 & 0.3248 & -0.0280 & 0.0347 \\ 0.3964 & 1.1088 & 0.0217 & 0.0085 \\ 0.0582 & 0.0040 & 0.6776 & 0.0652 \\ 0.0040 & 0.1463 & -0.0451 & 0.1469 \end{bmatrix}$$

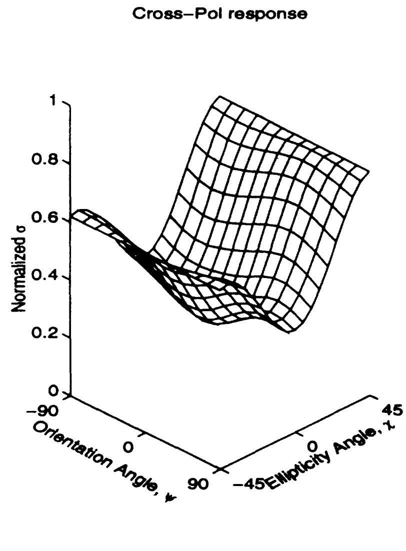
$$\begin{aligned} \sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= 0.45 \text{ dB} \\ \sigma_{vh}^* &= -4.43 \text{ dB} & & \\ \chi_d &= -4.66 \text{ dB} & & \\ \alpha &= 0.39 & \zeta &= 7.62^\circ \end{aligned}$$

* magnitude relative to σ_{vv} (see pg. 39 for details)

Degree of Polarization:

$$\begin{aligned} m_v &= 0.43 & m_h &= 0.56 \\ m_{45} &= 0.51 & m_{135} &= 0.46 \\ m_{lhc} &= 0.17 & m_{rhc} &= 0.10 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 25°
Independent Samples: 99

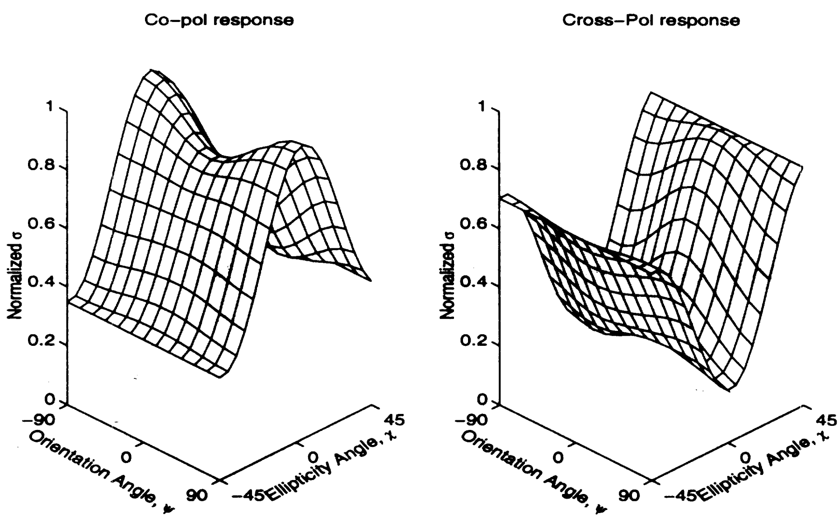
Normalized Mueller Matrix:

$$\mathbf{L}_m^\circ = 0.0550 \begin{bmatrix} 1.0000 & 0.3164 & -0.0560 & 0.0702 \\ 0.2116 & 1.1674 & -0.0012 & -0.0273 \\ 0.0355 & 0.0049 & 0.8496 & 0.0710 \\ -0.0808 & 0.1861 & 0.0575 & 0.4404 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -1.60 \text{ dB} & \sigma_{hh} &= -0.93 \text{ dB} \\ \sigma_{vh} &= -7.39 \text{ dB} & & \\ \chi_d &= -6.13 \text{ dB} & & \\ \alpha &= 0.60 & \zeta &= 0.60^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.65 & m_h &= 0.59 \\ m_{45} &= 0.68 & m_{135} &= 0.59 \\ m_{lhc} &= 0.36 & m_{rhc} &= 0.32 \end{aligned}$$



Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 30°
Independent Samples: 99

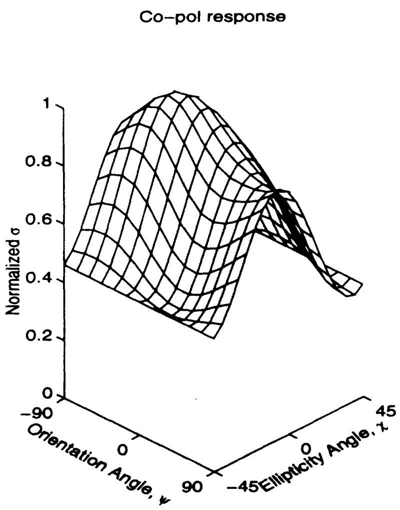
Normalized Mueller Matrix:

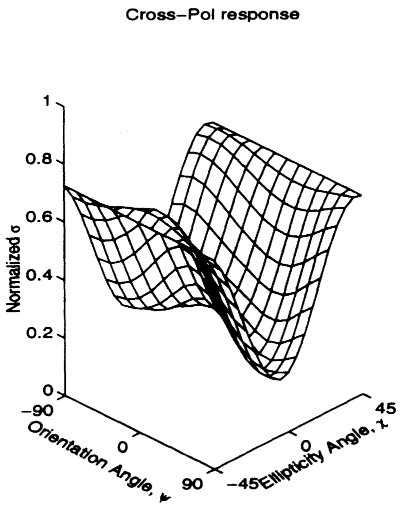
$$\mathbf{L}_m^\circ = 0.0696 \begin{bmatrix} 1.0000 & 0.3283 & -0.0993 & -0.0451 \\ 0.2231 & 0.9105 & -0.0213 & 0.0810 \\ -0.0546 & -0.0610 & 0.7569 & -0.0626 \\ 0.1237 & -0.1838 & 0.0973 & 0.3040 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -0.58 \text{ dB} & \sigma_{hh} &= -0.99 \text{ dB} \\ \sigma_{vh} &= -6.18 \text{ dB} & & \\ \chi_d &= -5.40 \text{ dB} & & \\ \alpha &= 0.56 & \zeta &= -8.57° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.64 & m_h &= 0.50 \\ m_{45} &= 0.63 & m_{135} &= 0.62 \\ m_{lhc} &= 0.24 & m_{rhc} &= 0.34 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 40°
Independent Samples: 99

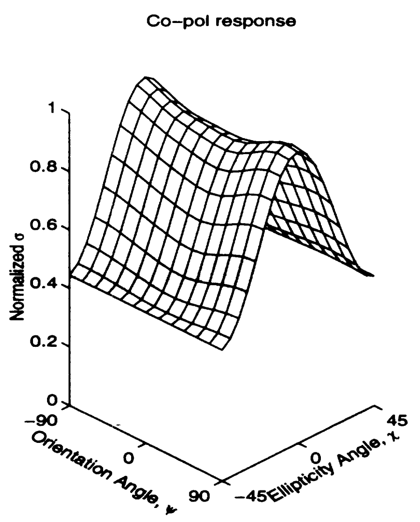
Normalized Mueller Matrix:

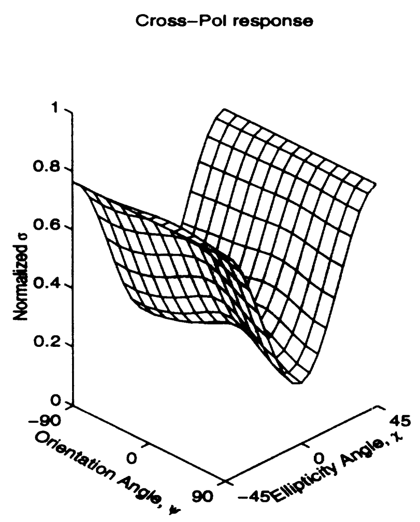
$$\mathbf{L}_m^{\circ} = 0.0753 \begin{bmatrix} 1.0000 & 0.3026 & -0.0249 & -0.0244 \\ 0.2223 & 1.0728 & -0.0091 & 0.0199 \\ 0.0058 & 0.0326 & 0.7540 & -0.0029 \\ 0.0115 & -0.0173 & 0.0506 & 0.3414 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= -0.24 \text{ dB} & \sigma_{hh} &= 0.07 \text{ dB} \\ \sigma_{vh} &= -6.05 \text{ dB} & & \\ \chi_d &= -5.96 \text{ dB} & & \\ \alpha &= 0.53 & \zeta &= -2.80° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.64 & m_h &= 0.56 \\ m_{45} &= 0.61 & m_{135} &= 0.55 \\ m_{lhc} &= 0.26 & m_{rhc} &= 0.27 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 50°
Independent Samples: 99

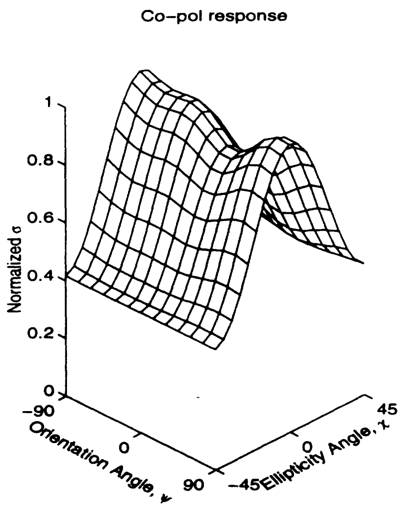
Normalized Mueller Matrix:

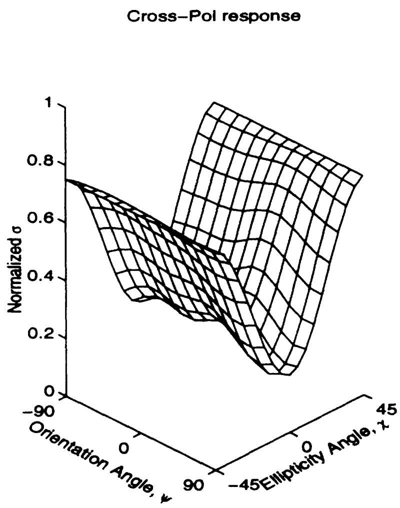
$$\mathbf{L}_m^{\circ} = 0.0919 \begin{bmatrix} 1.0000 & 0.2853 & -0.0416 & -0.0305 \\ 0.2156 & 1.0797 & -0.0107 & -0.0014 \\ -0.0665 & 0.0411 & 0.7566 & 0.0498 \\ -0.0102 & 0.0356 & -0.0541 & 0.3466 \end{bmatrix}$$

$$\sigma_{vv} = 0.63 \text{ dB} \qquad \sigma_{hh} = 0.96 \text{ dB}$$
$$\sigma_{vh} = -5.39 \text{ dB}$$
$$\chi_d = -6.18 \text{ dB}$$
$$\alpha = 0.53 \qquad \zeta = 5.38°$$

Degree of Polarization:

$$m_v = 0.65 \qquad m_h = 0.58$$
$$m_{45} = 0.60 \qquad m_{135} = 0.58$$
$$m_{lhc} = 0.29 \qquad m_{rhc} = 0.26$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

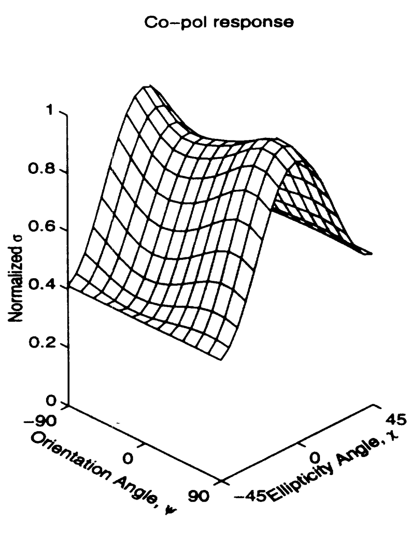
Normalized Mueller Matrix:

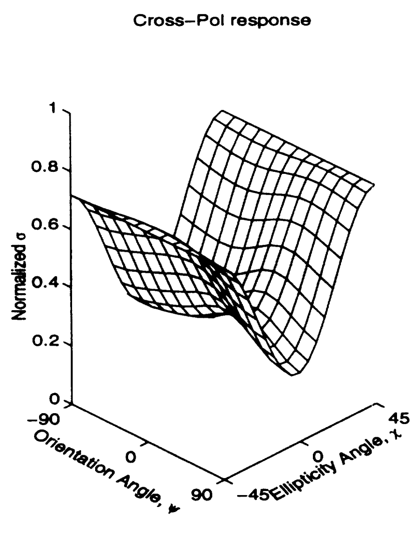
$$\mathbf{L}_m^\circ = 0.1252 \begin{bmatrix} 1.0000 & 0.3434 & 0.0127 & -0.0703 \\ 0.2633 & 1.0826 & 0.0373 & -0.0109 \\ 0.0374 & 0.0722 & 0.7128 & -0.0128 \\ 0.0691 & 0.0081 & -0.0822 & 0.3030 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 1.97 \text{ dB} & \sigma_{hh} &= 2.31 \text{ dB} \\ \sigma_{vh} &= -3.21 \text{ dB} & & \\ \chi_d &= -5.36 \text{ dB} & & \\ \alpha &= 0.49 & \zeta &= 3.90° \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.59 & m_h &= 0.52 \\ m_{45} &= 0.55 & m_{135} &= 0.52 \\ m_{lhc} &= 0.28 & m_{rhc} &= 0.20 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

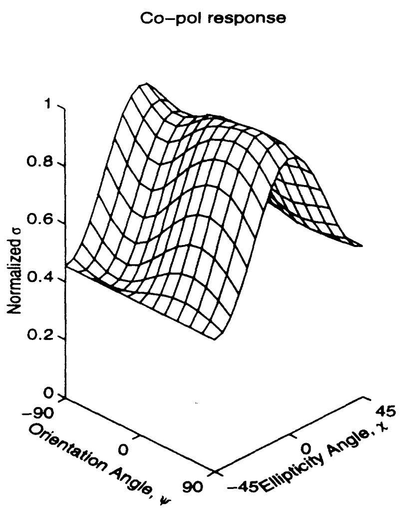
Normalized Mueller Matrix:

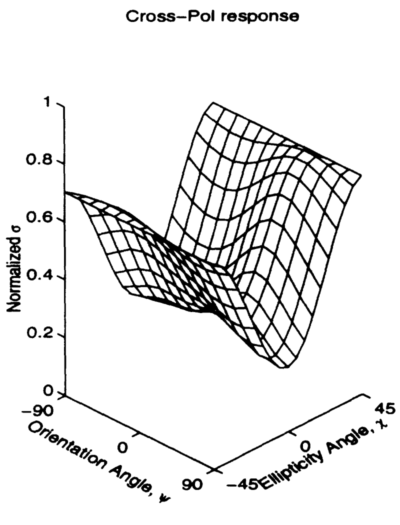
$$\mathbf{L}_m^\circ = 0.1373 \begin{bmatrix} 1.0000 & 0.3051 & 0.0073 & -0.0137 \\ 0.2307 & 0.9835 & 0.0352 & 0.0018 \\ 0.0349 & 0.0714 & 0.6745 & 0.1171 \\ 0.0130 & 0.0473 & -0.1750 & 0.2510 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 2.37 \text{ dB} & \sigma_{hh} &= 2.30 \text{ dB} \\ \sigma_{vh} &= -3.35 \text{ dB} & & \\ \chi_d &= -5.68 \text{ dB} & & \\ \alpha &= 0.49 & \zeta &= 17.51^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.63 & m_h &= 0.53 \\ m_{45} &= 0.57 & m_{135} &= 0.54 \\ m_{lhc} &= 0.26 & m_{rhc} &= 0.19 \end{aligned}$$





Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

$$\mathbf{L}_m^{\circ} = 0.1605 \begin{bmatrix} 1.0000 & 0.3272 & -0.0121 & -0.0177 \\ 0.2561 & 1.0599 & -0.0288 & -0.0483 \\ -0.0311 & -0.0243 & 0.7599 & 0.0130 \\ -0.0484 & 0.0972 & -0.0676 & 0.2920 \end{bmatrix}$$

$$\begin{aligned} \sigma_{vv} &= 3.05 \text{ dB} & \sigma_{hh} &= 3.30 \text{ dB} \\ \sigma_{vh} &= -2.30 \text{ dB} & & \\ \chi_d &= -5.48 \text{ dB} & & \\ \alpha &= 0.51 & \zeta &= 4.38^\circ \end{aligned}$$

Degree of Polarization:

$$\begin{aligned} m_v &= 0.59 & m_h &= 0.53 \\ m_{45} &= 0.57 & m_{135} &= 0.58 \\ m_{lhc} &= 0.25 & m_{rhc} &= 0.20 \end{aligned}$$