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 how 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 $\theta$.

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 $\theta$ in the direction of the unit vector $k$, 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 $\theta$ and the azimuth angle, $\phi$, 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 $z$-$y$ plane along direction $\hat{k}$, with electric field polarization components $\hat{h} = \hat{y}$ and $\hat{v} = \hat{h} \times \hat{k}$. 
either antenna
\[ \hat{k} = \sin \theta \hat{x} + \cos \theta \hat{z}. \] (1)
and the associated horizontal and vertical polarization unit vectors are given by:
\[ \hat{h} = \frac{\hat{z} \times \hat{k}}{|\hat{z} \times \hat{k}|} = \hat{y} \] (2)
\[ \hat{v} = \hat{h} \times \hat{k} = \cos \theta \hat{x} - \sin \theta \hat{z}. \] (3)

For a plane wave at a distance \( r \) from the center of the reference coordinate system, traveling in the direction \( \hat{k} \) as shown in Fig. 1, the electric field vector \( \mathbf{E} \) consists, in the general case, of a vertically polarized component, \( E_v \hat{v} \), and a horizontally polarized component, \( E_h \hat{h} \):
\[ \mathbf{E} = (E_v \hat{v} + E_h \hat{h}) e^{i k r} \] (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:
\[ E_v = a_v e^{-i\delta_v} \] (5)
\[ E_h = a_h e^{-i\delta_h} \] (6)
The total intensity of the wave is given by:
\[ I_0 = a_v^2 + a_h^2, \] (7)
and the polarization state is characterized by the angles \( \delta \) and \( \alpha \) where
\[ \delta = \delta_h - \delta_v, \] (8)
\[ \tan \alpha = \frac{a_h}{a_v}. \] (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 \( a_v = 0, \)
- v-polarized \( a_h = 0, \)
- linearly polarized \( \delta = 0, \)
- right-hand circularly polarized \( a_v = a_h \) and \( \delta = -\pi/2, \)
- left-hand circularly polarized \( a_v = a_h \) and \( \delta = \pi/2. \)

Alternatively, the polarization state may be described by the rotation angle \( \psi \) and the ellipticity angle \( \chi \) shown in Fig. 2, which are related to \( \alpha \) and \( \delta \) by:
\[ \tan 2\psi = (\tan 2\alpha) \cos \delta, \] (10)
\[ \sin 2\chi = (\sin 2\alpha) \sin \delta. \] (11)
Figure 2: Polarization ellipse in the $v-h$ plane for a wave traveling in the $k$ 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:

\[
\mathbf{F} = \begin{bmatrix}
I_0 \\
Q \\
U \\
V
\end{bmatrix} = \begin{bmatrix}
|E_v|^2 + |E_h|^2 \\
|E_v|^2 - |E_h|^2 \\
2\text{Re}(E_v E_h^*) \\
2\text{Im}(E_v E_h^*)
\end{bmatrix} = \begin{bmatrix}
a_v^2 + a_h^2 \\
a_v^2 - a_h^2 \\
2a_v a_h \cos \delta \\
2a_v a_h \sin \delta
\end{bmatrix} = \begin{bmatrix}
I_0 \\
I_0 \cos 2\psi \cos 2\chi \\
I_0 \sin 2\psi \cos 2\chi \\
I_0 \sin 2\chi
\end{bmatrix}
\]  
(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 \( \delta \):

\[
\frac{V}{U} = \tan \delta.
\]  
(13)

The modified Stokes vector \( \mathbf{F}_m \), a more modern form, is defined in terms of \( I_v, I_h, U \), and \( V \) as follows:

\[
\mathbf{F}_m = \begin{bmatrix}
I_v \\
I_h \\
U \\
V
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2}(1 + \cos 2\psi \cos 2\chi) \\
\frac{1}{2}(1 - \cos 2\psi \cos 2\chi) \\
\sin 2\psi \cos 2\chi \\
\sin 2\chi
\end{bmatrix} I_0
\]  
(14)

where

\[
I_v = |E_v|^2 = a_v^2, \quad I_h = |E_h|^2 = a_h^2.
\]  
(15)

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 \( \theta_t = \theta_r = 0 \) for convenience, \( \mathbf{k}_t = \mathbf{\hat{k}}_t = \mathbf{\hat{k}} \) and \( \mathbf{k} \) is given by (1). This definition, in which both \( \mathbf{\hat{k}}_t \) and \( \mathbf{\hat{k}}_r \) point from the antenna towards the target, is known as the backscatter alignment (BSA) convention. For the backscattering case in the BSA convention, \( \mathbf{h}_t = \mathbf{h}_r = \mathbf{h} \), \( \mathbf{v}_t = \mathbf{v}_r = \mathbf{v} \), and \( \mathbf{h} \) and \( \mathbf{v} \) are given by (2) and (3), respectively.
Figure 3: Coordinate systems and scattering geometry for the backscatter alignment (BSA) convention.
The scattering matrix $S$ of the target under observation relates the electric field $E'$ received by the radar to the transmitted electric field $E'$ illuminating the target. $E'$ is given by:

$$E' = E'_v \hat{v} + E'_h \hat{h}$$  \hspace{1cm} (17)$$

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

$$E^r = E^r_v \hat{v} + E^r_h \hat{h}.$$  \hspace{1cm} (18)$$

Using the vector notation:

$$\mathbf{E} = \begin{pmatrix} E_v \\ E_h \end{pmatrix},$$  \hspace{1cm} (19)$$

the two fields can be related by the scattering matrix $S$:

$$\begin{pmatrix} E^r_v \\ E^r_h \end{pmatrix} = \frac{e^{ikr}}{r} \begin{pmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{pmatrix} \begin{pmatrix} E^t_v \\ E^t_h \end{pmatrix},$$  \hspace{1cm} (20)$$

or

$$E^r = \frac{e^{ikr}}{r} S E^t.$$  \hspace{1cm} (21)$$

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

$$S_{hv} = S_{vh}.$$  \hspace{1cm} (22)$$

### 2.4 Mueller Matrix

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

$$F^r_m = \frac{1}{r^2} L_m F^t_m$$  \hspace{1cm} (23)$$

with

$$L_m = \begin{bmatrix}
|S_{vv}|^2 & |S_{vh}|^2 & \text{Re}(S_{vh}^* S_{vv}) & -\text{Im}(S_{vh}^* S_{vv}) \\
|S_{hv}|^2 & |S_{hh}|^2 & \text{Re}(S_{hh}^* S_{hv}) & -\text{Im}(S_{hh}^* S_{hv}) \\
2 \text{Re}(S_{vv} S_{hv}^*) & 2 \text{Re}(S_{vh} S_{hh}^*) & \text{Re}(S_{vv} S_{vv}^* + S_{vh} S_{hv}^*) & -\text{Im}(S_{vv} S_{hh}^* - S_{vh} S_{hv}^*) \\
2 \text{Im}(S_{vv} S_{hv}^*) & 2 \text{Im}(S_{vh} S_{hh}^*) & \text{Im}(S_{vv} S_{hh}^* + S_{vh} S_{hv}^*) & \text{Re}(S_{vv} S_{hh}^* - S_{vh} S_{hv}^*) 
\end{bmatrix}$$  \hspace{1cm} (24)$$
2.5 Polarization Synthesis

The polarimetric scattering response of a point target may be characterized by either its scattering matrix $S$ or its modified Mueller matrix $L_m$. 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 $L_m$ (either directly or by first measuring $S$ and then using (23) to obtain $L_m$) for many statistically independent observations (or spatial locations) of the surface under consideration and then performing an average for each element of $L_m$.

Additionally, if each averaged element is divided by the illuminated area $A_i$, the process leads to the differential modified Mueller matrix,

$$L_m^* = \frac{1}{A_i}(L_m),$$  \hspace{1cm}  (25)

which can be used to compute the backscattering coefficient $\sigma^o(\psi_t, \chi_t; \psi_t, \chi_t)$ 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 $\psi_t$ and ellipticity angle $\chi_t$, the antenna modified Stokes vector $A_m^t$ is given by $F_m^t$, as defined by (14), normalized to the total intensity $I_0$:

$$A_m^t = \frac{F_m^t}{I_0} = \begin{bmatrix} I_v^t \\ I_h^t \\ U^t \\ V^t \end{bmatrix} = \begin{bmatrix} \frac{1}{2} (1 + \cos 2\psi_t \cos 2\chi_t) \\ \frac{1}{2} (1 - \cos 2\psi_t \cos 2\chi_t) \\ \sin 2\psi_t \cos 2\chi_t \\ \sin 2\chi_t \end{bmatrix}.$$  \hspace{1cm}  (26)

A similar definition applies to $A_m^r$ for the receive antenna, and in terms of the two vectors, the polarization synthesis equation is given by:

$$\sigma^o(\psi_t, \chi_t; \psi_t, \chi_t) = 4\pi A_m^t \cdot T L_m \cdot A_m^r$$  \hspace{1cm}  (27)

where $T$ is a transformation matrix given by:

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & -1/2 \end{bmatrix}.$$  \hspace{1cm}  (28)

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

$$\sigma_{vv}^o = 4\pi L_{11}$$  \hspace{1cm}  (29)
$$\sigma_{hh}^o = 4\pi L_{22}$$  \hspace{1cm}  (30)
$$\sigma_{vh}^o = \sigma_{hv}^o = 4\pi L_{12} = 4\pi L_{21}$$  \hspace{1cm}  (31)

where $L_{ij}$ is the element of $L_m^o$ in row $i$ and column $j$.  

9
2.6 Polarization Response

For a given $L_m$ whose elements had been measured experimentally or calculated using a theoretical model, it is possible to apply (27) to compute $\sigma^2$ for a large number of combinations of the four angles $\psi_r$, $\chi_r$, $\psi_t$ and $\chi_t$ within the applicable limits of $-\pi/2$ to $\pi/2$ for $\psi_r$ and $\psi_t$ and $-\pi/4$ to $\pi/4$ for $\chi_r$ and $\chi_t$. 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:

Co-Polarized Response $\psi_r = \psi_t, \chi_r = \chi_t$

Cross-Polarized Response $\psi_r = \psi_t + \pi/2, \chi_r = -\chi_t$

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

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

(32)

where $a$ is the radius of the sphere. Indicated on the plots are the $(\psi_t, \chi_t)$ 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 $\chi_t$ and $\psi_t$. 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 $\sigma^2$, again normalized to the maximum value.

2.7 Degree of Polarization

According to (23), the receive modified Stokes vector $F^r_m$ is related to the transmit modified Stokes vector $F^t_m$ by:

$$F^r_m = \begin{bmatrix} I^r \\ H^r \\ U^r \\ V^r \end{bmatrix} = \frac{1}{r^2} L_m F^t_m$$

(33)

For a specified transmit polarization, $F^t_m$, and a given $L_m$, (33) leads to specific values for the elements of $F^r_m$. The degree of polarization $m$ is defined as:

$$m = \frac{[(I^r - I^t)_r]^2 + (U^r)^2 + (V^r)^2]^{1/2}}{I^r + I^t}.$$  

(34)
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 \( \mathbf{L}_m^c \) defined as:

\[
\mathbf{L}_m^c = \begin{bmatrix}
L_{11} & L_{12} & L_{13} & L_{14} \\
L_{21} & L_{22} & L_{23} & L_{24} \\
L_{31} & L_{32} & L_{33} & L_{34} \\
L_{41} & L_{42} & L_{43} & L_{44}
\end{bmatrix},
\]  

(35)

experimental observations have shown that the four elements in the top right quadrant \((L_{13}, L_{14}, L_{23}, \text{and } L_{24})\) and the elements in the bottom left quadrant \((L_{31}, L_{32}, L_{41}, \text{and } L_{42})\) 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

\[
\mathbf{F}_v^t = \begin{bmatrix}
1 \\
0 \\
0 \\
0
\end{bmatrix},
\]  

(36)

\[
m_v = \frac{L_{11} - L_{21}}{L_{11} + L_{21}} = \frac{\sigma_{vv}^o - \sigma_{vh}^o}{\sigma_{vv}^o + \sigma_{vh}^o}
\]  

(37)

2.7.2 Horizontally Polarized Transmit Polarization

\[
\mathbf{F}_h^t = \begin{bmatrix}
0 \\
1 \\
0 \\
0
\end{bmatrix},
\]  

(38)

\[
m_h = \frac{L_{22} - L_{12}}{L_{22} + L_{12}} = \frac{\sigma_{hh}^o - \sigma_{hv}^o}{\sigma_{hh}^o + \sigma_{hv}^o}
\]  

(39)

2.7.3 Other Transmit Polarizations

By introducing the intermediate coefficients \( a_1 \) through \( a_6 \) defined by:

\[
a_1 = (L_{11} - L_{21})^2,
\]  

(40)

\[
a_2 = (L_{22} - L_{12})^2,
\]  

(41)

\[
a_3 = L_{33}^2 + L_{43}^2,
\]  

(42)
we can provide simple expressions for the following four configurations of the transmit polarization state.

**45° and 135° Linear Polarization**

\[ a_4 = L_{34}^2 + L_{44}^2. \]  \hfill (43)

\[ a_5 = 2(L_{11} - L_{21})(L_{21} - L_{22}). \]  \hfill (44)

\[ a_6 = (L_{11} + L_{22} + L_{12} + L_{21})^2. \]  \hfill (45)

\[ \mathbf{F}_{45}^t = \begin{bmatrix} 1/2 \\ 1/2 \\ 1 \\ 0 \end{bmatrix} \]  \hfill (46)

\[ \mathbf{F}_{135}^t = \begin{bmatrix} 1/2 \\ 1/2 \\ -1 \\ 0 \end{bmatrix} \]  \hfill (47)

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

**Circular Polarization**

\[ \mathbf{F}_{RHIC}^t = \begin{bmatrix} 1/2 \\ 1/2 \\ 0 \\ -1 \end{bmatrix} \]  \hfill (49)

\[ \mathbf{F}_{LHC}^t = \begin{bmatrix} 1/2 \\ 1/2 \\ 0 \\ 1 \end{bmatrix} \]  \hfill (50)

\[ m_{RHIC} = m_{LHC} = \left[ \frac{a_1 + a_2 + a_5 + 4a_4}{a_6} \right]^{1/2} \]  \hfill (51)

2.8 Depolarization Ratio

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

\[ \chi_d = \frac{L_{12} + L_{21}}{L_{11} + L_{22}} = \frac{2\sigma_{hv}^*}{\sigma_{vv}^* + \sigma_{hh}^*}, \]  \hfill (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 \( \mathbf{L}_m^\circ \) assumes the simple form:

\[
\mathbf{L}_m^\circ = L_{11} \begin{bmatrix}
1 & \chi_d & 0 & 0 \\
\chi_d & 1 & 0 & 0 \\
0 & 0 & 1 - \chi_d & 0 \\
0 & 0 & 0 & 1 - 3\chi_d
\end{bmatrix}.
\]  

(53)

thereby reducing \( \mathbf{L}_m^\circ \) to two parameters, \( L_{11} \) and \( \chi_d \).

### 2.9 Co-Polarized Phase Parameters

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

\[
S_{vv} = |S_{vv}|e^{i\phi_{vv}}
\]

(54)

\[
S_{hh} = |S_{hh}|e^{i\phi_{hh}}
\]

(55)

\[
S_{hv} = |S_{hv}|e^{i\phi_{hv}}
\]

(56)

The co-polarized phase difference is defined as:

\[
\phi = \phi_{hh} - \phi_{vv}.
\]

(57)

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

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

(58)

where

\[
D = \alpha \cos(\phi - \zeta)
\]

(59)

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

(60)

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

(61)

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

Although a similar probability density function can be defined for the cross-polarized phase difference \( \phi_x = \phi_{hv} - \phi_{vv} \), \( p(\phi_x) \) 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 $\zeta$ and four values of the degree of correlation $\alpha$. 
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.
Figure 6: The probability density function $p(\phi)$ for a fixed value of $\zeta$ and four values of the degree of correlation $\alpha$. 

MMW POLARIMETRIC RADAR SYSTEM
<table>
<thead>
<tr>
<th>GHz</th>
<th>Power Only</th>
<th>Coherent 1-Antenna</th>
<th>Coherent on-Receive</th>
<th>Bistatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>94</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>140</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>215</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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.
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

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

\[
L = \begin{bmatrix}
I_v + I_h + I_p + I_m + I_i + I_r & 3(I_h - I_v) & 3(I_p - I_m) & 3(I_r - I_i) \\
Q_v + Q_h + Q_p + Q_m + Q_i + Q_r & 3(Q_h - Q_v) & 3(Q_p - Q_m) & 3(Q_r - Q_i) \\
U_v + U_h + U_p + U_m + U_i + U_r & 3(U_h - U_v) & 3(U_p - U_m) & 3(U_r - U_i) \\
V_v + V_h + V_p + V_m + V_i + V_r & 3(V_h - V_v) & 3(V_p - V_m) & 3(V_r - V_i)
\end{bmatrix}
\]

where \([I_i, Q_i, U_i, V_i]\) is the scattered Stokes vector associated with the \( i \)th 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, \( L_m \), 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 \( \langle |S_{vh}|^2 \rangle = \langle |S_{hv}|^2 \rangle \).
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 up 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.
<table>
<thead>
<tr>
<th>Polarization/Snow Condition</th>
<th>U-M</th>
<th>U-Mass</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV  Dry</td>
<td>+1.3 dB</td>
<td>-1.6 dB</td>
<td>2.9 dB</td>
</tr>
<tr>
<td>VH  Dry</td>
<td>-2.7 dB</td>
<td>-5.4 dB</td>
<td>2.7 dB</td>
</tr>
<tr>
<td>VV  Wet</td>
<td>-3.1 dB</td>
<td>-4.8 dB</td>
<td>1.7 dB</td>
</tr>
<tr>
<td>VH  Wet</td>
<td>-7.5 dB</td>
<td>-10.0 dB</td>
<td>2.5 dB</td>
</tr>
</tbody>
</table>

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 $\mathbf{L}_m^\circ$ (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 $\mathbf{L}_m^\circ$, 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°

Normalized Mueller Matrix:

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

\[
\begin{align*}
\sigma_{vv} &= -17.77 \text{ dB} \\
\sigma_{vh} &= -27.09 \text{ dB} \\
\chi_d &= -8.16 \text{ dB} \\
\alpha &= 0.61 \\
\zeta &= 8.26°
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.79 \\
m_{45} &= 0.68 \\
m_{\text{h}} &= 0.64 \\
m_{135} &= 0.70 \\
m_{\text{hc}} &= 0.47 \\
m_{r\text{hc}} &= 0.46
\end{align*}
\]

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


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 $\sigma_{uu}$
  Indicates that the calibration performed is relative to $\sigma_{uu}$. Thus only the ratios $\sigma_{hh}/\sigma_{uu}$ and $\sigma_{hv}/\sigma_{uu}$ are meaningful.

† value may be inaccurate
  Indicates that the value for $\zeta$ 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 $\zeta$ 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 $\pm 45^\circ$ and ellipticity of 0°.
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

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</table>
**Target:** Dry Aged Asphalt 1992  
**System/Frequency:** UHF - 35 GHz  
**Incidence Angle:** 20°  
**Independent Samples:** 120

**Normalized Mueller Matrix:**

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

\[
\sigma_{vv} = -6.44 \text{ dB} \quad \sigma_{hh} = -7.88 \text{ dB}
\]

\[
\sigma_{vh} = -17.43 \text{ dB} \quad \lambda = -10.33 \text{ dB}
\]

\[
\alpha = 0.77 \quad \zeta = 2.48^\circ
\]

**Degree of Polarization:**

\[
m_v = 0.86 \quad m_h = 0.81
\]

\[
m_{45} = 0.78 \quad m_{135} = 0.82
\]

\[
m_{\text{h-c}} = 0.61 \quad m_{\text{+h-c}} = 0.67
\]
Target: Dry Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

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

$$\sigma_{vv} = -10.61 \text{ dB} \quad \sigma_{hh} = -12.99 \text{ dB}$$

$$\sigma_{vh} = -20.74 \text{ dB} \quad \chi_d = -9.10 \text{ dB}$$

$$\alpha = 0.71 \quad \zeta = 4.77^\circ$$

Degree of Polarization:

$$m_v = 0.82 \quad m_h = 0.72$$

$$m_{45} = 0.76 \quad m_{135} = 0.76$$

$$m_{thc} = 0.55 \quad m_{rch} = 0.57$$
Target: Dry Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[
L_m^0 = 0.0012 \begin{bmatrix}
1.0000 & 0.0841 & -0.0437 & 0.0030 \\
0.0841 & 0.2068 & -0.0182 & 0.0006 \\
-0.0875 & -0.0364 & 0.3422 & -0.0171 \\
-0.0061 & -0.0012 & 0.0171 & 0.1739 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -18.22 \text{ dB} \quad \sigma_{hh} = -25.07 \text{ dB}
\]
\[
\sigma_{vh} = -28.97 \text{ dB} \quad \chi_d = -8.56 \text{ dB} \quad \alpha = 0.57 \quad \zeta = -3.80°
\]

Degree of Polarization:

\[
m_v = 0.85 \quad m_h = 0.44
\]
\[
m_{45} = 0.74 \quad m_{135} = 0.78 \quad m_{vh} = 0.64 \quad m_{hv} = 0.64
\]
Target: Dry Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.0592 \begin{bmatrix}
1.0000 & 0.0833 & -0.0228 & -0.0231 \\
0.0833 & 0.9163 & -0.0438 & 0.0639 \\
-0.0455 & -0.0875 & 0.7529 & -0.4103 \\
0.0463 & -0.1278 & 0.4103 & 0.5862 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -1.28 \text{ dB} \quad \sigma_{hh} = -1.66 \text{ dB}
\]

\[
\sigma_{vh} = -12.07 \text{ dB} \quad \zeta = -31.50°
\]

\[
\chi_d = -10.61 \text{ dB} \quad \alpha = 0.82
\]

Degree of Polarization:

\[
m_v = 0.85 \quad m_h = 0.85
\]

\[
m_{45} = 0.80 \quad m_{135} = 0.84
\]

\[
m_{h\perp c} = 0.67 \quad m_{r\perp c} = 0.73
\]
Target: Dry Aged Asphalt 1992  
System/Frequency: UM - 94 GHz.  
Incidence Angle: 45°  
Independent Samples: 102

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -6.94 \text{ dB} \quad \sigma_{hh} = -8.64 \text{ dB}
\]

\[
\sigma_{vh} = -14.28 \text{ dB} \quad \chi_d = -6.58 \text{ dB}
\]

\[
\alpha = 0.52 \quad \zeta = -24.94°
\]

Degree of Polarization:

\[
m_v = 0.69 \quad m_h = 0.59
\]

\[
m_{45} = 0.58 \quad m_{135} = 0.64
\]

\[
m_{\text{h}c} = 0.38 \quad m_{\text{h}c} = 0.26
\]
Target: Dry Aged Asphalt 1992
System/Frequency: UMT - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:
\[
L_m^\circ = 0.0042 \begin{bmatrix}
1.0000 & 0.0769 & -0.0654 & -0.0212 \\
0.0769 & 0.2574 & -0.0153 & 0.0404 \\
-0.1308 & -0.0305 & 0.1811 & -0.2192 \\
0.0425 & -0.0807 & 0.2192 & 0.0273
\end{bmatrix}
\]

\[
\sigma_{vv} = -12.77 \text{ dB} \quad \sigma_{hh} = -18.66 \text{ dB}
\]
\[
\sigma_{vh} = -23.91 \text{ dB} \quad \chi_d = -9.12 \text{ dB}
\]
\[
\alpha = 0.48 \quad \zeta = -64.58^\circ
\]

Degree of Polarization:
\[
m_v = 0.87 \quad m_h = 0.60
\]
\[
m_{45} = 0.63 \quad m_{135} = 0.70
\]
\[
m_{lhc} = 0.59 \quad m_{rhc} = 0.67
\]
Target: Wet Aged Asphalt 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

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

\[\sigma_{vv} = -9.26 \text{ dB} \quad \sigma_{hh} = -10.87 \text{ dB}\]
\[\sigma_{vh} = -25.32 \text{ dB} \quad \lambda_d = -15.33 \text{ dB}\]
\[\alpha = 0.93 \quad \zeta = 6.77°\]

Degree of Polarization:

\[m_v = 0.95 \quad m_h = 0.94\]
\[m_{45} = 0.93 \quad m_{135} = 0.93\]
\[m_{thc} = 0.89 \quad m_{rhc} = 0.88\]

Co-polar response

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

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -12.14 \, \text{dB} \quad \sigma_{hh} = -17.90 \, \text{dB}
\]
\[
\sigma_{vh} = -26.36 \, \text{dB} \quad \chi_d = -12.24 \, \text{dB}
\]
\[
\alpha = 0.86 \quad \zeta = 10.11°
\]

Degree of Polarization:

\[
m_v = 0.94 \quad m_h = 0.78
\]
\[
m_{45} = 0.90 \quad m_{135} = 0.91
\]
\[
m_{lh} = 0.82 \quad m_{rh} = 0.85
\]

Co-pol response

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

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -17.41 \text{ dB} \quad \sigma_{hh} = -27.49 \text{ dB}
\]
\[
\sigma_{vh} = -33.46 \text{ dB} \quad \lambda_d = -13.44 \text{ dB}
\]
\[
\alpha = 0.51 \quad \zeta = 24.30°
\]

Degree of Polarization:

\[
m_v = 0.96 \quad m_h = 0.61
\]
\[
m_{45} = 0.84 \quad m_{135} = 0.86
\]
\[
m_{\theta\phi} = 0.80 \quad m_{\phi\theta} = 0.86
\]
Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.0666 \begin{bmatrix}
1.0000 & 0.0304 & -0.0172 & -0.0507 \\
0.0304 & 0.7923 & 0.0111 & 0.0526 \\
-0.0344 & 0.0222 & 0.7296 & -0.4618 \\
0.1014 & -0.1051 & 0.4618 & 0.6688
\end{bmatrix}
\]

\[
\sigma_{vv} = -0.77 \text{ dB} \\
\sigma_{vh} = -15.94 \text{ dB} \\
\chi_d = -14.69 \text{ dB} \\
\alpha = 0.94 \\
\zeta = -33.45°
\]

Degree of Polarization:

\[
m_v = 0.95 \\
m_{45} = 0.94 \\
m_{thc} = 0.88 \\
m_h = 0.94 \\
m_{135} = 0.94 \\
m_{rhc} = 0.91
\]
Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^0 = 0.0113 \\
\begin{bmatrix}
1.0000 & 0.0590 & -0.0809 & -0.0106 \\
0.0590 & 0.3325 & -0.0334 & 0.0248 \\
-0.1619 & -0.0667 & 0.4360 & -0.2145 \\
0.0213 & -0.0495 & 0.2145 & 0.3181
\end{bmatrix}
\]

\[\sigma_{vv} = -8.48 \text{ dB} \quad \sigma_{hh} = -13.27 \text{ dB}\]
\[\sigma_{vh} = -20.78 \text{ dB} \quad \chi_d = -10.53 \text{ dB} \quad \alpha = 0.75 \quad \zeta = -29.63°\]

Degree of Polarization:

\[m_v = 0.90 \quad m_h = 0.73\]
\[m_{45} = 0.78 \quad m_{135} = 0.84\]
\[m_{thc} = 0.73 \quad m_{rhc} = 0.71\]
Target: Wet Aged Asphalt 1992
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -15.71 \text{ dB} \quad \sigma_{hh} = -24.79 \text{ dB}
\]

\[
\sigma_{vh} = -29.04 \text{ dB} \quad \chi_d = -10.82 \text{ dB}
\]

\[
\alpha = 0.63 \quad \zeta = -14.62°
\]

Degree of Polarization:

\[
m_v = 0.92 \quad m_h = 0.52
\]

\[
m_{45} = 0.81 \quad m_{135} = 0.87
\]

\[
m_{lhc} = 0.76 \quad m_{rhc} = 0.82
\]

Co-pol response

Cross-Pol response
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

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References:
None
Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_m^c = 0.0078 \begin{bmatrix}
1.0000 & 0.1115 & -0.0348 & 0.0674 \\
0.1115 & 0.7958 & 0.0116 & -0.0269 \\
-0.0696 & 0.0231 & 0.6020 & -0.0216 \\
-0.1347 & 0.0539 & 0.0216 & 0.3791 \\
\end{bmatrix}
\]

\[\sigma_{vv} = -10.09 \text{ dB} \quad \sigma_{hh} = -11.08 \text{ dB}\]
\[\sigma_{vh} = -19.61 \text{ dB} \quad \chi_d = -9.06 \text{ dB}\]
\[\alpha = 0.55 \quad \zeta = -2.52^\circ\]

Degree of Polarization:

\[m_v = 0.81 \quad m_h = 0.76\]
\[m_{45} = 0.59 \quad m_{135} = 0.63\]
\[m_{vhc} = 0.38 \quad m_{rhc} = 0.43\]

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:

\[
L_m^c = 0.0064 \begin{bmatrix}
1.0000 & 0.2144 & -0.0010 & -0.0099 \\
0.2144 & 0.8179 & 0.1238 & -0.0023 \\
-0.0020 & 0.2477 & 0.5959 & 0.1005 \\
0.0198 & 0.0047 & -0.1005 & 0.1670
\end{bmatrix}
\]

\[
\sigma_{vv} = -10.94 \text{ dB} \quad \sigma_{hh} = -11.81 \text{ dB} \\
\sigma_{vh} = -17.62 \text{ dB} \\
\lambda_d = -6.27 \text{ dB} \\
\alpha = 0.44 \quad \zeta = 14.76°
\]

Degree of Polarization:

\[
m_v = 0.65 \quad m_h = 0.63 \\
m_{45} = 0.58 \quad m_{135} = 0.53 \\
m_{thc} = 0.27 \quad m_{rhc} = 0.16
\]
Target: Dry Recent Asphalt 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -12.31 \text{ dB} \quad \sigma_{hh} = -13.53 \text{ dB}
\]

\[
\sigma_{vh} = -19.10 \text{ dB} \quad \chi_d = -6.22 \text{ dB}
\]

\[
\alpha = 0.60 \quad \zeta = 1.41°
\]

Degree of Polarization:

\[
m_v = 0.66 \quad m_h = 0.58
\]

\[
m_{45} = 0.66 \quad m_{135} = 0.72
\]

\[
m_{lhc} = 0.41 \quad m_{rhc} = 0.24
\]
**Target:** Dry Recent Asphalt 1994  
**System/Frequency:** UM - 35 GHz.  
**Incidence Angle:** 60°  
**Independent Samples:** 100

**Normalized Mueller Matrix:**

\[
\mathbf{L}_{nm}^\circ = 0.0027 \begin{bmatrix}
1.0000 & 0.1384 & -0.0715 & 0.0465 \\
0.1384 & 0.5097 & 0.0220 & -0.0304 \\
-0.0130 & 0.0440 & 0.5475 & 0.0386 \\
0.0931 & 0.0606 & -0.0386 & 0.2707 \\
\end{bmatrix}
\]

\[\sigma_{\nu\nu} = -14.76 \text{ dB} \quad \sigma_{hh} = -17.69 \text{ dB}\]

\[\sigma_{\nu h} = -23.35 \text{ dB} \quad \lambda_d = -7.37 \text{ dB}\]

\[\alpha = 0.58 \quad \zeta = 5.38^\circ\]

**Degree of Polarization:**

\[m_\nu = 0.77 \quad m_h = 0.58\]

\[m_{45} = 0.62 \quad m_{135} = 0.73\]

\[m_{\nu h} = 0.45 \quad m_{\nu r h} = 0.39\]
Target Name: Concrete 1992
System: UM

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

Data List:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th>condition</th>
<th>data no.</th>
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</table>

References:
None
Target: Concrete 1992
System/Frequency: UM · 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
\mathbf{L}^0_m = 0.0025 \begin{bmatrix}
1.0000 & 0.0232 & -0.0082 & -0.0073 \\
0.0232 & 0.8779 & -0.0104 & 0.0072 \\
-0.0164 & -0.0208 & 0.9192 & 0.0225 \\
0.0147 & -0.0144 & -0.0225 & 0.8729 \\
\end{bmatrix}
\]

\[
\sigma_{uu} = -15.09 \text{ dB} \quad \sigma_{hh} = -15.66 \text{ dB}
\]
\[
\sigma_{vh} = -31.45 \text{ dB} \quad \in\ = 1.44^\circ
\]
\[
\chi = -16.08 \text{ dB} \quad \zeta = 1.44^\circ
\]
\[
\alpha = 0.96
\]

Degree of Polarization:

\[
m_v = 0.95 \quad m_h = 0.95
\]
\[
m_{45} = 0.96 \quad m_{135} = 0.96
\]
\[
m_{lhc} = 0.91 \quad m_{rhc} = 0.91
\]
Target: Concrete 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^2 = 0.0026 \\
\begin{bmatrix}
1.0000 & 0.0282 & 0.0029 & 0.0151 \\
0.0282 & 0.5922 & -0.0063 & -0.0072 \\
0.0057 & -0.0126 & 0.6872 & 0.0898 \\
-0.0301 & 0.0145 & -0.0898 & 0.6307
\end{bmatrix}
\]

\[
\sigma_{vv} = -14.81 \text{ dB} \quad \sigma_{hh} = -17.09 \text{ dB} \\
\sigma_{vh} = -30.30 \text{ dB} \quad \chi_d = -14.50 \text{ dB} \\
\alpha = 0.86 \quad \xi = 7.76°
\]

Degree of Polarization:

\[
m_v = 0.95 \quad m_h = 0.91 \\
m_{45} = 0.88 \quad m_{135} = 0.87 \\
m_{lhc} = 0.80 \quad m_{rhc} = 0.82
\]
Target: Concrete 1992
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.0007 \begin{bmatrix}
1.0000 & 0.0257 & -0.0346 & 0.0226 \\
0.0257 & 0.2352 & -0.0140 & -0.0140 \\
-0.0691 & -0.0280 & 0.3871 & 0.1157 \\
-0.0451 & 0.0279 & -0.1157 & 0.3356 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -20.64 \text{ dB} \quad \sigma_{hh} = -26.92 \text{ dB}
\]
\[
\sigma_{vh} = -36.54 \text{ dB} \quad \lambda_d = -13.81 \text{ dB}
\]
\[
\alpha = 0.78 \quad \zeta = 17.75°
\]

Degree of Polarization:

\[
m_v = 0.95 \quad m_h = 0.82 \\
m_{45} = 0.86 \quad m_{135} = 0.87 \\
m_{135c} = 0.82 \quad m_{rhc} = 0.81
\]
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:
\[ \text{rms height} = 2.56 \text{ mm} \]
\[ \text{correlation length} = 37.5 \text{ mm} \]

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References:
None
Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

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

\[ \sigma_{vv} = -6.15 \text{ dB} \quad \sigma_{hh} = -5.13 \text{ dB} \]
\[ \sigma_{vh} = -13.92 \text{ dB} \]
\[ \chi_\delta = -8.31 \text{ dB} \]
\[ \alpha = 0.70 \quad \zeta = -16.52^\circ \]

Degree of Polarization:

\[ m_v = 0.73 \quad m_h = 0.80 \]
\[ m_{45} = 0.81 \quad m_{135} = 0.70 \]
\[ m_{lh} = 0.65 \quad m_{rh} = 0.39 \]
Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: $30^\circ$
Independent Samples: 100

Normalized Mueller Matrix:

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

$$\sigma_{vv} = -7.94 \text{ dB} \quad \sigma_{hh} = -7.87 \text{ dB}$$

$$\sigma_{vh} = -15.58 \text{ dB} \quad \sigma_{hv} = -15.58 \text{ dB}$$

$$\chi_d = -7.68 \text{ dB} \quad \chi_l = 0.71$$

$$\zeta = -10.02^\circ$$

Degree of Polarization:

$$m_v = 0.71 \quad m_h = 0.72$$

$$m_{45} = 0.77 \quad m_{135} = 0.73$$

$$m_{lhc} = 0.49 \quad m_{rhc} = 0.46$$
Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

Normalized Mueller Matrix:

\[ L_{nm}^\circ = 0.0080 \begin{bmatrix} 1.0000 & 0.1797 & -0.0275 & -0.0450 \\ 0.1797 & 1.4149 & 0.0532 & -0.0647 \\ -0.0549 & 0.1063 & 0.9516 & -0.0669 \\ 0.0899 & 0.1294 & 0.0669 & 0.5922 \end{bmatrix} \]

\[ \sigma_{vv} = -10.00 \text{ dB} \quad \sigma_{hh} = -8.49 \text{ dB} \]
\[ \sigma_{vh} = -17.46 \text{ dB} \]
\[ \lambda_d = -8.27 \text{ dB} \]
\[ \alpha = 0.65 \]
\[ \zeta = -4.96^\circ \]

Degree of Polarization:

\[ m_v = 0.70 \quad m_h = 0.78 \]
\[ m_{45} = 0.73 \quad m_{135} = 0.69 \]
\[ m_{thc} = 0.57 \quad m_{rhc} = 0.36 \]
Target: Gravel 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

Normalized Mueller Matrix:

\[ L_m^s = 0.0051 \begin{bmatrix} 1.0000 & 0.1986 & -0.0378 & -0.0315 \\ 0.1986 & 0.9966 & 0.0425 & -0.0215 \\ -0.0756 & 0.0849 & 0.7105 & -0.0596 \\ 0.0630 & 0.0429 & 0.0596 & 0.3133 \end{bmatrix} \]

\[ \sigma_{vv} = -11.89 \text{ dB} \quad \sigma_{hh} = -11.91 \text{ dB} \]
\[ \sigma_{vh} = -18.91 \text{ dB} \quad \chi_d = -7.01 \text{ dB} \]
\[ \alpha = 0.52 \quad \zeta = -6.64° \]

Degree of Polarization:

\[ m_v = 0.67 \quad m_h = 0.67 \]
\[ m_{45} = 0.61 \quad m_{135} = 0.60 \]
\[ m_{lhc} = 0.32 \quad m_{rhc} = 0.21 \]

Co-pol response
Cross-Pol response
**Target Name:** Smooth Soil 1992  
**System:** UM

![Smooth Soil 1992 Graph](image)

**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/cm³
- air-voids volume fraction = 0.36

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

Normalized Mueller Matrix:

\[
L_m^o = 0.0017 \begin{bmatrix}
1.0000 & 0.0296 & -0.0160 & 0.0204 \\
0.0296 & 0.9917 & -0.0344 & -0.0185 \\
-0.0320 & -0.0688 & 0.9632 & 0.0926 \\
-0.0409 & 0.0370 & -0.0926 & 0.9039
\end{bmatrix}
\]

\[
\sigma_{vv} = -16.72 \text{ dB} \quad \sigma_{hh} = -16.76 \text{ dB}
\]
\[
\sigma_{vh} = -32.00 \text{ dB} \quad \lambda_d = -15.26 \text{ dB}
\]
\[
\alpha = 0.94 \quad \zeta = 5.67°
\]

Degree of Polarization:

\[
m_v = 0.94 \quad m_h = 0.95
\]
\[
m_{45} = 0.94 \quad m_{135} = 0.95
\]
\[
m_{hc} = 0.88 \quad m_{hc} = 0.90
\]
Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
\begin{bmatrix}
1.0000 & 0.0554 & 0.0109 & 0.0061 \\
0.0554 & 0.9862 & 0.0126 & 0.0000 \\
0.0219 & 0.0251 & 0.9132 & 0.0645 \\
-0.0122 & -0.0000 & -0.0645 & 0.8024
\end{bmatrix}
\]

\[
\sigma_{vv} = -21.22 \text{ dB} \quad \sigma_{hh} = -21.28 \text{ dB}
\]

\[
\sigma_{vh} = -33.78 \text{ dB} \quad \chi_d = -12.53 \text{ dB}
\]

\[
\alpha = 0.87 \quad \zeta = 4.30^\circ
\]

Degree of Polarization:

\[
m_v = 0.90 \quad m_h = 0.89
\]

\[
m_{45} = 0.88 \quad m_{135} = 0.87
\]

\[
m_{hc} = 0.76 \quad m_{rhc} = 0.78
\]
**Target:** Smooth Soil 1992 (dry)
**System/Frequency:** UM - 35 GHz.
**Incidence Angle:** 70°
**Independent Samples:** 240

**Normalized Mueller Matrix:**

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

\[
\sigma_{vh} = -27.09 \text{ dB} \quad \sigma_{hh} = -28.89 \text{ dB}
\]

\[
\sigma_{vh} = -38.76 \text{ dB} \\
\lambda_d = -10.86 \text{ dB} \\
\alpha = 0.80 \\
\zeta = 3.61°
\]

**Degree of Polarization:**

\[
\begin{align*}
\mathit{m}_v &= 0.87 \\
\mathit{m}_{45} &= 0.82 \\
\mathit{m}_{135} &= 0.82 \\
\mathit{m}_{hc} &= 0.67 \\
\mathit{m}_{rhc} &= 0.68
\end{align*}
\]
Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
L_m^\circ = \begin{bmatrix}
1.0000 & 0.0087 & -0.0064 & -0.0047 \\
0.0087 & 0.8042 & -0.0207 & 0.0037 \\
-0.0128 & -0.0415 & 0.8934 & 0.0179 \\
0.0094 & -0.0073 & -0.0179 & 0.8760 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -10.95 \text{ dB} \quad \sigma_{hh} = -11.90 \text{ dB}
\]

\[
\sigma_{vh} = -31.55 \text{ dB} \\
\chi_d = -20.15 \text{ dB} \\
\alpha = 0.99 \\
\zeta = 1.16°
\]

Degree of Polarization:

\[
m_v = 0.98 \quad m_h = 0.98
\]
\[
m_{45} = 0.99 \quad m_{135} = 0.99
\]
\[
m_{\phi c} = 0.97 \quad m_{\phi c} = 0.97
\]
Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: \(45^\circ\)
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^0 = 0.0018 \begin{bmatrix}
1.0000 & 0.0154 & -0.0198 & -0.0064 \\
0.0154 & 0.3197 & -0.0101 & 0.0077 \\
-0.0396 & -0.0202 & 0.5074 & 0.0868 \\
0.0127 & -0.0153 & -0.0868 & 0.4765 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= -16.35 \text{ dB} \\
\sigma_{vh} &= -34.47 \text{ dB} \\
\lambda_d &= -16.32 \text{ dB} \\
\alpha &= 0.88 \\
\zeta &= 10.00^\circ
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.97 \\
m_h &= 0.91 \\
m_{45} &= 0.91 \\
m_{135} &= 0.92 \\
m_{hc} &= 0.86 \\
m_{rhc} &= 0.90
\end{align*}
\]
Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[
L_m^0 = 0.0005 \begin{bmatrix}
1.0000 & 0.0151 & -0.0243 & 0.0115 \\
0.0151 & 0.1917 & -0.0013 & -0.0097 \\
-0.0487 & -0.0026 & 0.2286 & 0.1019 \\
-0.0229 & 0.0195 & -0.1019 & 0.1984 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -22.02 \text{ dB} \quad \sigma_{hh} = -29.20 \text{ dB}
\]
\[
\sigma_{vh} = -40.23 \text{ dB} \quad \chi_d = -15.96 \text{ dB}
\]
\[
\alpha = 0.54 \quad \zeta = 25.52°
\]

Degree of Polarization:

\[
m_v = 0.97 \quad m_h = 0.86
\]
\[
m_{45} = 0.76 \quad m_{135} = 0.80
\]
\[
m_{lhc} = 0.77 \quad m_{rhc} = 0.74
\]
Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
L_m^2 = \begin{bmatrix}
1.0000 & 0.0990 & 0.0143 & 0.0397 \\
0.0990 & 1.0547 & -0.0009 & -0.0194 \\
0.0286 & -0.0018 & 0.8384 & 0.0436 \\
-0.0793 & 0.0388 & -0.0436 & 0.6404 \\
\end{bmatrix}
\]

\[\sigma_{vv} = -9.47 \text{ dB} \quad \sigma_{hh} = -9.24 \text{ dB}\]
\[\sigma_{vh} = -19.52 \text{ dB}\]
\[\chi_d = -10.16 \text{ dB}\]
\[\alpha = 0.72 \quad \zeta = 3.37^\circ\]

Degree of Polarization:

\[m_v = 0.82 \quad m_h = 0.83\]
\[m_{45} = 0.75 \quad m_{135} = 0.74\]
\[m_{hc} = 0.54 \quad m_{rhc} = 0.60\]
Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -10.75 \text{ dB} \quad \sigma_{hh} = -12.49 \text{ dB}
\]
\[
\sigma_{vh} = -19.67 \text{ dB} \quad \lambda_d = -8.13 \text{ dB}
\]
\[
\alpha = 0.70 \quad \zeta = 4.95°
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.68
\]
\[
m_{45} = 0.72 \quad m_{135} = 0.76
\]
\[
m_{vh} = 0.51 \quad m_{rh} = 0.48
\]
Target: Smooth Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[
L_m^0 = 0.0013 \begin{bmatrix}
1.0000 & 0.1170 & -0.0192 & 0.0150 \\
0.1170 & 0.5317 & -0.0087 & -0.0115 \\
-0.0384 & -0.0174 & 0.5603 & 0.0644 \\
-0.0300 & 0.0230 & -0.0644 & 0.3262 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -17.77 \text{ dB} \quad \sigma_{hh} = -20.51 \text{ dB}
\]
\[
\sigma_{vh} = -27.09 \text{ dB} \quad \zeta = 8.26°
\]
\[
\chi_d = -8.16 \text{ dB} \\
\alpha = 0.61
\]

Degree of Polarization:

\[
m_v = 0.79 \quad m_h = 0.64
\]
\[
m_{45} = 0.68 \quad m_{135} = 0.70
\]
\[
m_{hc} = 0.47 \quad m_{rhc} = 0.46
\]
**Target**: Smooth Soil 1992(wet)
**System/Frequency**: UM - 94 GHz.
**Incidence Angle**: $20^\circ$
**Independent Samples**: 120

**Normalized Mueller Matrix**:

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

$$\sigma_{vv} = -6.98 \text{ dB} \quad \sigma_{hh} = -7.94 \text{ dB}$$
$$\sigma_{vh} = -26.64 \text{ dB}$$
$$\chi_d = -19.21 \text{ dB}$$
$$\alpha = 0.95$$
$$\zeta = 38.67^\circ$$

**Degree of Polarization**:

$$m_v = 0.98 \quad m_h = 0.99$$
$$m_{45} = 0.93 \quad m_{135} = 0.96$$
$$m_{lhc} = 0.98 \quad m_{rhc} = 0.90$$
Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
\mathbf{L}^c_{nm} = \begin{bmatrix}
1.0000 & 0.0343 & -0.0492 & 0.0461 \\
0.0343 & 0.5232 & -0.0114 & -0.0504 \\
-0.0983 & -0.0227 & 0.5106 & 0.4184 \\
-0.0922 & 0.1007 & -0.4184 & 0.4420
\end{bmatrix}
\]

\[\sigma_{vv} = -14.10 \text{ dB} \quad \sigma_{hh} = -16.92 \text{ dB}\]
\[\sigma_{vh} = -28.75 \text{ dB} \quad \chi_d = -13.47 \text{ dB}\]
\[\alpha = 0.88 \quad \zeta = 41.30°\]

Degree of Polarization:

\[m_v = 0.94 \quad m_h = 0.90\]
\[m_{45} = 0.88 \quad m_{135} = 0.89\]
\[m_{1hc} = 0.84 \quad m_{rhc} = 0.83\]
Target: Smooth Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -22.41 \text{ dB} \quad \sigma_{hh} = -28.55 \text{ dB}
\]
\[
\sigma_{vh} = -37.37 \text{ dB} \quad \chi_d = -12.90 \text{ dB}
\]
\[
\alpha = 0.69 \quad \zeta = 70.55°
\]

Degree of Polarization:

\[
m_v = 0.95 \quad m_h = 0.80
\]
\[
m_{45} = 0.77 \quad m_{135} = 0.82
\]
\[
m_{lhc} = 0.80 \quad m_{rhc} = 0.77
\]
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/cm³
air-voids volume fraction = 0.45

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**Target:** Rough Soil 1992 (dry)

**System/Frequency:** UM - 35 GHz.

**Incidence Angle:** 20°

**Independent Samples:** 120

**Normalized Mueller Matrix:**

\[
\mathbf{L}^0_m = \begin{bmatrix}
1.0000 & 0.0356 & -0.0206 & -0.0082 \\
0.0356 & 0.9325 & -0.0440 & 0.0221 \\
-0.0413 & -0.0880 & 0.9305 & -0.0247 \\
0.0164 & -0.0443 & 0.0247 & 0.8593
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= -13.34 \text{ dB} & \sigma_{hh} &= -13.64 \text{ dB} \\
\sigma_{vh} &= -27.83 \text{ dB} \\
\chi_d &= -14.34 \text{ dB} \\
\alpha &= 0.93 \\
\zeta &= -1.58°
\end{align*}
\]

**Degree of Polarization:**

\[
\begin{align*}
m_v &= 0.93 & m_h &= 0.93 \\
m_{45} &= 0.93 & m_{135} &= 0.93 \\
m_{h_c} &= 0.84 & m_{rhc} &= 0.89
\end{align*}
\]
Target: Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^\circ = 0.0017 \begin{bmatrix}
1.0000 & 0.0676 & -0.0046 & 0.0117 \\
0.0676 & 0.9463 & -0.0009 & 0.0035 \\
-0.0093 & -0.0017 & 0.8492 & 0.1769 \\
-0.0235 & -0.0070 & -0.1769 & 0.7140 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -16.79 \text{ dB} \quad \sigma_{hh} = -17.03 \text{ dB}
\]
\[
\sigma_{vh} = -28.49 \text{ dB} \quad \lambda_d = -11.58 \text{ dB}
\]
\[
\alpha = 0.82 \quad \zeta = 12.75°
\]

Degree of Polarization:

\[
m_v = 0.87 \quad m_h = 0.87
\]
\[
m_{45} = 0.84 \quad m_{135} = 0.83
\]
\[
m_{h+} = 0.68 \quad m_{r+} = 0.73
\]
**Target:** Rough Soil 1992 (dry)  
**System/Frequency:** UM - 35 GHz.  
**Incidence Angle:** 70°  
**Independent Samples:** 240

**Normalized Mueller Matrix:**

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

\[
\sigma_{vv} = -18.84 \text{ dB} \quad \sigma_{hh} = -19.16 \text{ dB} \\
\sigma_{vh} = -27.69 \text{ dB} \\
\chi_a = -8.69 \text{ dB} \\
\alpha = 0.66 \quad \zeta = 10.51°
\]

**Degree of Polarization:**

\[
m_v = 0.77 \quad m_h = 0.75 \\
m_{45} = 0.70 \quad m_{135} = 0.70 \\
m_{hc} = 0.45 \quad m_{rhc} = 0.49
\]
Target: Rough Soil 1992 (wet)
System/Frequency: UHF - 35 GHz.
Incidence Angle: $20^\circ$
Independent Samples: 120

Normalized Mueller Matrix:

\[
\mathbf{I}_m^0 = 0.0179 \\
\begin{bmatrix}
1.0000 & 0.0248 & -0.0237 & -0.0276 \\
0.0248 & 0.8973 & -0.0612 & 0.0277 \\
-0.0474 & -0.1224 & 0.9135 & 0.0269 \\
0.0551 & -0.0555 & -0.0269 & 0.8638
\end{bmatrix}
\]

\[
\sigma_{vv} = -6.48 \text{ dB} \quad \sigma_{hh} = -6.95 \text{ dB}
\]

\[
\sigma_{vh} = -22.53 \text{ dB} \quad \chi_d = -15.82 \text{ dB}
\]

\[
\alpha = 0.94 \quad \zeta = 1.74^\circ
\]

Degree of Polarization:

\[
m_v = 0.95 \quad m_h = 0.96
\]

\[
m_{45} = 0.94 \quad m_{135} = 0.94
\]

\[
m_{h\alpha} = 0.89 \quad m_{r\alpha} = 0.90
\]
Target: Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^o = 0.0068 \begin{bmatrix}
1.0000 & 0.0567 & -0.0154 & 0.0009 \\
0.0567 & 0.7003 & -0.0190 & -0.0163 \\
-0.0309 & -0.0379 & 0.6580 & 0.2775 \\
-0.0018 & 0.0325 & -0.2775 & 0.5445
\end{bmatrix}
\]

\[
\sigma_{\nu\nu} = -10.68 \text{ dB} \quad \sigma_{hh} = -12.22 \text{ dB}
\]

\[
\sigma_{\nu h} = -23.14 \text{ dB}
\]

\[
\gamma = -11.76 \text{ dB}
\]

Degree of Polarization:

\[
m_v = 0.89 \quad m_h = 0.85
\]

\[
m_{45} = 0.79 \quad m_{135} = 0.81
\]

\[
m_{thc} = 0.71 \quad m_{rhc} = 0.68
\]
**Target:** Rough Soil 1992 (wet)  
**System/Frequency:** UM - 35 GHz.  
**Incidence Angle:** 70°  
**Independent Samples:** 240

**Normalized Mueller Matrix:**

\[
L^c_m = 0.0014 \begin{bmatrix}
1.0000 & 0.0735 & -0.0106 & 0.0296 \\
0.0735 & 0.7441 & -0.0055 & -0.0257 \\
-0.0213 & -0.0109 & 0.4413 & 0.2569 \\
-0.0592 & 0.0514 & -0.2569 & 0.2943 \\
\end{bmatrix}
\]

\[
\sigma_{uu} = -17.64 \text{ dB} \quad \sigma_{hh} = -18.92 \text{ dB}
\]

\[
\sigma_{vh} = -28.97 \text{ dB} \quad \chi_d = -10.74 \text{ dB}
\]

\[
\alpha = 0.52 \quad \zeta = 34.93°
\]

**Degree of Polarization:**

\[
m_v = 0.87 \quad m_h = 0.82
\]

\[
m_{45} = 0.55 \quad m_{135} = 0.56
\]

\[
m_{lhc} = 0.44 \quad m_{rhc} = 0.44
\]
Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: $20^\circ$
Independent Samples: 120

Normalized Mueller Matrix:

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

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

Degree of Polarization:

$$m_v = 0.90 \quad m_h = 0.90$$
$$m_{45} = 0.83 \quad m_{135} = 0.88$$
$$m_{lhc} = 0.72 \quad m_{rhc} = 0.83$$
Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.0095 \begin{bmatrix}
1.0000 & 0.0998 & -0.0409 & -0.0275 \\
0.0998 & 0.8591 & -0.0124 & 0.0552 \\
-0.0818 & -0.0248 & 0.7180 & -0.2759 \\
0.0549 & -0.1104 & 0.2759 & 0.5184
\end{bmatrix}
\]

\[
\sigma_{vv} = -9.21 \text{ dB} \quad \sigma_{hh} = -9.87 \text{ dB}
\]
\[
\sigma_{vh} = -19.22 \text{ dB} \quad \chi_d = -9.69 \text{ dB}
\]
\[
\alpha = 0.73 \quad \zeta = -24.05°
\]

Degree of Polarization:

\[
m_v = 0.82 \quad m_h = 0.80
\]
\[
m_{45} = 0.73 \quad m_{135} = 0.77
\]
\[
m_{hpc} = 0.56 \quad m_{rhc} = 0.61
\]
Target: Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[
L_m^0 = 0.0041 \begin{bmatrix}
1.0000 & 0.1477 & 0.0069 & 0.0043 \\
0.1477 & 0.9434 & 0.0083 & -0.0184 \\
0.0137 & 0.0166 & 0.6408 & -0.1741 \\
-0.0085 & 0.0368 & 0.1741 & 0.3453
\end{bmatrix}
\]

\[
\sigma_{\text{vv}} = -12.88 \text{ dB} \quad \sigma_{\text{hh}} = -13.13 \text{ dB}
\]

\[
\sigma_{\text{vh}} = -21.19 \text{ dB} \quad \chi_\text{d} = -8.18 \text{ dB}
\]

\[
\alpha = 0.54 \quad \zeta = -19.45^\circ
\]

Degree of Polarization:

\[
m_v = 0.74 \quad m_h = 0.73
\]

\[
m_{\text{45}} = 0.60 \quad m_{135} = 0.59
\]

\[
m_{\text{hce}} = 0.36 \quad m_{\text{rhc}} = 0.34
\]
Target: Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
L_m^\circ = 0.0292 \begin{bmatrix}
1.0000 & 0.0382 & -0.0361 & -0.0641 \\
0.0382 & 0.7430 & -0.0138 & 0.0693 \\
-0.0722 & -0.0276 & 0.7327 & -0.3399 \\
0.1283 & -0.1387 & 0.3399 & 0.6564 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -4.36 \text{ dB} \quad \sigma_{hh} = -5.65 \text{ dB}
\]
\[
\sigma_{vh} = -18.54 \text{ dB} \quad \chi_d = -13.59 \text{ dB}
\]
\[
\alpha = 0.90 \quad \zeta = -26.08\degree
\]

Degree of Polarization:

\[
m_v = 0.94 \quad m_h = 0.92
\]
\[
m_{45} = 0.89 \quad m_{135} = 0.91
\]
\[
m_{lhc} = 0.83 \quad m_{rhc} = 0.85
\]
Target: Rough Soil 1992 (wet)  
System/Frequency: UM - 94 GHz.  
Incidence Angle: 45°  
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^0 = 0.0086 \begin{bmatrix}
1.0000 & 0.0652 & -0.0411 & 0.0119 \\
0.0652 & 0.9320 & -0.0590 & 0.0183 \\
-0.0821 & -0.1181 & 0.8437 & -0.1304 \\
-0.0238 & -0.0367 & 0.1304 & 0.7133
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= -9.65 \text{ dB} \\
\sigma_{vh} &= -21.51 \text{ dB} \\
\lambda_d &= -11.71 \text{ dB} \\
\alpha &= 0.82 \\
\zeta &= -9.51°
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.88 \\
m_{45} &= 0.81 \\
m_{vh} &= 0.68 \\
m_{135} &= 0.85 \\
m_{rhc} &= 0.74
\end{align*}
\]
**Target:** Rough Soil 1992 (wet)
**System/Frequency:** UM - 94 GHz.
**Incidence Angle:** 70°
**Independent Samples:** 240

**Normalized Mueller Matrix:**

\[
L_m^0 = 0.0021 \begin{bmatrix}
1.0000 & 0.0802 & -0.0202 & 0.0123 \\
0.0802 & 1.0277 & -0.0196 & -0.0067 \\
-0.0404 & -0.0392 & 0.7828 & 0.2241 \\
-0.0246 & 0.0135 & -0.2241 & 0.6225 \\
\end{bmatrix}
\]

\[
\sigma_{uv} = -15.86 \text{ dB} \quad \sigma_{hh} = -15.74 \text{ dB}
\]
\[
\sigma_{vh} = -26.82 \text{ dB} \quad \lambda_d = -11.02 \text{ dB}
\]
\[
\alpha = 0.73 \quad \zeta = 17.69°
\]

**Degree of Polarization:**

\[
m_v = 0.85 \quad m_h = 0.86 \]
\[
m_{45} = 0.74 \quad m_{135} = 0.75 \]
\[
m_{vh} = 0.59 \quad m_{rh} = 0.63 \]
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/cm³
air-voids volume fraction = 0.50

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

Normalized Mueller Matrix:

\[
L^o_m = 0.0045 \begin{bmatrix}
1.0000 & 0.0928 & -0.0165 & 0.0226 \\
0.0928 & 1.0817 & -0.0197 & -0.0221 \\
-0.0330 & -0.0394 & 0.9355 & -0.0367 \\
-0.0453 & 0.0442 & 0.0367 & 0.7498 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -12.49 \text{ dB} \quad \sigma_{hh} = -12.15 \text{ dB}
\]
\[
\sigma_{vh} = -22.81 \text{ dB} \quad \chi_d = -10.50 \text{ dB}
\]
\[
\alpha = 0.81 \quad \zeta = -2.49°
\]

Degree of Polarization:

\[
m_v = 0.83 \quad m_h = 0.84
\]
\[
m_{45} = 0.82 \quad m_{135} = 0.83
\]
\[
m_{ihc} = 0.66 \quad m_{rhc} = 0.67
\]
Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^0 = 0.0022 \begin{bmatrix}
1.0000 & 0.1918 & 0.0124 & -0.0067 \\
0.1918 & 1.1549 & -0.0170 & -0.0057 \\
0.0249 & -0.0339 & 0.9208 & 0.0198 \\
0.0133 & 0.0114 & -0.0198 & 0.5372
\end{bmatrix}
\]

\[
\sigma_{vv} = -15.59 \text{ dB} \quad \sigma_{hh} = -14.97 \text{ dB}
\]
\[
\sigma_{vh} = -22.77 \text{ dB} \quad \chi_d = -7.50 \text{ dB}
\]
\[
\alpha = 0.68 \quad \zeta = 1.56°
\]

Degree of Polarization:

\[
m_v = 0.68 \quad m_h = 0.72
\]
\[
m_{45} = 0.73 \quad m_{135} = 0.73
\]
\[
m_{hc} = 0.44 \quad m_{rhc} = 0.41
\]
Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

\[ \mathbf{L}_n^0 = 0.0018 \begin{bmatrix} 1.0000 & 0.1789 & -0.0041 & 0.0161 \\ 0.1789 & 0.9536 & -0.0030 & -0.0053 \\ -0.0082 & -0.0061 & 0.7484 & 0.0446 \\ -0.0322 & 0.0107 & -0.0446 & 0.3906 \end{bmatrix} \]

\[ \sigma_{vv} = -16.40 \text{ dB} \quad \sigma_{hh} = -16.61 \text{ dB} \]
\[ \sigma_{vh} = -23.87 \text{ dB} \]
\[ \chi_d = -7.37 \text{ dB} \]
\[ \alpha = 0.58 \quad \zeta = 4.48° \]

Degree of Polarization:

\[ m_v = 0.70 \quad m_h = 0.68 \]
\[ m_{45} = 0.65 \quad m_{135} = 0.65 \]
\[ m_{hvc} = 0.33 \quad m_{h hc} = 0.35 \]
Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
\mathbf{L}_m^o = 0.0217 \begin{bmatrix}
1.0000 & 0.0715 & 0.0078 & -0.0182 \\
0.0715 & 1.0765 & -0.0217 & 0.0138 \\
0.0075 & -0.0434 & 0.9667 & -0.0419 \\
0.0365 & -0.0277 & 0.0419 & 0.8238
\end{bmatrix}
\]

\[
\sigma_{vv} = -5.63 \text{ dB} \quad \quad \sigma_{hh} = -5.31 \text{ dB}
\]

\[
\sigma_{vh} = -17.09 \text{ dB} \quad \quad \chi_d = -11.62 \text{ dB}
\]

\[
\alpha = 0.86 \quad \quad \zeta = -2.68^\circ
\]

Degree of Polarization:

\[
m_v = 0.87 \quad m_h = 0.88 \\
m_{45} = 0.87 \quad m_{135} = 0.88 \\
m_{45c} = 0.75 \quad m_{135c} = 0.74
\]
Target: Very Rough Soil 1992 (wet)
System/Frequency: U M - 35 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -6.88 \text{ dB} \quad \sigma_{hh} = -6.23 \text{ dB}
\]
\[
\sigma_{vh} = -17.04 \text{ dB} \\
\chi_\delta = -10.50 \text{ dB} \\
\alpha = 0.77 \quad \zeta = -3.01°
\]

Degree of Polarization:

\[
m_v = 0.83 \\
m_h = 0.86 \\
m_{\theta} = 0.77 \\
m_{\phi} = 0.81 \\
m_{\beta} = 0.65 \\
m_{\beta} = 0.63
\]
Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 240

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -15.76 \text{ dB} \\
\sigma_{vh} = -25.24 \text{ dB} \\
\chi_d = -10.15 \text{ dB} \\
\alpha = 0.78 \\
\zeta = 5.70°
\]

Degree of Polarization:

\[
m_t = 0.80 \\
m_{45} = 0.79 \\
m_{135} = 0.82 \\
m_{045} = 0.63 \\
m_{450} = 0.64
\]
Target: Very Rough Soil 1992 (dry)
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 120

Normalized Mueller Matrix:

\[
L_m^c = 0.0147 \begin{bmatrix}
1.0000 & 0.1391 & -0.0338 & -0.0418 \\
0.1391 & 0.9361 & -0.0540 & 0.0151 \\
-0.0676 & -0.1080 & 0.7864 & -0.0874 \\
0.0836 & -0.0303 & 0.0874 & 0.5083 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -7.34 \text{ dB} \quad \sigma_{hh} = -7.63 \text{ dB}
\]
\[
\sigma_{vh} = -15.91 \text{ dB} \quad \chi_d = -8.43 \text{ dB}
\]
\[
\alpha = 0.68 \quad \zeta = -7.69°
\]

Degree of Polarization:

\[
m_v = 0.76 \quad m_h = 0.75
\]
\[
m_{45} = 0.70 \quad m_{135} = 0.73
\]
\[
m_{h,c} = 0.52 \quad m_{r,c} = 0.43
\]

Co-pol response

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

Normalized Mueller Matrix:

\[
L_m^\circ = 0.0187 \begin{bmatrix}
1.0000 & 0.1622 & 0.0255 & -0.0081 \\
0.1622 & 0.8801 & -0.0109 & 0.0135 \\
0.0510 & -0.0218 & 0.6619 & -0.0704 \\
0.0162 & -0.0271 & 0.0704 & 0.3375 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -6.28 \text{ dB} \quad \sigma_{hh} = -6.83 \text{ dB}
\]

\[
\sigma_{vh} = -14.18 \text{ dB} \quad \chi_d = -7.63 \text{ dB}
\]

\[
\alpha = 0.54 \quad \zeta = -8.01^\circ
\]

Degree of Polarization:

\[
m_v = 0.72 \quad m_h = 0.69
\]

\[
m_{45} = 0.61 \quad m_{135} = 0.60
\]

\[
m_{thc} = 0.31 \quad m_{rhs} = 0.33
\]

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:

\[
L_m^\circ = 0.0086 \begin{bmatrix}
1.0000 & 0.1614 & -0.0013 & 0.0341 \\
0.1614 & 0.7581 & -0.0088 & -0.0041 \\
-0.0025 & -0.0176 & 0.6600 & -0.0680 \\
-0.0683 & 0.0082 & 0.0680 & 0.3372 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= -9.68 \text{ dB} \\
\sigma_{vh} &= -17.60 \text{ dB} \\
\chi_d &= -7.36 \text{ dB} \\
\alpha &= 0.58 \\
\zeta &= -7.77°
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.72 \\
m_{45} &= 0.64 \\
m_{h} &= 0.65 \\
m_{135} &= 0.65 \\
m_{hc} &= 0.33 \\
m_{rh} &= 0.38
\end{align*}
\]
Target:  Very Rough Soil 1992 (wet)
System/Frequency:  UM - 94 GHz.
Incidence Angle:  20°
Independent Samples:  120

Normalized Mueller Matrix:

\[
L_m^\circ = 0.0415 \begin{bmatrix}
1.0000 & 0.0669 & -0.0245 & -0.0287 \\
0.0669 & 0.7095 & -0.0283 & 0.0202 \\
-0.0490 & -0.0566 & 0.7701 & -0.1735 \\
0.0574 & -0.0403 & 0.1735 & 0.6362 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -2.83 \text{ dB} \quad \sigma_{hh} = -4.32 \text{ dB}
\]

\[
\sigma_{vh} = -14.57 \text{ dB} \quad \chi_d = -11.06 \text{ dB}
\]

\[
\alpha = 0.86 \quad \zeta = -13.86°
\]

Degree of Polarization:

\[
m_v = 0.88 \quad m_h = 0.83 \\
m_{45} = 0.87 \quad m_{135} = 0.87 \\
m_{lhc} = 0.76 \quad m_{rhc} = 0.72
\]
Target: Very Rough Soil 1992 (wet)
System/Frequency: UM - 94 GHz.
Incidence Angle: 45°
Independent Samples: 180

Normalized Mueller Matrix:

\[
L_m^o = 0.0210 \begin{bmatrix}
1.0000 & 0.0499 & -0.0200 & -0.0478 \\
0.0499 & 0.7753 & -0.0201 & 0.0589 \\
-0.0401 & -0.0403 & 0.5759 & -0.4126 \\
0.0957 & -0.1177 & 0.4126 & 0.4761 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -5.78 \text{ dB} \quad \sigma_{hh} = -6.89 \text{ dB}
\]
\[
\sigma_{vh} = -18.81 \text{ dB} \quad \lambda_d = -12.50 \text{ dB}
\]
\[
\alpha = 0.76 \quad \zeta = -38.11°
\]

Degree of Polarization:

\[
m_v = 0.91 \quad m_h = 0.89
\]
\[
m_{45} = 0.76 \quad m_{135} = 0.77
\]
\[
m_{ihc} = 0.68 \quad m_{rhc} = 0.70
\]
Target:  Very Rough Soil 1992 (wet)
System/Frequency:  UM - 94 GHz.
Incidence Angle:  70°
Independent Samples:  240

Normalized Mueller Matrix:

\[
L_m^o = \begin{bmatrix}
1.0000 & 0.0624 & -0.0231 & 0.0094 \\
0.0624 & 0.7971 & -0.0225 & 0.0012 \\
-0.0461 & -0.0449 & 0.7839 & -0.0461 \\
-0.0188 & -0.0024 & 0.0461 & 0.6592
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= -11.31 \text{ dB} \\
\sigma_{vh} &= -23.37 \text{ dB} \\
\chi_d &= -11.59 \text{ dB} \\
\alpha &= 0.81 \\
\zeta &= -3.65°
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.88 \\
m_{45} &= 0.82 \\
m_{thc} &= 0.68 \\
m_h &= 0.86 \\
m_{135} &= 0.83 \\
m_{rhc} &= 0.71
\end{align*}
\]
**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 ≤ 10 mm).

---

**Ground Truth:**

grain size = 0.2-1 mm

---

**Data List:**

<table>
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<th>freq.</th>
<th>condition</th>
<th>data no.</th>
<th>page no.</th>
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</thead>
<tbody>
<tr>
<td>26</td>
<td>225</td>
<td>dry, $m_g = 0.0$</td>
<td>sand.1.1</td>
<td>116</td>
</tr>
<tr>
<td>26</td>
<td>225</td>
<td>wet, $m_g = 0.10$</td>
<td>sand.1.2</td>
<td>117</td>
</tr>
</tbody>
</table>

---

**References:**

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

Modified Mueller Matrix:

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

\[
\sigma_{vv} = 0.30 \text{ dB} \quad \sigma_{hh} = 0.76 \text{ dB}
\]
\[
\sigma_{vh} = -3.90 \text{ dB} \quad \chi_d = -4.44 \text{ dB}
\]
\[
\alpha = 0.25 \quad \zeta = 2.93°
\]

Degree of Polarization:

\[
m_v = 0.45 \quad m_h = 0.49
\]
\[
m_{45} = 0.41 \quad m_{135} = 0.40
\]
\[
m_{lh} = 0.06 \quad m_{rh} = 0.07
\]
Target: Sand 1989
System/Frequency: UM - 225 GHz.
Incidence Angle: 26°
Independent Samples: 1000

Modified Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.0152 \begin{bmatrix}
1.0000 & 0.1216 & 0.0196 & -0.0049 \\
0.1216 & 0.7431 & 0.0000 & 0.0020 \\
0.0392 & 0.0000 & 0.6039 & 0.0824 \\
0.0098 & -0.0039 & -0.0824 & 0.3853
\end{bmatrix}
\]

\[
\sigma_{vv} = -7.19 \text{ dB} \quad \sigma_{hh} = -8.48 \text{ dB}
\]
\[
\sigma_{vh} = -16.34 \text{ dB} \quad \chi_d = -8.55 \text{ dB}
\]
\[
\alpha = 0.58 \quad \zeta = 9.46^\circ
\]

Degree of Polarization:

\[
m_v = 0.78 \quad \quad m_h = 0.72
\]
\[
m_{45} = 0.64 \quad \quad m_{135} = 0.62
\]
\[
m_{hc} = 0.42 \quad \quad m_{rhc} = 0.41
\]
Target Name: Short Grass 1989
System: UMass
Spotsize: 1 m (6 dB two-way)

Target Description: October 1989 measurement of field grass.

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

Data List:

<table>
<thead>
<tr>
<th>( \theta_i )</th>
<th>freq.</th>
<th>condition</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 ( \pm ) 10</td>
<td>225</td>
<td>short</td>
<td>grass.1.1</td>
<td>119</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[
L_m^\circ = 0.0178 \begin{bmatrix}
1.0000 & 0.1498 & 0.0148 & -0.0269 \\
0.1498 & 0.9135 & -0.0148 & 0.0280 \\
0.0295 & -0.0295 & 0.7711 & 0.0580 \\
0.0538 & -0.0559 & -0.0580 & 0.5738 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -6.50 \text{ dB} \quad \sigma_{hh} = -6.90 \text{ dB}
\]
\[
\sigma_{vh} = -14.75 \text{ dB} \\
\chi_d = -8.05 \text{ dB} \\
\alpha = 0.71 \\
\zeta = 4.93°
\]

Degree of Polarization:

\[
m_v = 0.74 \quad m_h = 0.72 \\
m_{45} = 0.70 \quad m_{135} = 0.70 \\
m_{ihc} = 0.52 \quad m_{rhc} = 0.53
\]
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$^{-2}$

<table>
<thead>
<tr>
<th>soil moisture profile, $m_g$</th>
<th>depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1&quot;</td>
</tr>
<tr>
<td>8:10 am</td>
<td>0.41</td>
</tr>
<tr>
<td>9:30 am</td>
<td>0.32</td>
</tr>
<tr>
<td>10:00 am</td>
<td>0.30</td>
</tr>
<tr>
<td>12:30 pm</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Data List:

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<tr>
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<th>freq.</th>
<th>time</th>
<th>condition</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>35</td>
<td>11:55</td>
<td>short</td>
<td>grass.2.1</td>
<td>121</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>10:46</td>
<td>short</td>
<td>grass.2.2</td>
<td>122</td>
</tr>
<tr>
<td>45</td>
<td>35</td>
<td>9:50</td>
<td>short</td>
<td>grass.2.3</td>
<td>123</td>
</tr>
<tr>
<td>60</td>
<td>35</td>
<td>12:49</td>
<td>short</td>
<td>grass.2.4</td>
<td>124</td>
</tr>
</tbody>
</table>

References:
None
Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

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

\[
\sigma_{vv} = -10.19 \text{ dB} \quad \sigma_{hh} = -9.74 \text{ dB}
\]
\[
\sigma_{vh} = -15.99 \text{ dB} \quad \lambda_d = -6.04 \text{ dB}
\]
\[
\alpha = 0.64 \quad \zeta^\dagger = -23.44°
\]

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

Degree of Polarization:

\[
m_v = 0.62 \quad m_h = 0.63
\]
\[
m_{45} = 0.68 \quad m_{135} = 0.72
\]
\[
m_{lh} = 0.43 \quad m_{rh} = 0.29
\]

Co-pol response

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

Normalized Mueller Matrix:

$$L_m \mathcal{L} = 0.0030$$

\[
\begin{bmatrix}
1.0000 & 0.4207 & -0.1914 & -0.0364 \\
0.4207 & 0.8952 & -0.1173 & 0.0354 \\
-0.3829 & -0.2347 & 0.6782 & 0.0073 \\
0.0728 & -0.0708 & -0.0073 & -0.1631 \\
\end{bmatrix}
\]

$$\sigma_{vv} = -14.28 \text{ dB} \quad \sigma_{hh} = -14.76 \text{ dB}$$
$$\sigma_{vh} = -18.04 \text{ dB}$$
$$\chi_d = -3.53 \text{ dB}$$
$$\alpha = 0.27 \quad \zeta^\dagger = 1.62°$$

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

Degree of Polarization:

$$m_v = 0.49 \quad m_h = 0.41$$
$$m_{45} = 0.35 \quad m_{135} = 0.59$$
$$m_{lhc} = 0.25 \quad m_{rhc} = 0.28$$

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

Normalized Mueller Matrix:

\[
L_m^\circ = 0.0030 \begin{bmatrix}
1.0000 & 0.2344 & -0.0510 & -0.0753 \\
0.2344 & 1.0740 & 0.0700 & 0.0468 \\
-0.1020 & 0.1400 & 0.7741 & 0.2694 \\
0.1506 & -0.0935 & -0.2694 & 0.3052 \\
\end{bmatrix}
\]

\[\sigma_{vv} = -14.29 \text{ dB} \quad \sigma_{hh} = -13.98 \text{ dB}\]
\[\sigma_{vh} = -20.59 \text{ dB} \quad \chi_d = -6.46 \text{ dB}\]
\[\alpha = 0.58 \quad \zeta^\dagger = 26.53°\]

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

Degree of Polarization:

\[m_v = 0.64 \quad m_h = 0.65\]
\[m_{45} = 0.65 \quad m_{135} = 0.65\]
\[m_{thc} = 0.38 \quad m_{rhc} = 0.29\]
Target: Short Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_m^0 = 0.0024 
\begin{bmatrix}
1.0000 & 0.2235 & -0.0007 & 0.1134 \\
0.2235 & 0.7826 & 0.0539 & -0.1117 \\
-0.0015 & 0.1077 & 0.6364 & 0.0545 \\
-0.2268 & 0.2234 & -0.0545 & 0.1894 \\
\end{bmatrix}
\]

\[\sigma_{vv} = -15.23 \text{ dB} \quad \sigma_{hh} = -16.30 \text{ dB} \]

\[\sigma_{vh} = -21.74 \text{ dB} \quad \chi_d = -6.01 \text{ dB} \]

\[\alpha = 0.47 \quad \zeta^\dagger = 7.52° \]

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

Degree of Polarization:

\[m_v = 0.66 \quad m_H = 0.61 \]

\[m_{45} = 0.59 \quad m_{135} = 0.57 \]

\[m_{\text{hsc}} = 0.36 \quad m_{\text{rhc}} = 0.20 \]
**Target Name:** Tall Grass 1994  
**System:** UM

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

**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$^2$

<table>
<thead>
<tr>
<th>soil moisture profile</th>
<th>depth</th>
<th>$m_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1&quot;</td>
<td>1-2&quot;</td>
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<td></td>
<td>0.11</td>
<td>0.11</td>
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**Data List:**

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<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th>condition</th>
<th>data no.</th>
<th>page no.</th>
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<tbody>
<tr>
<td>20</td>
<td>35</td>
<td>tall</td>
<td>grass.3.1</td>
<td>126</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>tall</td>
<td>grass.3.2</td>
<td>127</td>
</tr>
<tr>
<td>45</td>
<td>35</td>
<td>tall</td>
<td>grass.3.3</td>
<td>128</td>
</tr>
<tr>
<td>60</td>
<td>35</td>
<td>tall</td>
<td>grass.3.4</td>
<td>129</td>
</tr>
</tbody>
</table>

**References:**  
None
Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_m^c = 0.0078
\begin{bmatrix}
1.0000 & 0.0683 & -0.0113 & 0.0433 \\
0.0683 & 1.2485 & 0.0645 & -0.0372 \\
-0.0226 & 0.1290 & 0.9519 & -0.0464 \\
-0.0865 & 0.0743 & 0.0464 & 0.8152 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -10.08 \text{ dB} \quad \sigma_{hh} = -9.11 \text{ dB}
\]
\[
\sigma_{vh} = -21.73 \text{ dB} \quad \chi_d = -12.16 \text{ dB}
\]
\[
\alpha = 0.79 \quad \zeta = -3.00°
\]

Degree of Polarization:

\[
m_v = 0.88 \quad m_h = 0.90
\]
\[
m_{45} = 0.82 \quad m_{135} = 0.79
\]
\[
m_{thc} = 0.68 \quad m_{rhc} = 0.72
\]
Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_m^c = 0.0047 \begin{bmatrix}
1.0000 & 0.1764 & -0.0686 & 0.0521 \\
0.1764 & 1.5993 & 0.0421 & -0.0761 \\
-0.1371 & 0.0843 & 1.1419 & -0.1264 \\
-0.1042 & 0.1522 & 0.1264 & 0.7891
\end{bmatrix}
\]

\[\sigma_{vv} = -12.29 \text{ dB} \quad \sigma_{hh} = -10.25 \text{ dB} \]
\[\sigma_{vh} = -19.82 \text{ dB} \quad \lambda_d = -8.67 \text{ dB} \]
\[\alpha = 0.77 \quad \zeta = -7.46° \]

Degree of Polarization:

\[
m_v = 0.72 \quad m_h = 0.81 \\
m_{45} = 0.83 \quad m_{135} = 0.79 \\
m_{thc} = 0.58 \quad m_{rhc} = 0.59
\]
Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 45°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_m^2 = 0.0025 
\begin{bmatrix}
1.0000 & 0.1428 & -0.0001 & 0.0399 \\
0.1428 & 1.3775 & 0.0751 & -0.0938 \\
-0.0001 & 0.1502 & 0.9969 & -0.0761 \\
-0.0799 & 0.1876 & 0.0761 & 0.7113 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -15.02 \text{ dB} \\
\sigma_{vh} = -23.47 \text{ dB} \\
\chi_d = -9.20 \text{ dB} \\
\alpha = 0.73 \\
\zeta = -5.09°
\]

Degree of Polarization:

\[
m_v = 0.75 \\ m_h = 0.83 \\ m_{45} = 0.79 \\ m_{135} = 0.74 \\ m_{lhc} = 0.60 \\ m_{rhc} = 0.54
\]
Target: Tall Grass 1994
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 100

Normalized Mueller Matrix:

\[
L_{m} = 0.0011 \begin{bmatrix}
1.0000 & 0.2164 & -0.0432 & 0.0234 \\
0.2164 & 1.5238 & 0.0327 & -0.0623 \\
-0.0864 & 0.0654 & 1.0990 & -0.0308 \\
-0.0467 & 0.1246 & 0.0308 & 0.6662 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -18.54 \text{ dB} \quad \sigma_{hh} = -16.71 \text{ dB}
\]
\[
\sigma_{vh} = -25.19 \text{ dB}
\]
\[
\chi_d = -7.66 \text{ dB}
\]
\[
\alpha = 0.72 \quad \zeta = -2.00°
\]

Degree of Polarization:

\[
m_v = 0.65 \quad m_h = 0.76
\]
\[
m_{45} = 0.78 \quad m_{135} = 0.76
\]
\[
m_{hkc} = 0.51 \quad m_{rhc} = 0.47
\]
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.

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<tr>
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<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>tree.1.1</td>
<td>131</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>66</td>
<td>tree.1.2</td>
<td>132</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[ L_m^o = 0.0219 \begin{bmatrix}
1.0000 & 0.0939 & -0.0020 & 0.0097 \\
0.0939 & 1.0502 & 0.0204 & -0.0171 \\
-0.0041 & 0.0407 & 0.9568 & 0.0420 \\
-0.0194 & 0.0341 & -0.0420 & 0.7988 \\
\end{bmatrix} \]

\[ \sigma_{vv} = -5.60 \text{ dB} \quad \sigma_{hh} = -5.39 \text{ dB} \]
\[ \sigma_{vh} = -15.88 \text{ dB} \]
\[ \chi_d = -10.38 \text{ dB} \]
\[ \alpha = 0.86 \quad \zeta = 2.74^\circ \]

Degree of Polarization:

\[ m_v = 0.83 \quad m_h = 0.84 \]
\[ m_{45} = 0.86 \quad m_{135} = 0.85 \]
\[ m_{ihc} = 0.73 \quad m_{irhc} = 0.70 \]
Target: American Elm 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

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

\[
\sigma_{vv} = -8.11 \text{ dB} \quad \sigma_{hh} = -7.92 \text{ dB}
\]
\[
\sigma_{vh} = -18.25 \text{ dB} \quad \lambda_d = -10.24 \text{ dB}
\]
\[
\alpha = 0.80 \quad \zeta = 4.92^\circ
\]

Degree of Polarization:

\[
m_v = 0.82 \quad m_h = 0.83
\]
\[
m_{45} = 0.81 \quad m_{135} = 0.81
\]
\[
m_{lhc} = 0.64 \quad m_{rhc} = 0.65
\]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
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<tbody>
<tr>
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<td>225</td>
<td>1</td>
<td>tree.2.1</td>
<td>134</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>31</td>
<td>tree.2.2</td>
<td>135</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[
L_m^o = 0.0098 \begin{bmatrix}
1.0000 & 0.0613 & 0.0007 & 0.0132 \\
0.0613 & 0.9715 & 0.0210 & -0.0039 \\
0.0014 & 0.0420 & 0.9216 & 0.0067 \\
-0.0263 & 0.0078 & -0.0067 & 0.7747
\end{bmatrix}
\]

\[
\sigma_{vv} = -9.10 \text{ dB} \quad \sigma_{hh} = -9.22 \text{ dB}
\]

\[
\sigma_{vh} = -21.22 \text{ dB} \quad \lambda_d = -12.06 \text{ dB}
\]

\[
\alpha = 0.86 \quad \zeta = 0.45^\circ
\]

Degree of Polarization:

\[
m_v = 0.88 \quad m_h = 0.88
\]

\[
m_{45} = 0.88 \quad m_{135} = 0.88
\]

\[
m_{hc} = 0.73 \quad m_{rhc} = 0.76
\]
Target: Arborvitae 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

\[
\mathbf{L}^0_m = 0.0068 \begin{bmatrix}
0.0713 & 0.0713 & -0.0025 & -0.0030 \\
1.0078 & 0.0087 & 0.0131 \\
-0.0051 & 0.0174 & 0.9239 & 0.0519 \\
0.0059 & 0.0263 & -0.0519 & 0.7995 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -10.68 \text{ dB} \quad \sigma_{hh} = -10.65 \text{ dB}
\]
\[
\sigma_{vh} = -22.15 \text{ dB} \\
\chi_d = -11.49 \text{ dB} \\
\alpha = 0.86 \quad \zeta = 3.45^\circ
\]

Degree of Polarization:

\[
m_v = 0.87 \quad m_h = 0.87 \\
m_{45} = 0.86 \quad m_{135} = 0.86 \\
m_{lh} = 0.77 \quad m_{rh} = 0.72
\]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>tree.3.1</td>
<td>137</td>
</tr>
</tbody>
</table>

References:

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

Modified Mueller Matrix:

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

\[
\sigma_{vv} = -4.79 \text{ dB} \quad \sigma_{hh} = -4.52 \text{ dB}
\]
\[
\sigma_{vh} = -13.83 \text{ dB}
\]
\[
\chi_d = -9.17 \text{ dB}
\]
\[
\alpha = 0.85 \quad \zeta = 6.11^\circ
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.79
\]
\[
m_{45} = 0.86 \quad m_{135} = 0.84
\]
\[
m_{hc} = 0.67 \quad m_{rhc} = 0.66
\]

Co-pol response

Cross-Pol response
**Target Name:** Pinoak 1994  
**System:** UMass  
**Spotsizel:** 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:**

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>35</td>
<td>8</td>
<td>tree.4.1</td>
<td>139</td>
</tr>
<tr>
<td>horizontal</td>
<td>95</td>
<td>7</td>
<td>tree.4.2</td>
<td>140</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>8</td>
<td>tree.4.3</td>
<td>141</td>
</tr>
</tbody>
</table>

**References:**  
None
Target: Pinoak 1994
System/Frequency: UMass - 35 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

\[
L^\circ_m = 0.0040 \begin{bmatrix}
1.0000 & 0.0380 & -0.0120 & 0.0268 \\
0.0380 & 0.7350 & 0.0157 & -0.0345 \\
-0.0240 & 0.0313 & 0.6047 & -0.0011 \\
-0.0536 & 0.0691 & 0.0011 & 0.5287 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -13.02 \text{ dB} \quad \sigma_{hh} = -14.36 \text{ dB}
\]

\[
\sigma_{vh} = -27.22 \text{ dB} \quad \chi_d = -13.58 \text{ dB}
\]

\[
\alpha^\dagger = 0.66 \quad \zeta = -0.11^\circ
\]

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

Degree of Polarization:

\[
m_v = 0.93 \quad m_h = 0.91
\]

\[
m_{45} = 0.68 \quad m_{135} = 0.69
\]

\[
m_{lh} = 0.64 \quad m_{rh} = 0.58
\]
Target: Pinoak 1994
System/Frequency: UMass - 95 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

\[
L_m^0 = \begin{bmatrix}
1.0000 & 0.0845 & 0.0051 & 0.0194 \\
0.0845 & 0.8548 & 0.0026 & -0.0244 \\
0.0102 & 0.0052 & 0.8228 & -0.0922 \\
-0.0389 & 0.0488 & 0.0922 & 0.6730 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -16.62 \text{ dB} \quad \sigma_{hh} = -17.30 \text{ dB}
\]

\[
\sigma_{vh} = -27.35 \text{ dB} \\
\chi_d = -10.40 \text{ dB} \\
\alpha = 0.82 \quad \zeta = -7.03^\circ
\]

Degree of Polarization:

\[
m_v = 0.84 \quad m_h = 0.82 \\
m_{45} = 0.82 \quad m_{135} = 0.82 \\
m_{hc} = 0.69 \quad m_{rhc} = 0.66
\]
Target: Pinoak 1994
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

\[
\mathbf{L}_m^0 = \begin{bmatrix}
1.0000 & 0.0694 & -0.0001 & -0.0109 \\
0.0694 & 1.0266 & 0.0239 & 0.0075 \\
-0.0002 & 0.0478 & 0.9034 & 0.1127 \\
0.0218 & -0.0150 & -0.1127 & 0.7647 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -17.96 \text{ dB} \quad \sigma_{hh} = -17.85 \text{ dB}
\]

\[
\sigma_{vh} = -29.55 \text{ dB} \quad \chi_d = -11.65 \text{ dB}
\]

\[
\alpha = 0.83 \quad \zeta = 7.69^\circ
\]

Degree of Polarization:

\[
m_v = 0.87 \quad m_h = 0.87
\]

\[
m_{45} = 0.84 \quad m_{135} = 0.84
\]

\[
m_{hc} = 0.72 \quad m_{rh} = 0.71
\]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
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<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>tree.5.1</td>
<td>143</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[
L_m^c = 0.0469 
\begin{bmatrix}
1.0000 & 0.0793 & -0.0385 & 0.0123 \\
0.0793 & 0.9767 & -0.0217 & -0.0296 \\
-0.0771 & -0.0433 & 0.9508 & 0.0732 \\
-0.0246 & 0.0592 & -0.0732 & 0.8058 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -2.30 \text{ dB} \quad \sigma_{hh} = -2.40 \text{ dB}
\]
\[
\sigma_{v\ell} = -13.30 \text{ dB} \quad \chi_d = -10.96 \text{ dB}
\]
\[
\alpha = 0.89 \quad \zeta = 4.76^\circ
\]

Degree of Polarization:

\[
m_v = 0.85 \quad m_h = 0.85
\]
\[
m_{45} = 0.89 \quad m_{135} = 0.90
\]
\[
m_{0h} = 0.79 \quad m_{+h} = 0.74
\]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>tree.6.1</td>
<td>145</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>65</td>
<td>tree.6.2</td>
<td>146</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[ \mathbf{L}_m^0 = \begin{bmatrix} 1.0000 & 0.1198 & 0.0079 & -0.0064 \\ 0.1198 & 1.0473 & 0.0044 & 0.0118 \\ 0.0157 & 0.0089 & 0.8958 & 0.0717 \\ 0.0127 & -0.0236 & -0.0717 & 0.6583 \end{bmatrix} \]

\[ \sigma_{vv} = -3.00 \text{ dB} \quad \sigma_{hh} = -2.80 \text{ dB} \]

\[ \sigma_{vh} = -12.21 \text{ dB} \]

\[ \chi_d = -9.32 \text{ dB} \]

\[ \alpha = 0.76 \quad \zeta = 5.27^\circ \]

Degree of Polarization:

\[ m_v = 0.79 \quad m_h = 0.79 \]

\[ m_{45} = 0.79 \quad m_{135} = 0.78 \]

\[ m_{thc} = 0.57 \quad m_{rhc} = 0.59 \]
Target: Silver Maple 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

\[
L_m^o = 0.0120 \begin{bmatrix}
1.0000 & 0.1045 & 0.0076 & 0.0052 \\
0.1045 & 1.1115 & 0.0162 & 0.0041 \\
0.0152 & 0.0323 & 0.9508 & 0.0788 \\
-0.0103 & -0.0081 & -0.0788 & 0.7723
\end{bmatrix}
\]

\[
\sigma_{vv} = -8.22 \text{ dB} \quad \sigma_{hh} = -7.76 \text{ dB}
\]

\[
\sigma_{vh} = -18.02 \text{ dB} \quad \zeta = 5.23^\circ
\]

\[
\chi_d = -10.04 \text{ dB} \quad \alpha = 0.82
\]

Degree of Polarization:

\[
m_v = 0.81 \quad m_h = 0.83
\]

\[
m_{45} = 0.83 \quad m_{135} = 0.82
\]

\[
m_{h} = 0.66 \quad m_{r} = 0.68
\]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>71</td>
<td>tree.7.1</td>
<td>148</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

\[
L_m = \begin{bmatrix}
1.0000 & 0.0996 & -0.0007 & 0.0090 \\
0.0996 & 1.1023 & -0.0033 & -0.0076 \\
-0.0015 & -0.0066 & 0.9201 & 0.0558 \\
-0.0179 & 0.0151 & -0.0558 & 0.7792
\end{bmatrix}
\]

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

Degree of Polarization:

\[
m_v = 0.82 \quad m_h = 0.83
\]
\[
m_{45} = 0.80 \quad m_{135} = 0.80
\]
\[
m_{thc} = 0.68 \quad m_{rhc} = 0.68
\]
Target Name: Willow 1994
System: UMass
Spot size: 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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>year</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>1990</td>
<td>tree.8.1</td>
<td>150</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>99</td>
<td>1990</td>
<td>tree.8.2</td>
<td>151</td>
</tr>
<tr>
<td>horizontal</td>
<td>35</td>
<td>12</td>
<td>1994</td>
<td>tree.8.3</td>
<td>152</td>
</tr>
<tr>
<td>horizontal</td>
<td>95</td>
<td>12</td>
<td>1994</td>
<td>tree.8.4</td>
<td>153</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>12</td>
<td>1994</td>
<td>tree.8.5</td>
<td>154</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

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

\[
\sigma_{vv} = -4.29 \text{ dB} \quad \sigma_{hh} = -4.12 \text{ dB}
\]
\[
\sigma_{vh} = -17.00 \text{ dB}
\]
\[
\chi_d = -12.79 \text{ dB}
\]
\[
\alpha = 0.89 \quad \zeta = 3.95^\circ
\]

Degree of Polarization:

\[
m_v = 0.90 \quad m_h = 0.90
\]
\[
m_{45} = 0.90 \quad m_{135} = 0.90
\]
\[
m_{lhc} = 0.78 \quad m_{rhc} = 0.81
\]
Target: Weeping Willow
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

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

\[
\sigma_{vv} = -4.51 \text{ dB} \quad \sigma_{hh} = -4.08 \text{ dB}
\]

\[
\sigma_{vh} = -15.01 \text{ dB} \quad \chi_d = -10.72 \text{ dB}
\]

\[
\alpha = 0.85 \quad \zeta = 2.99^\circ
\]

Degree of Polarization:

\[
m_v = 0.84 \quad m_h = 0.85
\]

\[
m_{45} = 0.85 \quad m_{135} = 0.85
\]

\[
m_{hc} = 0.71 \quad m_{rhc} = 0.73
\]
Target: Weeping Willow
System/Frequency: UMass - 35 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

\[
L_m^\circ = 0.0015 \begin{bmatrix}
1.0000 & 0.1335 & -0.0290 & 0.0372 \\
0.1335 & 1.1195 & 0.0210 & -0.0309 \\
-0.0581 & 0.0420 & 0.6895 & -0.0415 \\
-0.0745 & 0.0618 & 0.0415 & 0.4225 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -17.26 \text{ dB} \quad \sigma_{hh} = -16.77 \text{ dB}
\]
\[
\sigma_{vh} = -26.01 \text{ dB} \\
\chi_{45} = -9.00 \text{ dB} \\
\alpha^2 = 0.53 \\
\zeta = -4.27^\circ
\]

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

Degree of Polarization:

\[
m_v = 0.77 \\
m_{45} = 0.58 \\
m_{thc} = 0.35 \\
m_h = 0.79 \\
m_{135} = 0.58 \\
m_{rhc} = 0.38
\]
Target: Weeping Willow
System/Frequency: UMass - 95 GHz.
Incidence Angle: horizontal
Independant Samples: > 150

Modified Mueller Matrix:

\[
L^*_{m} = 1.0000 \\
0.1214 0.7628 -0.0120 -0.0041 \\
-0.0892 -0.0240 0.7464 -0.0578 \\
-0.1130 0.0083 0.0578 0.5916
\]

\[
\sigma_{vv}^{*} = 0.00 \text{ dB} \quad \sigma_{hh}^{*} = -1.18 \text{ dB}
\]
\[
\sigma_{vh}^{*} = -9.16 \text{ dB} \quad \lambda_{d} = -8.61 \text{ dB}
\]
\[
\alpha = 0.77 \quad \zeta = -4.94^\circ
\]

* magnitude relative to $\sigma_{vv}$ (see pg. 39 for details)

Degree of Polarization:

\[
m_{v} = 0.79 \quad m_{h} = 0.73
\]
\[
m_{45} = 0.73 \quad m_{135} = 0.78
\]
\[
m_{hc} = 0.55 \quad m_{rhc} = 0.68
\]
Target: Weeping Willow
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

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

\[\sigma_{vv} = -16.48 \text{ dB} \]
\[\sigma_{vh} = -28.25 \text{ dB} \]
\[\chi_d = -11.42 \text{ dB} \]
\[\alpha = 0.83 \]
\[\zeta = 11.91^\circ \]

Degree of Polarization:

\[m_v = 0.88 \]
\[m_h = 0.86 \]
\[m_{45} = 0.83 \]
\[m_{135} = 0.85 \]
\[m_{h4c} = 0.78 \]
\[m_{rhc} = 0.64 \]
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:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th># of expmts.</th>
<th>data no.</th>
<th>page no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal</td>
<td>225</td>
<td>1</td>
<td>tree.9.1</td>
<td>156</td>
</tr>
<tr>
<td>horizontal</td>
<td>225</td>
<td>51</td>
<td>tree.9.2</td>
<td>157</td>
</tr>
</tbody>
</table>

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

Modified Mueller Matrix:

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

\[
\sigma_{vv} = -6.29 \text{ dB} \quad \sigma_{hh} = -5.85 \text{ dB}
\]
\[
\sigma_{vh} = -15.32 \text{ dB} \quad \chi_d = -9.25 \text{ dB}
\]
\[
\alpha = 0.75 \quad \zeta = -4.38^\circ
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.80
\]
\[
m_{45} = 0.77 \quad m_{135} = 0.77
\]
\[
m_{lh} = 0.57 \quad m_{rh} = 0.57
\]
Target: White Pine 1990
System/Frequency: UMass - 225 GHz.
Incidence Angle: horizontal
Independent Samples: > 150

Modified Mueller Matrix:

\[
L_m = 0.0107 
\begin{bmatrix}
1.0000 & 0.1831 & 0.0143 & 0.0025 \\
0.1831 & 1.1709 & 0.0296 & -0.0102 \\
0.0285 & 0.0592 & 0.8953 & 0.0288 \\
-0.0051 & 0.0204 & -0.0288 & 0.6286 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = -8.71 \text{ dB} \quad \sigma_{hh} = -8.03 \text{ dB}
\]
\[
\sigma_{vh} = -16.09 \text{ dB} \quad \chi_4 = -7.73 \text{ dB}
\]
\[
\alpha = 0.70 \quad \zeta = 2.16^\circ
\]

Degree of Polarization:

\[
m_v = 0.69 \quad m_h = 0.73
\]
\[
m_{45} = 0.72 \quad m_{135} = 0.70
\]
\[
m_{lhc} = 0.51 \quad m_{rhc} = 0.49
\]
**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).

<table>
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<tr>
<th>date</th>
<th>leaf water content</th>
</tr>
</thead>
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<tr>
<td>5/27</td>
<td>62%</td>
</tr>
<tr>
<td>6/1</td>
<td>61%</td>
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<td>6/6</td>
<td>60%</td>
</tr>
<tr>
<td>6/17</td>
<td>56%</td>
</tr>
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<td>6/18</td>
<td>56%</td>
</tr>
<tr>
<td>6/20</td>
<td>53%</td>
</tr>
<tr>
<td>6/21</td>
<td>48%</td>
</tr>
</tbody>
</table>

(note: computation of the illumination area for 35 GHz system was uncertain, therefore, these data are normalized to L₁₁. Affected quantities on the following pages are indicated by an asterisk).

**References:**  
Data List:

<table>
<thead>
<tr>
<th>$\theta_i$</th>
<th>freq.</th>
<th>condition</th>
<th>date</th>
<th>data no.</th>
<th>page no.</th>
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</thead>
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<td>160</td>
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<td>tree.10.2</td>
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<td>35</td>
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<td>6/06</td>
<td>tree.10.3</td>
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<td>tree.10.4</td>
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<td>6/06</td>
<td>tree.10.5</td>
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<td>drying</td>
<td>6/21</td>
<td>tree.10.35</td>
<td>194</td>
</tr>
</tbody>
</table>
Normalized Mueller Matrix:

\[
\mathbf{\mathbb{M}} = \begin{bmatrix}
1.0000 & 0.1012 & -0.0232 & -0.0488 \\
0.1118 & 0.6834 & -0.0199 & 0.0171 \\
-0.0072 & -0.0373 & 0.6779 & -0.0393 \\
0.0928 & 0.0011 & 0.0087 & 0.5043
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^\ast &= 0.00 \text{ dB} \\
\sigma_{vh}^\ast &= -9.73 \text{ dB} \\
\chi_d &= -8.98 \text{ dB} \\
\alpha &= 0.72 \\
\zeta &= -2.32^\circ
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.80 \\
m_{45} &= 0.75 \\
m_{135} &= 0.72 \\
m_{\text{thr}} &= 0.61 \\
m_{\text{rhc}} &= 0.52
\end{align*}
\]
Normalized Mueller Matrix:

\[
L^0_{rm} = 1.0000 \begin{bmatrix}
1.0000 & 0.1502 & -0.0199 & 0.0428 \\
0.1976 & 0.8292 & -0.0571 & -0.0129 \\
-0.1072 & -0.0112 & 0.8758 & -0.0896 \\
-0.0629 & 0.0543 & 0.0146 & 0.6571 \\
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.81 \text{ dB} \\
\sigma_{vh}^* = -7.60 \text{ dB} \\
\chi_d = -7.21 \text{ dB} \\
\alpha = 0.84 \quad \zeta = -3.89^\circ 
\]

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

Degree of Polarization:

\[
m_v = 0.68 \quad m_h = 0.70 \\
m_{45} = 0.81 \quad m_{135} = 0.80 \\
m_{lh} = 0.61 \quad m_{rh} = 0.63 
\]
Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 10°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[ \sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.29 \text{ dB} \]
\[ \sigma_{vh}^* = -10.15 \text{ dB} \]
\[ \chi_d = -9.56 \text{ dB} \]
\[ \alpha = 0.88 \quad \zeta = -5.13^\circ \]

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

Degree of Polarization:

\[ m_v = 0.83 \quad m_h = 0.76 \]
\[ m_{45} = 0.85 \quad m_{135} = 0.82 \]
\[ m_{lh} = 0.81 \quad m_{rh} = 0.72 \]
Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 15°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0897 & -0.0438 & 0.0233 \\
0.1303 & 0.8738 & -0.0578 & 0.0080 \\
-0.1204 & -0.0608 & 0.7758 & -0.1042 \\
0.0566 & 0.0373 & 0.0795 & 0.6274
\end{bmatrix}
\]

\[
\sigma^*_{vv} = 0.00 \text{ dB} \quad \sigma^*_{hh} = -0.59 \text{ dB} \\
\sigma^*_{vh} = -9.59 \text{ dB} \\
\lambda_d = -9.30 \text{ dB} \\
\alpha = 0.76 \quad \zeta = -7.46°
\]

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

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.82 \\
m_{45} = 0.74 \quad m_{135} = 0.76 \\
m_{lhc} = 0.65 \quad m_{rhc} = 0.57
\]
Target: Rhododendron - 6/6/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 15°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[ \sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.52 \text{ dB} \]
\[ \sigma_{vh} = -10.62 \text{ dB} \]
\[ \chi_d = -9.92 \text{ dB} \]
\[ \alpha = 0.83 \quad \zeta = -2.16° \]

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

Degree of Polarization:

\[ m_v = 0.81 \quad m_h = 0.83 \]
\[ m_{45} = 0.82 \quad m_{135} = 0.82 \]
\[ m_{1hc} = 0.71 \quad m_{rhc} = 0.66 \]

Co-pol response

Cross-Pol response

164
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \begin{bmatrix}
1.0000 & 0.0646 & -0.0068 & -0.0140 \\
0.0800 & 0.6500 & -0.0002 & 0.0345 \\
-0.0177 & -0.0044 & 0.7438 & 0.0064 \\
0.0534 & -0.0455 & -0.0245 & 0.6378 \\
\end{bmatrix}
\]

\[\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} \\
\sigma_{vh}^* &= -11.41 \text{ dB} \\
\chi_d &= -10.57 \text{ dB} \\
\alpha &= 0.86 \\
\zeta &= 1.28°
\end{align*}\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.85 \\
m_h &= 0.82 \\
m_{45} &= 0.84 \\
m_{135} &= 0.86 \\
m_{h_c} &= 0.71 \\
m_{rhc} &= 0.76
\end{align*}
\]
Normalized Mueller Matrix:

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

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.77 \text{ dB} \\
\sigma_{vh}^* = -9.81 \text{ dB} \\
\chi = -9.44 \text{ dB} \\
\alpha = 0.82 \quad \zeta = -9.33^\circ
\]

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

Degree of Polarization:

\[
m_v = 0.80 \quad m_h = 0.79 \\
m_{45} = 0.79 \quad m_{135} = 0.78 \\
m_{lh} = 0.69 \quad m_{rh} = 0.68
\]
Target: Rhododendron - 6/06/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0773 & -0.0630 & 0.0296 \\
0.0884 & 0.7817 & -0.0612 & 0.0003 \\
-0.1104 & -0.1078 & 0.8134 & -0.0890 \\
-0.0543 & 0.0245 & 0.0571 & 0.7162 \\
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.07 \text{ dB} \\
\sigma_{vh}^* = -10.82 \text{ dB} \\
\chi_d = -10.32 \text{ dB} \\
\alpha = 0.87 \quad \zeta = -5.45°
\]

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

Degree of Polarization:

\[
m_v = 0.85 \quad m_h = 0.83 \\
m_{45} = 0.84 \quad m_{135} = 0.85 \\
m_{lhc} = 0.74 \quad m_{rhc} = 0.78
\]
Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 25°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 1.0000 \begin{bmatrix}
1.0000 & 0.0641 & -0.0126 & 0.0112 \\
0.0965 & 0.7238 & 0.0154 & -0.0101 \\
0.0243 & -0.0138 & 0.7348 & -0.1212 \\
0.0056 & 0.0322 & 0.0753 & 0.6054 \\
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.40 \text{ dB} \\
\sigma_{vh}^* = -10.95 \text{ dB} \quad \chi_d = -10.31 \text{ dB} \\
\alpha = 0.80 \quad \zeta = -8.34°
\]

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

Degree of Polarization:

\[
m_v = 0.82 \quad m_h = 0.84 \\
m_{45} = 0.80 \quad m_{135} = 0.80 \\
m_{ihc} = 0.69 \quad m_{rhc} = 0.65
\]
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0838 & -0.0334 & 0.0189 \\
0.1020 & 0.8699 & -0.0308 & -0.0259 \\
-0.0376 & -0.0667 & 0.8191 & -0.0916 \\
-0.0397 & 0.0535 & 0.0640 & 0.6915
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \\
\sigma_{vh}^* = -10.32 \text{ dB} \\
\chi_d = -10.03 \text{ dB} \\
\alpha = 0.81 \\
\zeta = -5.88°
\]

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

Degree of Polarization:

\[
m_v = 0.82 \\
m_h = 0.83 \\
m_{45} = 0.80 \\
m_{135} = 0.80 \\
m_{hc} = 0.71 \\
m_{rh} = 0.66
\]
Target: Rhododendron - 6/03/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^* = \begin{bmatrix}
1.0000 & 0.0571 & -0.0169 & -0.0070 \\
0.0913 & 0.7110 & -0.0220 & 0.0242 \\
-0.0645 & -0.0160 & 0.7628 & -0.0841 \\
0.0642 & -0.0316 & 0.0234 & 0.6500
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.48 \text{ dB} \]
\[\sigma_{vh}^* = -11.30 \text{ dB} \]
\[\chi_d = -10.62 \text{ dB} \]
\[\alpha = 0.84 \quad \zeta = -4.35° \]

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

Degree of Polarization:

\[m_v = 0.84 \quad m_h = 0.85\]
\[m_{45} = 0.83 \quad m_{135} = 0.84\]
\[m_{lhc} = 0.72 \quad m_{rhc} = 0.72\]
Target: Rhododendron - 6/06/1991  
System/Frequency: UM - 35 GHz.  
Incidence Angle: 30°  
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_{m}^{o} = 1.0000 \\
1.0000 & 0.0853 & -0.0412 & 0.0125 \\
0.0850 & 0.7866 & -0.0304 & -0.0170 \\
-0.0547 & -0.0208 & 0.8324 & -0.0588 \\
-0.0397 & 0.0403 & 0.0037 & 0.7341
\]

\[\sigma_{vv}^{*} = 0.00 \text{ dB} \quad \sigma_{hh}^{*} = -1.04 \text{ dB}\]
\[\sigma_{vh}^{*} = -10.70 \text{ dB} \quad \chi_{d} = -10.21 \text{ dB} \quad \alpha = 0.88 \quad \zeta = -2.28°\]

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

Degree of Polarization:

\[m_{v} = 0.85 \quad m_{h} = 0.81 \]
\[m_{45} = 0.88 \quad m_{135} = 0.84 \]
\[m_{hc} = 0.77 \quad m_{rhc} = 0.75 \]
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0676 & -0.0275 & -0.0130 \\
0.1064 & 0.8370 & -0.0278 & -0.0018 \\
-0.0677 & -0.0381 & 0.8384 & -0.1215 \\
-0.0030 & -0.0026 & 0.0782 & 0.7073
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.77 \text{ dB}
\]
\[
\sigma_{vh}^* = -10.60 \text{ dB} \quad \chi_d = -10.23 \text{ dB}
\]
\[
\alpha = 0.85 \quad \zeta = -7.36°
\]

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

Degree of Polarization:

\[
m_v = 0.81 \quad m_h = 0.85 \\
m_{45} = 0.83 \quad m_{135} = 0.85 \\
m_{lhc} = 0.73 \quad m_{rhc} = 0.70
\]
**Target:** Rhododendron - 5/27/1991  
**System/Frequency:** UM - 35 GHz.  
**Incidence Angle:** 50°  
**Independent Samples:** 99

Normalized Mueller Matrix:

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

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.22 \text{ dB}\]

\[\sigma_{vh}^* = -10.32 \text{ dB}\]

\[\chi_d = -9.75 \text{ dB}\]

\[\alpha = 0.83 \quad \zeta = -4.23°\]

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

**Degree of Polarization:**

\[
\begin{align*}
m_v &= 0.81 \\
m_{45} &= 0.82 \\
m_{135} &= 0.80 \\
m_{thc} &= 0.68 \\
\end{align*}
\]

\[
\begin{align*}
m_h &= 0.81 \\
m_{rhc} &= 0.71 \\
\end{align*}
\]

---

**Co-polar response**  
**Cross-Pol response**

---

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System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:
\[ \mathbf{L}_m^* = \begin{bmatrix} 1.0000 & 0.1120 & -0.0111 & -0.0017 \\ 0.1363 & 0.8326 & -0.0116 & 0.0015 \\ -0.0213 & -0.0242 & 0.8103 & -0.0902 \\ 0.0312 & -0.0081 & 0.0640 & 0.6770 \end{bmatrix} \]

\[ \sigma^*_{vv} = 0.00 \text{ dB} \quad \sigma^*_{hh} = -0.80 \text{ dB} \]
\[ \sigma^*_{vh} = -9.06 \text{ dB} \]
\[ \chi_d = -8.68 \text{ dB} \]
\[ \alpha = 0.82 \quad \zeta = -5.92^\circ \]

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

Degree of Polarization:
\[ m_v = 0.76 \quad m_h = 0.76 \]
\[ m_{45} = 0.78 \quad m_{135} = 0.79 \]
\[ m_{lhc} = 0.67 \quad m_{rhc} = 0.65 \]
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[
\sigma^+_{vv} = 0.00 \text{ dB} \quad \sigma^+_{hh} = -1.16 \text{ dB}
\]

\[
\sigma^*_{vh} = -8.64 \text{ dB} \quad \chi_d = -8.10 \text{ dB} \quad \alpha = 0.72 \quad \zeta = 0.77°
\]

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

Degree of Polarization:

\[
m_v = 0.73 \quad m_h = 0.74
\]

\[
m_{45} = 0.68 \quad m_{135} = 0.72
\]

\[
m_{lhc} = 0.54 \quad m_{+hc} = 0.56
\]
Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 10°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = \begin{bmatrix}
1.0000 & 0.1342 & 0.0215 & 0.0329 \\
0.1248 & 0.9812 & 0.0169 & -0.0215 \\
0.0056 & 0.1076 & 0.8322 & -0.0010 \\
-0.0065 & 0.0708 & 0.0295 & 0.6842 \\
\end{bmatrix}
\]

\[\begin{align*}
\sigma_{vv} &= 8.30 \text{ dB} \\
\sigma_{vh} &= -0.57 \text{ dB} \\
\chi_d &= -8.84 \text{ dB} \\
\alpha &= 0.77 \\
\zeta &= -1.15°
\end{align*}\]

Degree of Polarization:

\[\begin{align*}
m_v &= 0.78 \\
m_{45} &= 0.77 \\
m_{h} &= 0.77 \\
m_{135} &= 0.72 \\
m_{hc} &= 0.64 \\
m_{rhc} &= 0.59
\end{align*}\]
Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = 0.5932 \begin{bmatrix}
1.0000 & 0.1116 & 0.0276 & 0.0372 \\
0.1092 & 1.0573 & 0.0578 & 0.0158 \\
0.0781 & 0.0437 & 0.8850 & -0.0263 \\
-0.0317 & -0.0153 & 0.0399 & 0.7017 \\
\end{bmatrix}
\]

\[\sigma_{vv} = 8.72 \text{ dB} \quad \sigma_{hh} = 8.97 \text{ dB}\]
\[\sigma_{vh} = -0.85 \text{ dB} \quad \chi_d = -9.69 \text{ dB}\]
\[\alpha = 0.77 \quad \zeta = -2.39°\]

Degree of Polarization:

\[m_v = 0.81 \quad m_h = 0.81\]
\[m_{45} = 0.77 \quad m_{135} = 0.78\]
\[m_{hc} = 0.57 \quad m_{rhc} = 0.67\]
Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

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

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

Degree of Polarization:

$$m_v = 0.82$$  \quad $$m_h = 0.85$$
$$m_{45} = 0.80$$  \quad $$m_{135} = 0.80$$
$$m_{ihc} = 0.65$$  \quad $$m_{rhc} = 0.67$$
Target: Rhododendron – 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[\sigma_{vv} = 7.93 \text{ dB} \quad \sigma_{hh} = 8.83 \text{ dB} \]
\[\sigma_{vh} = -0.89 \text{ dB} \quad \chi_d = -9.29 \text{ dB} \]
\[\alpha = 0.84 \quad \zeta = -5.74° \]

Degree of Polarization:

\[m_v = 0.80 \quad m_h = 0.78 \]
\[m_{45} = 0.83 \quad m_{135} = 0.79 \]
\[m_{h45} = 0.70 \quad m_{rhc} = 0.69 \]
Target:  Rhododendron - 5/31/1991
System/Frequency:  UM - 94 GHz.
Incidence Angle:  50°
Independent Samples:  99

Normalized Mueller Matrix:

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

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

Degree of Polarization:

\[m_v = 0.86 \quad m_h = 0.84\]
\[m_{45} = 0.82 \quad m_{135} = 0.82\]
\[m_{lh} = 0.74 \quad m_{rh} = 0.74\]
Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[ \sigma_{vv} = 7.15 \text{ dB} \quad \sigma_{hh} = 7.36 \text{ dB} \]
\[ \sigma_{vh} = -3.58 \text{ dB} \]
\[ \chi_d = -10.84 \text{ dB} \]
\[ \alpha = 0.87 \quad \zeta = -4.17° \]

Degree of Polarization:

\[ m_v = 0.89 \quad m_h = 0.81 \]
\[ m_{45} = 0.85 \quad m_{135} = 0.85 \]
\[ m_{thc} = 0.75 \quad m_{rhc} = 0.76 \]
Target: Rhododendron - 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L^0_m = 0.3684 \begin{bmatrix}
1.0000 & 0.0922 & 0.0412 & 0.0237 \\
0.0859 & 0.9749 & 0.0219 & -0.0136 \\
0.0446 & 0.1007 & 0.8685 & -0.0121 \\
-0.0624 & 0.0131 & 0.0055 & 0.7488
\end{bmatrix}
\]

\[
\sigma_{vv} = 6.66 \text{ dB} \quad \sigma_{hh} = 6.55 \text{ dB}
\]
\[
\sigma_{vh} = -3.85 \text{ dB} \quad \chi_{d} = -10.45 \text{ dB}
\]
\[
\alpha = 0.82 \quad \zeta = -0.62°
\]

Degree of Polarization:

\[
m_v = 0.84 \quad m_h = 0.83
\]
\[
m_{45} = 0.83 \quad m_{135} = 0.79
\]
\[
m_{hc} = 0.67 \quad m_{rhc} = 0.73
\]
Target: Rhododendron – 5/31/1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 0.1937 \begin{bmatrix}
1.0000 & 0.1236 & -0.0079 & 0.0215 \\
0.1245 & 1.1673 & -0.0027 & -0.0319 \\
-0.0499 & 0.0558 & 0.9347 & 0.0241 \\
-0.0325 & 0.0267 & -0.0186 & 0.7682
\end{bmatrix}
\]

\[
\sigma_{vv} = 3.86 \text{ dB} \quad \sigma_{hh} = 4.54 \text{ dB}
\]
\[
\sigma_{vh} = -5.20 \text{ dB} \quad \chi_d = -9.41 \text{ dB}
\]
\[
\alpha = 0.79 \quad \zeta = 1.44°
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.81
\]
\[
m_{45} = 0.79 \quad m_{135} = 0.77
\]
\[
m_{lhc} = 0.64 \quad m_{rhc} = 0.64
\]
Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.1199 & -0.0303 & 0.0447 \\
0.1401 & 0.7699 & -0.0361 & -0.0143 \\
-0.0567 & -0.0514 & 0.7740 & -0.0973 \\
-0.0542 & 0.0568 & 0.0679 & 0.5955
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.14 \text{ dB}\]
\[\sigma_{vh}^* = -8.86 \text{ dB} \quad \chi_d = -8.33 \text{ dB}\]
\[\alpha = 0.79 \quad \zeta = -6.88°\]

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

Degree of Polarization:

\[m_v = 0.76 \quad m_h = 0.74\]
\[m_{45} = 0.77 \quad m_{135} = 0.77\]
\[m_{ihc} = 0.61 \quad m_{rhc} = 0.61\]
Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 1.0000 \begin{bmatrix}
1.0000 & 0.1402 & -0.0199 & 0.0193 \\
0.1446 & 0.7896 & 0.0138 & 0.0192 \\
0.0627 & 0.0317 & 0.6906 & -0.0446 \\
0.0226 & -0.0088 & 0.0442 & 0.4974
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.03 \text{ dB} \\
\sigma_{vh}^* &= -8.46 \text{ dB} & \chi_d &= -7.98 \text{ dB} \\
\alpha &= 0.67 & \zeta &= -4.27°
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.75 & m_h &= 0.70 \\
m_{45} &= 0.72 & m_{135} &= 0.63 \\
m_{thc} &= 0.48 & m_{thc} &= 0.51
\end{align*}
\]
Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[\sigma_{uv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.62 \text{ dB} \]
\[\sigma_{vh}^* = -10.00 \text{ dB} \]
\[\lambda_d = -9.71 \text{ dB} \]
\[\alpha = 0.82 \quad \zeta = -1.22° \]

* magnitude relative to \(\sigma_{uv}\) (see pg. 39 for details)

Degree of Polarization:

\[m_v = 0.83 \quad m_h = 0.78 \]
\[m_{45} = 0.81 \quad m_{135} = 0.79 \]
\[m_{\text{h}} = 0.70 \quad m_{\text{r}} = 0.67 \]
Target: Rhododendron - 6/17/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0725 & -0.0234 & 0.0120 \\
0.0854 & 0.7385 & 0.0054 & 0.0107 \\
-0.0003 & -0.0521 & 0.8277 & -0.0375 \\
0.0111 & 0.0248 & -0.0291 & 0.7056
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^- &= 0.00 \, \text{dB} \quad & \sigma_{hh}^* &= -1.32 \, \text{dB} \\
\sigma_{vh}^* &= -11.03 \, \text{dB} \quad & \zeta &= -0.31° \\
\chi_d &= -10.42 \, \text{dB} \\
\alpha &= 0.89
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.84 \quad & m_h &= 0.82 \\
m_{45} &= 0.87 \quad & m_{135} &= 0.90 \\
m_{hc} &= 0.76 \quad & m_{rhc} &= 0.75
\end{align*}
\]
Target: Rhododendron - 6/18/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.26 \text{ dB} \]
\[\sigma_{vh}^* = -10.55 \text{ dB} \]
\[\chi_d = -9.97 \text{ dB} \]
\[\alpha = 0.86 \quad \zeta = -3.10° \]

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

Degree of Polarization:

\[
m_v = 0.83 \\
m_{45} = 0.84 \\
m_{135} = 0.83 \\
m_{h} = 0.80 \\
m_{hc} = 0.74 \\
m_{+hc} = 0.71
\]
Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}_m^o = 1.0000 \\
0.1056 & 0.7448 & -0.0011 & 0.0080 \\
0.0595 & 0.0210 & 0.7547 & 0.0211 \\
-0.0158 & 0.0558 & -0.0511 & 0.6283
\]

* magnitude relative to \( \sigma_{uv} \) (see pg. 39 for details)

Degree of Polarization:

\[
\begin{align*}
\sigma_{uv}^* &= 0.00 \text{ dB} \\
\sigma_{vh}^* &= -10.15 \text{ dB} \\
\chi_d &= -9.56 \text{ dB} \\
\alpha &= 0.80 \\
\zeta &= 2.99°
\end{align*}
\]

\[
\begin{align*}
m_v &= 0.81 \\
m_h &= 0.79 \\
m_{45} &= 0.82 \\
m_{135} &= 0.76 \\
m_{hc} &= 0.67 \\
m_{rhc} &= 0.66
\end{align*}
\]

Co-pol response

Cross-Pol response

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

Normalized Mueller Matrix:

\[
L_m^\circ = \begin{bmatrix}
1.0000 & 0.0405 & -0.0177 & 0.0421 \\
0.0449 & 0.8023 & -0.0267 & -0.0202 \\
-0.0409 & -0.0412 & 0.8448 & -0.0870 \\
-0.0740 & 0.0576 & 0.0455 & 0.7890
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \, \text{dB} \quad \sigma_{hh}^* = -0.96 \, \text{dB}\]
\[\sigma_{vh}^* = -13.69 \, \text{dB} \]
\[\lambda_d = -13.24 \, \text{dB} \]
\[\alpha = 0.91 \quad \zeta = -4.64°\]

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

Degree of Polarization:

\[m_v = 0.92 \quad m_h = 0.91\]
\[m_{45} = 0.90 \quad m_{135} = 0.90\]
\[m_{h_v} = 0.84 \quad m_{r_h} = 0.87\]
Target: Rhododendron - 6/21/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

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

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.26 \text{ dB}\]
\[\sigma_{vh}^* = -13.03 \text{ dB} \quad \chi_d = -12.44 \text{ dB} \quad \alpha = 0.80 \quad \zeta = 2.33°\]

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

Degree of Polarization:

\[m_v = 0.89 \quad m_h = 0.89 \quad m_{45} = 0.80 \quad m_{135} = 0.80 \quad m_{lhc} = 0.72 \quad m_{rhc} = 0.71\]
Target: Rhododendron - 6/17/1991
System/Frequency: UM - 35 GHz.
Incidence Angle: $90^\circ$
Independent Samples: 99

Normalized Mueller Matrix:

$$\mathbf{L}_m^0 = \begin{bmatrix} 1.0000 & 0.0641 & -0.0126 & -0.0064 \\ 0.0750 & 0.6862 & -0.0037 & 0.0025 \\ -0.0143 & 0.0154 & 0.7369 & -0.0154 \\ 0.0146 & -0.0065 & -0.0004 & 0.6336 \end{bmatrix}$$

$$\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.64 \text{ dB}$$
$$\sigma_{vh}^* = -11.58 \text{ dB} \quad \chi_d = -10.83 \text{ dB}$$
$$\alpha = 0.83 \quad \zeta = -0.63^\circ$$

* magnitude relative to $\sigma_{vv}$ (see pg. 39 for details)

Degree of Polarization:

$$m_v = 0.86 \quad m_h = 0.83$$
$$m_{45} = 0.84 \quad m_{135} = 0.81$$
$$m_{\text{hce}} = 0.72 \quad m_{\text{rce}} = 0.71$$

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:

\[
\mathbf{L}_{m}^{0} = 1.0000 \begin{bmatrix}
1.0000 & 0.0613 & -0.0234 & 0.0371 \\
0.0821 & 0.7831 & -0.0231 & -0.0066 \\
-0.0833 & -0.0082 & 0.7539 & -0.0271 \\
-0.0301 & 0.0388 & 0.0006 & 0.6446
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.06 \text{ dB}\]
\[\sigma_{vh}^* = -11.44 \text{ dB} \quad \chi_d = -10.94 \text{ dB}\]
\[\alpha = 0.79 \quad \zeta = -1.13°\]

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

Degree of Polarization:

\[m_v = 0.85 \quad \tilde{m}_h = 0.86\]
\[m_{45} = 0.78 \quad m_{135} = 0.80\]
\[m_{lhc} = 0.67 \quad m_{rhc} = 0.69\]

Co-pol response

Cross-Pol response

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Normalized Mueller Matrix:

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

\[
\sigma^\circ_{vv} = 0.00 \text{ dB} \quad \sigma^\circ_{hh} = -1.28 \text{ dB}
\]

\[
\sigma^\circ_{v\chi} = -14.24 \text{ dB} \quad \chi^\circ_d = -13.65 \text{ dB}
\]

\[
\alpha = 0.80 \quad \zeta = 5.16^\circ
\]

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

Degree of Polarization:

\[
m_v = 0.92 \quad m_h = 0.92
\]

\[
m_{45} = 0.79 \quad m_{135} = 0.80
\]

\[
m_{thc} = 0.75 \quad m_{t hc} = 0.74
\]
**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:**  
Data List:

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

Normalized Mueller Matrix:
\[
\mathbf{L}_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0840 & -0.0127 & -0.0008 \\
0.0942 & 0.8388 & -0.0102 & 0.0343 \\
-0.0200 & -0.0184 & 0.8491 & -0.0321 \\
0.0581 & -0.0486 & 0.0112 & 0.7045 \\
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.76 \text{ dB}\]
\[\sigma_{vh}^* = -10.50 \text{ dB} \quad \chi_d = -10.14 \text{ dB}\]
\[\alpha = 0.85 \quad \zeta = -1.60°\]

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

Degree of Polarization:
\[m_v = 0.83 \quad m_h = 0.82\]
\[m_{45} = 0.85 \quad m_{135} = 0.85\]
\[m_{thc} = 0.68 \quad m_{rhc} = 0.73\]

Co-pol response

Cross-Pol response
Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.0819 & -0.0083 & -0.0164 \\
0.0920 & 0.7746 & -0.0197 & 0.0199 \\
-0.0512 & 0.0221 & 0.8327 & -0.0848 \\
0.0385 & -0.0429 & 0.0237 & 0.7369 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.11 \text{ dB} \\
\sigma_{vh}^* &= -10.61 \text{ dB} \\
\lambda_d &= -10.09 \text{ dB} \\
\alpha &= 0.89 & \zeta &= -3.96°
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.83 & m_h &= 0.81 \\
m_{45} &= 0.87 & m_{135} &= 0.85 \\
m_{h,c} &= 0.76 & m_{r,h,c} &= 0.78
\end{align*}
\]
Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^2 = 1.0000
\begin{bmatrix}
1.0000 & 0.0626 & -0.0467 & 0.0296 \\
0.1011 & 0.6433 & -0.0428 & 0.0075 \\
-0.1086 & -0.0694 & 0.7515 & -0.0476 \\
-0.0140 & 0.0395 & 0.0011 & 0.6077 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} \\
\sigma_{vh}^* &= -10.87 \text{ dB} \\
\chi_d &= -10.02 \text{ dB} \\
\alpha &= 0.85 \\
\zeta &= -2.05°
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.82 \\
m_{45} &= 0.84 \\
m_{lhe} &= 0.70 \\
m_h &= 0.83 \\
m_{135} &= 0.86 \\
m_{rhe} &= 0.71
\end{align*}
\]
Target: Spirea 1991
System/Frequency: U.M. - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}^0_m = \begin{bmatrix}
1.0000 & 0.0844 & 0.0191 & 0.0249 \\
0.1075 & 0.7219 & 0.0308 & -0.0072 \\
0.0393 & 0.0621 & 0.7451 & -0.0461 \\
-0.0157 & 0.0243 & 0.0403 & 0.5843 \\
\end{bmatrix}
\]

\[
\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.42 \text{ dB}
\]
\[
\sigma_{vh}^* = -10.18 \text{ dB} \\
\lambda_d = -9.53 \text{ dB} \\
\alpha = 0.78 \quad \zeta = -3.72^\circ
\]

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

Degree of Polarization:

\[
m_v = 0.81 \quad m_h = 0.80 \]
\[
m_{45} = 0.80 \quad m_{135} = 0.78 \]
\[
m_{lhc} = 0.63 \quad m_{rhc} = 0.63
\]

Co-pol response

Cross-Pol response
Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 1.0000 \begin{bmatrix}
1.0000 & 0.1113 & -0.0145 & 0.0013 \\
0.1181 & 0.7032 & 0.0019 & 0.0106 \\
0.0074 & -0.0169 & 0.7083 & -0.0194 \\
0.0335 & -0.0097 & 0.0225 & 0.5309
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -1.53 \text{ dB} \\
\sigma_{vh}^* &= -9.41 \text{ dB} \\
\chi_d &= -8.71 \text{ dB} \\
\alpha &= 0.74 & \zeta &= -1.94°
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.79 & m_h &= 0.73 \\
m_{45} &= 0.75 & m_{135} &= 0.75 \\
m_{lh} &= 0.57 & m_{rh} &= 0.57
\end{align*}
\]
Target: Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
 L_m = 1.0000 \\
 0.1234 \\
 0.6840 \\
 -0.0406 \\
 -0.0175 \\
 -0.0240 \\
 -0.0495 \\
 -0.0568 \\
 0.6826 \\
 -0.0036 \\
 -0.0314 \\
 0.0305 \\
 -0.0351 \\
 0.4419
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.65 \text{ dB}\]
\[\sigma_{vh}^* = -8.22 \text{ dB} \quad \chi_d = -7.48 \text{ dB}\]
\[\alpha = 0.68 \quad \zeta = 1.60°\]

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

Degree of Polarization:

\[m_v = 0.70 \quad m_h = 0.70\]
\[m_{45} = 0.68 \quad m_{135} = 0.72\]
\[m_{lh} = 0.48 \quad m_{rh} = 0.46\]
Normalized Mueller Matrix:

\[
L_m^\circ = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.1289 & -0.0189 & 0.0314 \\
0.1708 & 0.5968 & -0.0214 & -0.0221 \\
-0.0241 & -0.0414 & 0.6280 & -0.0105 \\
-0.0464 & 0.0245 & -0.0155 & 0.4188 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* & = 0.00 \text{ dB} \\
\sigma_{vh}^* & = -8.24 \text{ dB} \\
\chi_d & = -7.27 \text{ dB} \\
\alpha & = 0.68 \\
\zeta & = 0.28^\circ
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v & = 0.71 \\
m_h & = 0.65 \\
m_{45} & = 0.69 \\
m_{135} & = 0.69 \\
m_{lhc} & = 0.49 \\
m_{rhc} & = 0.48
\end{align*}
\]
Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}^\circ = \begin{bmatrix}
1.0000 & 0.1049 & 0.0029 & -0.0353 \\
0.1022 & 1.0384 & -0.0184 & -0.0039 \\
0.0135 & 0.0558 & 0.9457 & -0.0053 \\
-0.0009 & -0.0184 & 0.0127 & 0.8090
\end{bmatrix}
\]

\[
\sigma_{vv} = 6.88 \text{ dB} \quad \sigma_{hh} = 7.04 \text{ dB}
\]
\[
\sigma_{vh} = -2.97 \text{ dB} \quad \chi_d = -9.93 \text{ dB}
\]
\[
\alpha = 0.86 \quad \zeta = -0.59^\circ
\]

Degree of Polarization:

\[
m_v = 0.81 \quad m_h = 0.82
\]
\[
m_{45} = 0.89 \quad m_{135} = 0.80
\]
\[
m_{thc} = 0.74 \quad m_{rhc} = 0.71
\]
Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^\circ = 0.3154 \begin{bmatrix}
1.0000 & 0.1088 & 0.0247 & 0.0492 \\
0.1149 & 0.9478 & -0.0167 & -0.0226 \\
0.0269 & 0.0434 & 0.8898 & 0.0130 \\
-0.0875 & 0.0626 & -0.0233 & 0.7568 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = 5.98 \text{ dB} \quad \sigma_{hh} = 5.75 \text{ dB}
\]
\[
\sigma_{vh} = -3.53 \text{ dB} \quad \zeta = 1.26°
\]
\[
\lambda_d = -9.40 \text{ dB} \quad \alpha = 0.85
\]

Degree of Polarization:

\[
m_v = 0.80 \quad m_h = 0.80
\]
\[
m_{45} = 0.85 \quad m_{135} = 0.79
\]
\[
m_{hc} = 0.68 \quad m_{rhc} = 0.73
\]
Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^c = 0.2543 \begin{bmatrix}
1.0000 & 0.1285 & -0.0048 & 0.0107 \\
0.1208 & 1.0161 & -0.0085 & 0.0167 \\
0.0180 & 0.0432 & 0.8798 & 0.0439 \\
-0.0054 & -0.0137 & -0.0652 & 0.6927
\end{bmatrix}
\]

\[
\sigma_{vv} = 5.05 \text{ dB} \quad \sigma_{hh} = 5.11 \text{ dB}
\]

\[
\sigma_{vh} = -4.00 \text{ dB} \quad \chi_d = -9.08 \text{ dB}
\]

\[
\alpha = 0.78 \quad \zeta = 3.97°
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.78
\]

\[
m_{45} = 0.82 \quad m_{135} = 0.74
\]

\[
m_{hc} = 0.59 \quad m_{rhc} = 0.64
\]
Target: Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = \begin{bmatrix}
1.0000 & 0.1669 & -0.0420 & -0.0325 \\
0.1703 & 1.0097 & -0.0498 & 0.0653 \\
0.0833 & -0.1008 & 0.7479 & 0.1206 \\
0.0143 & 0.0707 & -0.1535 & 0.5304
\end{bmatrix}
\]

\[
\sigma_{vv} = 4.10 \text{ dB} \quad \sigma_{hh} = 4.14 \text{ dB}
\]
\[
\sigma_{vh} = -3.63 \text{ dB} \quad \sigma_{hv} = 4.14 \text{ dB}
\]
\[
\lambda_{d} = -7.75 \text{ dB} \\
\alpha = 0.65 \quad \zeta = 12.10°
\]

Degree of Polarization:

\[
m_v = 0.71 \quad m_h = 0.72 \\
m_{45} = 0.69 \quad m_{135} = 0.62 \\
m_{5hc} = 0.49 \quad m_{rhc} = 0.45
\]

Co-polar response

Cross-Polar response
Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.2670 & -0.0485 & 0.0222 \\
0.2944 & 0.5755 & -0.0558 & -0.0172 \\
-0.0704 & -0.0787 & 0.4856 & 0.0382 \\
0.0152 & 0.0271 & -0.0954 & 0.0949 \\
\end{bmatrix}
\]

\[\begin{align*}
\sigma_{vv}^r &= 0.00 \text{ dB} \\
\sigma_{vh}^r &= -5.52 \text{ dB} \\
\chi_d &= -4.48 \text{ dB} \\
\alpha &= 0.39 \\
\zeta &= 12.96°
\end{align*}\]

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

Degree of Polarization:

\[\begin{align*}
m_v &= 0.55 \\
m_h &= 0.38 \\
m_{45} &= 0.48 \\
m_{135} &= 0.51 \\
m_{thc} &= 0.25 \\
m_{trhc} &= 0.20
\end{align*}\]
Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\begin{bmatrix}
1.0000 & 0.1860 & 0.0004 & 0.0161 \\
0.2625 & 0.6001 & -0.0393 & -0.0035 \\
0.0371 & -0.0387 & 0.4808 & 0.1157 \\
-0.0072 & 0.0062 & -0.1129 & 0.1561
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= -2.22 \text{ dB} \\
\sigma_{vh}^* &= -6.49 \text{ dB} \\
\chi_d &= -5.52 \text{ dB} \\
\alpha &= 0.44 & \zeta &= 19.75°
\end{align*}
\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.58 & m_h &= 0.53 \\
m_{45} &= 0.54 & m_{135} &= 0.48 \\
m_{lhc} &= 0.26 & m_{rhc} &= 0.24
\end{align*}
\]
Target: Defoliated Spirea 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L^0_m = \begin{bmatrix}
1.0000 & 0.2245 & -0.0465 & 0.0552 \\
0.2398 & 0.7928 & -0.0341 & -0.0259 \\
-0.0224 & -0.0495 & 0.5934 & 0.2166 \\
-0.1200 & 0.0620 & -0.2008 & 0.2488 \\
\end{bmatrix}
\]

\[
\sigma_{uv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.01 \text{ dB}
\]
\[
\sigma_{vh}^* = -6.34 \text{ dB} \quad \chi = -5.87 \text{ dB}
\]
\[
\alpha = 0.53 \quad \zeta = 26.36°
\]

* magnitude relative to \(\sigma_{uv}\) (see pg. 39 for details)

Degree of Polarization:

\[
m_v = 0.62 \quad m_h = 0.56
\]
\[
m_{45} = 0.58 \quad m_{135} = 0.55
\]
\[
m_{h hc} = 0.29 \quad m_{r hc} = 0.34
\]
Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^o = 0.1463 \begin{bmatrix}
1.0000 & 0.1671 & -0.0193 & 0.0074 \\
0.1329 & 0.7801 & -0.0324 & -0.0212 \\
-0.0375 & 0.0067 & 0.7244 & 0.1053 \\
-0.0388 & -0.0152 & -0.0928 & 0.5236 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= 2.64 \text{ dB} \\
\sigma_{vh} &= -5.59 \text{ dB} \\
\lambda_d &= -7.73 \text{ dB} \\
\alpha &= 0.72 \\
\zeta &= 9.02°
\end{align*}
\]

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.77 \\
m_{45} &= 0.74 \\
m_{135} &= 0.69 \\
m_{hc} &= 0.51 \\
m_{rh} &= 0.54
\end{align*}
\]
Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}_m^0 = 0.1356 \begin{bmatrix}
1.0000 & 0.1419 & 0.0009 & 0.0226 \\
0.1279 & 0.7784 & -0.0297 & -0.0133 \\
-0.0353 & 0.0141 & 0.6663 & 0.0318 \\
-0.0551 & 0.0284 & -0.0398 & 0.4797 \\
\end{bmatrix}
\]

\[
\sigma_{vv} = 2.32 \text{ dB} \quad \sigma_{hh} = 1.23 \text{ dB}
\]
\[
\sigma_{vh} = -6.38 \text{ dB} \quad \chi_d = -8.19 \text{ dB}
\]
\[
\alpha = 0.65 \quad \zeta = 3.58°
\]

Degree of Polarization:

\[
m_v = 0.78 \quad m_h = 0.69 \\
m_{45} = 0.68 \quad m_{135} = 0.65 \\
m_{lh0} = 0.48 \quad m_{rh0} = 0.49
\]
Target: Defoliated Spirea 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[ \mathbf{L}_m^o = 0.3367 \begin{bmatrix} 1.0000 & 0.1050 & -0.0009 & 0.0056 \\ 0.0994 & 0.8383 & 0.0070 & -0.0081 \\ -0.0289 & 0.0316 & 0.7545 & 0.1268 \\ -0.0595 & 0.0168 & -0.1096 & 0.5796 \end{bmatrix} \]

\[ \sigma_{vv} = 6.26 \text{ dB} \quad \sigma_{hh} = 5.50 \text{ dB} \]
\[ \sigma_{vh} = -3.64 \text{ dB} \]
\[ \chi_\theta = -9.54 \text{ dB} \]
\[ \alpha = 0.74 \quad \zeta = 10.05° \]

Degree of Polarization:

\[ m_v = 0.82 \quad m_h = 0.78 \]
\[ m_{45} = 0.75 \quad m_{135} = 0.75 \]
\[ m_{lhc} = 0.57 \quad m_{rhc} = 0.60 \]
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, there-fore, 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,”
### Data List:

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<td>w/leaves</td>
<td>tree.12.7</td>
<td>222</td>
</tr>
<tr>
<td>25</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.8</td>
<td>223</td>
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<tr>
<td>30</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.9</td>
<td>224</td>
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<tr>
<td>40</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.10</td>
<td>225</td>
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<td>50</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.11</td>
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<td>60</td>
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<td>w/leaves</td>
<td>tree.12.12</td>
<td>227</td>
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<tr>
<td>70</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.13</td>
<td>228</td>
</tr>
<tr>
<td>90</td>
<td>94</td>
<td>w/leaves</td>
<td>tree.12.14</td>
<td>229</td>
</tr>
</tbody>
</table>
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 20°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^q = 1.0000
\begin{bmatrix}
1.0000 & 0.2907 & -0.0468 & 0.0449 \\
0.4072 & 0.6593 & -0.0688 & 0.0187 \\
-0.0635 & -0.0639 & 0.5047 & -0.0376 \\
-0.0973 & 0.0100 & -0.0006 & 0.0354
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.81 \text{ dB}\]
\[\sigma_{vh}^* = -4.57 \text{ dB} \quad \chi_d = -3.76 \text{ dB}\]
\[\alpha = 0.33 \quad \zeta = -3.91°\]

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

Degree of Polarization:

\[m_v = 0.43 \quad m_h = 0.39\]
\[m_{45} = 0.44 \quad m_{135} = 0.45\]
\[m_{thc} = 0.14 \quad m_{rhc} = 0.11\]
Normalized Mueller Matrix:

\[
\mathbf{L}_m^c = 1.0000
\begin{bmatrix}
0.3331 & -0.0879 & -0.0776 \\
0.9160 & -0.0294 & 0.0869 \\
-0.0513 & 0.7732 & 0.0371 \\
-0.0653 & -0.0453 & 0.0812
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.38 \text{ dB}\]
\[\sigma_{vh}^* = -3.50 \text{ dB} \quad \lambda_d = -3.31 \text{ dB}\]
\[\alpha = 0.45 \quad \zeta = 5.51^\circ\]

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

Degree of Polarization:

\[m_v = 0.33 \quad m_h = 0.47\]
\[m_{45} = 0.56 \quad m_{135} = 0.56\]
\[m_{lh} = 0.21 \quad m_{rh} = 0.10\]
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:
\[
\mathbf{L}_m^0 = 1.0000 \\
\begin{bmatrix}
1.0000 & 0.2482 & -0.0224 & 0.0364 \\
0.3381 & 0.7974 & -0.0504 & -0.0223 \\
-0.0204 & -0.0755 & 0.5569 & -0.0764 \\
-0.0229 & 0.0559 & 0.0441 & 0.1518 \\
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} \\
\sigma_{vh}^* &= -5.33 \text{ dB} \\
\chi_d &= -4.87 \text{ dB} \\
\alpha &= 0.40 \\
\zeta &= -9.65^\circ
\end{align*}
\]

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

Degree of Polarization:
\[
\begin{align*}
m_v &= 0.50 \\
m_{45} &= 0.46 \\
m_{thc} &= 0.20 \\
m_h &= 0.53 \\
m_{135} &= 0.48 \\
m_{rhc} &= 0.12
\end{align*}
\]
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[ \mathbf{L}_m = \begin{bmatrix} 1.0000 & 0.2261 & -0.0645 & 0.0029 \\ 0.2605 & 0.7320 & -0.0096 & -0.0041 \\ -0.0733 & -0.0727 & 0.5591 & -0.0053 \\ -0.0055 & 0.0125 & 0.0635 & 0.2141 \end{bmatrix} \]

\[ \sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.36 \text{ dB} \]
\[ \sigma_{vh}^* = -6.14 \text{ dB} \]
\[ \chi_d = -5.51 \text{ dB} \]
\[ \alpha = 0.46 \quad \varsigma = -9.46° \]

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

Degree of Polarization:

\[ m_v = 0.59 \quad m_h = 0.53 \]
\[ m_{45} = 0.48 \quad m_{135} = 0.56 \]
\[ m_{lhc} = 0.26 \quad m_{rhc} = 0.21 \]
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 60°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{I}_m^0 = \begin{bmatrix}
1.0000 & 0.3082 & -0.0716 & 0.0446 \\
0.4071 & 0.7366 & -0.0429 & -0.0100 \\
-0.1221 & -0.0348 & 0.5973 & 0.0122 \\
-0.0445 & 0.0535 & -0.0255 & 0.0660 \\
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -1.33 \text{ dB}\]
\[\sigma_{vh}^* = -4.47 \text{ dB}\]
\[\chi_d = -3.85 \text{ dB}\]
\[\alpha = 0.39 \quad \zeta = 3.25°\]

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

Degree of Polarization:

\[m_v = 0.43 \quad m_h = 0.41\]
\[m_{45} = 0.47 \quad m_{135} = 0.51\]
\[m_{hc} = 0.13 \quad m_{rhc} = 0.09\]
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}_m^\circ = 1.0000 \begin{bmatrix}
1.0000 & 0.3049 & -0.0742 & 0.0292 \\
0.3645 & 0.9050 & -0.0621 & 0.0062 \\
-0.1241 & -0.0865 & 0.5653 & 0.0460 \\
0.0184 & 0.0463 & -0.0679 & 0.0706
\end{bmatrix}
\]

\[\sigma_{vv}^* = 0.00 \text{ dB} \quad \sigma_{hh}^* = -0.43 \text{ dB} \]
\[\sigma_{vh}^* = -4.75 \text{ dB} \]
\[\chi_d = -4.54 \text{ dB} \]
\[\alpha = 0.34 \quad \zeta = 10.16^\circ \]

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

Degree of Polarization:

\[m_v = 0.47 \quad m_h = 0.50\]
\[m_{45} = 0.40 \quad m_{135} = 0.48\]
\[m_{lhc} = 0.09 \quad m_{rhc} = 0.12\]
Target: Spruce 1991
System/Frequency: UM - 35 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 1.0000 \begin{bmatrix}
1.0000 & 0.3248 & -0.0280 & 0.0347 \\
0.3964 & 1.1088 & 0.0217 & 0.0085 \\
0.0582 & 0.0040 & 0.6776 & 0.0652 \\
0.0040 & 0.1463 & -0.0451 & 0.1469 \\
\end{bmatrix}
\]

\[\begin{align*}
\sigma_{vv}^* &= 0.00 \text{ dB} & \sigma_{hh}^* &= 0.45 \text{ dB} \\
\sigma_{vh}^* &= -4.43 \text{ dB} \\
\chi_d &= -4.66 \text{ dB} \\
\alpha &= 0.39 & \zeta &= 7.62°
\end{align*}\]

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

Degree of Polarization:

\[
\begin{align*}
m_v &= 0.43 & m_h &= 0.56 \\
m_{45} &= 0.51 & m_{135} &= 0.46 \\
m_{\theta_{hc}} &= 0.17 & m_{\phi_{hc}} &= 0.10
\end{align*}
\]
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 25°
Independent Samples: 99

Normalized Mueller Matrix:

\[ L_m^o = 0.0550 \begin{bmatrix} 1.0000 & 0.3164 & -0.0560 & 0.0702 \\ 0.2116 & 1.1674 & -0.0012 & -0.0273 \\ 0.0355 & 0.0049 & 0.8496 & 0.0710 \\ -0.0808 & 0.1861 & 0.0575 & 0.4404 \end{bmatrix} \]

\[ \sigma_{vv} = -1.60 \text{ dB} \quad \sigma_{hh} = -0.93 \text{ dB} \]
\[ \sigma_{vh} = -7.39 \text{ dB} \]
\[ \chi_d = -6.13 \text{ dB} \]
\[ \alpha = 0.60 \quad \zeta = 0.60° \]

Degree of Polarization:

\[ m_v = 0.65 \quad m_h = 0.59 \]
\[ m_{45} = 0.68 \quad m_{135} = 0.59 \]
\[ m_{hc} = 0.36 \quad m_{rhc} = 0.32 \]
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 30°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^c = 0.0696 \begin{bmatrix}
1.0000 & 0.3283 & -0.0993 & -0.0451 \\
0.2231 & 0.9105 & -0.0213 & 0.0810 \\
-0.0546 & -0.0610 & 0.7569 & -0.0626 \\
0.1237 & -0.1838 & 0.0973 & 0.3040
\end{bmatrix}
\]

\[
\sigma_{vv} = -0.58 \text{ dB} \quad \sigma_{hh} = -0.99 \text{ dB}
\]
\[
\sigma_{vh} = -6.18 \text{ dB} \quad \chi_d = -5.40 \text{ dB}
\]
\[
\alpha = 0.56 \quad \zeta = -8.57°
\]

Degree of Polarization:

\[
m_v = 0.64 \quad m_h = 0.50
\]
\[
m_{45} = 0.63 \quad m_{135} = 0.62
\]
\[
m_{hzc} = 0.24 \quad m_{+hzc} = 0.34
\]
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 40°
Independent Samples: 99

Normalized Mueller Matrix:

\[
\mathbf{L}_m^\circ = 0.0753 \begin{bmatrix}
1.0000 & 0.3026 & -0.0249 & -0.0244 \\
0.2223 & 1.0728 & -0.0091 & 0.0199 \\
0.0058 & 0.0326 & 0.7540 & -0.0029 \\
0.0115 & -0.0173 & 0.0506 & 0.3414
\end{bmatrix}
\]

\[
\sigma_{uv} = -0.24 \text{ dB} \quad \sigma_{hh} = 0.07 \text{ dB}
\]
\[
\sigma_{vh} = -6.05 \text{ dB} \quad \chi_d = -5.96 \text{ dB}
\]
\[
\alpha = 0.53 \quad \zeta = -2.80°
\]

Degree of Polarization:

\[
m_v = 0.64 \quad m_h = 0.56 \\
m_{45} = 0.61 \quad m_{135} = 0.55 \\
m_{thc} = 0.26 \quad m_{rhc} = 0.27
\]
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 50°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = \begin{bmatrix}
1.0000 & 0.2853 & -0.0416 & -0.0305 \\
0.2156 & 1.0797 & -0.0107 & -0.0014 \\
-0.0665 & 0.0411 & 0.7566 & 0.0498 \\
-0.0102 & 0.0356 & -0.0541 & 0.3466
\end{bmatrix}
\]

\[\sigma_{vv} = 0.63 \text{ dB} \quad \sigma_{hh} = 0.96 \text{ dB} \]
\[\sigma_{vh} = -5.39 \text{ dB} \]
\[\chi_d = -6.18 \text{ dB} \]
\[\alpha = 0.53 \quad \zeta = 5.38°\]

Degree of Polarization:

\[m_v = 0.65 \quad m_h = 0.58 \]
\[m_{45} = 0.60 \quad m_{135} = 0.58 \]
\[m_{lh} = 0.29 \quad m_{rh} = 0.26\]
**Target:** Spruce 1991
**System/Frequency:** UM - 94 GHz.
**Incidence Angle:** 60°
**Independent Samples:** 99

**Normalized Mueller Matrix:**

\[
L_m^\circ = 0.1252 \\
\begin{bmatrix}
1.0000 & 0.3434 & 0.0127 & -0.0703 \\
0.2633 & 1.0826 & 0.0373 & -0.0109 \\
0.0374 & 0.0722 & 0.7128 & -0.0128 \\
0.0691 & 0.0081 & -0.0822 & 0.3030
\end{bmatrix}
\]

\[
\begin{align*}
\sigma_{vv} &= 1.97 \text{ dB} \\
\sigma_{vh} &= -3.21 \text{ dB} \\
\chi_d &= -5.36 \text{ dB} \\
\alpha &= 0.49
\end{align*}
\]

\[
\begin{align*}
\sigma_{hh} &= 2.31 \text{ dB} \\
\zeta &= 3.90°
\end{align*}
\]

**Degree of Polarization:**

\[
\begin{align*}
m_v &= 0.59 \\
m_h &= 0.52 \\
m_{45} &= 0.55 \\
m_{135} &= 0.52 \\
m_{h\theta c} &= 0.28 \\
m_{rhc} &= 0.20
\end{align*}
\]

Co-pol response

Cross-Pol response
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 70°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^0 = 0.1373 \begin{bmatrix}
1.0000 & 0.3051 & 0.0073 & -0.0137 \\
0.2307 & 0.9835 & 0.0352 & 0.0018 \\
0.0349 & 0.0714 & 0.6745 & 0.1171 \\
0.0130 & 0.0473 & -0.1750 & 0.2510
\end{bmatrix}
\]

\[\sigma_{uv} = 2.37 \text{ dB} \quad \sigma_{kh} = 2.30 \text{ dB}\]
\[\sigma_{vh} = -3.35 \text{ dB} \quad \chi_d = -5.68 \text{ dB}\]
\[\alpha = 0.49 \quad \zeta = 17.51°\]

Degree of Polarization:

\[m_v = 0.63 \quad m_h = 0.53\]
\[m_{45} = 0.57 \quad m_{135} = 0.54\]
\[m_{h45} = 0.26 \quad m_{r45} = 0.19\]
Target: Spruce 1991
System/Frequency: UM - 94 GHz.
Incidence Angle: 90°
Independent Samples: 99

Normalized Mueller Matrix:

\[
L_m^e = 0.1605 \begin{bmatrix}
1.0000 & 0.3272 & -0.0121 & -0.0177 \\
0.2561 & 1.0599 & -0.0288 & -0.0483 \\
-0.0311 & -0.0243 & 0.7599 & 0.0130 \\
-0.0484 & 0.0972 & -0.0676 & 0.2920
\end{bmatrix}
\]

\[
\sigma_{vv} = 3.05 \text{ dB} \quad \sigma_{hh} = 3.30 \text{ dB}
\]
\[
\sigma_{vh} = -2.30 \text{ dB} \quad \chi_d = -5.48 \text{ dB}
\]
\[
\alpha = 0.51 \quad \zeta = 4.38°
\]

Degree of Polarization:

\[
m_v = 0.59 \quad m_h = 0.53
\]
\[
m_{45} = 0.57 \quad m_{135} = 0.58
\]
\[
m_{h\perp c} = 0.25 \quad m_{r\perp c} = 0.20
\]