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POLARIMETRIC REQUIREMENTS CONSIDERATIONS FOR A 35 GHz POLARIMETRIC TEST BED SAR

By

William A. Holm

Prepared for

ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN
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Under

Purchase Order Number 219184

October 1983

GEORGIA INSTITUTE OF TECHNOLOGY

A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332

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SECTION 1
INTRODUCTION

The Georgia Institute of Technology Engineering Experiment Station (GIT/EES) was tasked by the Environmental Research Institute of Michigan (ERIM) to assist in defining the polarimetric requirements for the 35 GHz Polarimetric Test Bed Synthetic Aperture Radar (SAR) being designed by ERIM. This final technical report documents the results of that effort.

The 35 GHz Polarimetric Test Bed SAR is currently being designed to take high range resolution, high cross-range resolution, full polarimetric data of various targets and clutter scenarios. The data will be used to assist in the development and testing of stationary target/clutter discrimination and identification algorithms based on (1) high resolution imaging techniques, (2) polarimetric techniques, or (3) a combination of both imaging and polarimetric techniques.

The test bed SAR will be capable of taking full polarimetric data in the sense that 2x2 complex polarization scattering matrices will be extractable from the data. The radar polarimetric requirements to achieve this goal are the subject of this report.

In Section 2 of this report, a brief elementary review of polarization of elecromagnetic waves and scattering matrix theory is given. Polarization terms are defined and conventions are given. The complex 2x2 scattering matrix is defined and expressed in terms of five physically significant parameters. Scattering matrices and their associated parameters are given for some simple targets.

In Section 3 of this report, polarimetric requirements for a full polarimetric SAR are discussed. These requirements include considerations of the transmit and receive polarizations, polarization channel isolation, measurement time scales, bandwidth considerations, data format requirements, and polarization calibration targets.

SECTION 2

ELEMENTARY POLARIZATION THEORY

2.1 INTRODUCTION

Scattering matrix theory provides the mathematical framework for the description of radar target backscatter and, therefore, provides the basis for the development of radar target discrimination/classification algorithms. There exist two general approaches to the theoretical development of radar scattering theory. One approach, that of Sinclair and Jones,[1] is based upon the description of transmitted and received backscattered electromagnetic energy in terms of complex voltage measurements. The other approach, that of Mueller and Stokes,[2] is based upon the description of transmitted and received backscattered electromagnetic energy in terms of real power measurements. The Sinclair and Jones approach is used here to develop the theory of radar polarization scattering. Before this review of scattering matrix theory is given, however, a brief review of polarization is presented.

2.2. POLARIZATION

Electromagnetic radiation is a vector quantity, i.e., electromagnetic radiation possesses polarization. Consider a monochromatic plane electromagnetic wave propagating along the +z-axis of a right-handed coordinate system. The electric field of this wave may be represented as

$$\vec{E} = E_{ox}\cos(\omega t-kz+\alpha_x)\ \hat{x} + E_{oy}\cos(\omega t-kz+\alpha_y)\ \hat{y} \qquad (1)$$

where $\hat{x}$, $\hat{y}$ are unit vectors along the +x-axis (horizontal) and +y-axis (vertical), respectively, $\omega = 2\pi f$ (f is frequency), and $k = 2\pi/\lambda$ (λ is wavelength) . Equation (1) can be written as

$$\vec{E} = \mathrm{Re}[e^{i(\Theta+\alpha_x)} (E_{ox}\hat{x} + E_{oy} e^{i\delta}\hat{y})] \tag{2}$$

where $i = \sqrt{-1}$, $\Theta = \omega t - kz$, Re is "take the real part of," and $\delta = \alpha_y - \alpha_x$ is the relative phase difference between the two components. Dropping the "Re" and time harmonic factor, $e^{i\Theta}$, and remembering that they are implicitly understood, $\vec{E}$ in matrix notation becomes,

$$\vec{E} = e^{i\alpha_x} \begin{bmatrix} E_{ox} \\ E_{oy} e^{i\delta} \end{bmatrix} \tag{3}$$

where

$$\hat{x} = \binom{1}{0}, \text{ and } \hat{y} = \binom{0}{1}. \tag{4}$$

The ratio E_{oy}/E_{ox} and the parameter δ determine the polarization of the wave.

In general, the tip of the $\vec{E}$-vector traces out an ellipse in the x-y plane (fixed z) as time evolves (see Figure 1). The major axis of the ellipse is rotated by an angle ψ with respect to the x-axis. For a non-rotated ellipse, $\delta = \pi/2$. Thus, Equation (3) may be written

$$\vec{E} = e^{i\alpha} \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} E_{ox'} \\ iE_{oy'} \end{bmatrix} \tag{5}$$

where $E_{ox'}$ and $E_{oy'}$ are components with respect to the rotated primed coordinate system and $-90^o \leq \psi \leq 90^o$. From Figure 1, $E_{ox'}$ and $E_{oy'}$ can be expressed in terms of a and τ as

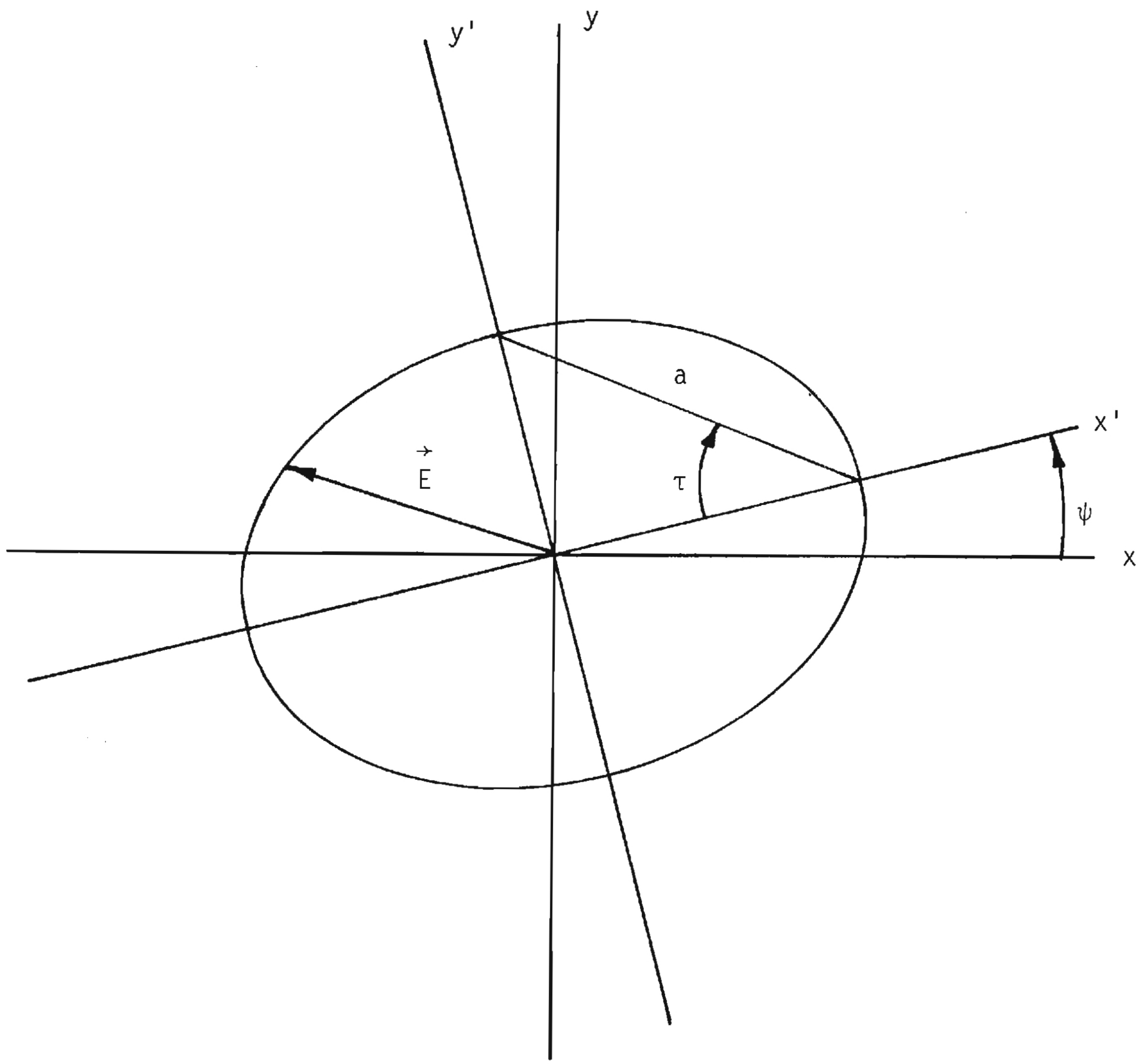


Figure 1. Elliptical Polarization.

$$E_{ox'} = a \cos \tau \qquad (6)$$

$$E_{oy'} = a \sin \tau$$

where $-45^o \leq \tau \leq 45^o$. Thus, Equation (5) becomes (dropping the absolute phase factor)

$$\vec{E} = a \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \cos\tau \\ i \sin\tau \end{bmatrix} \qquad (7)$$

which can be re-written as

$$\vec{E} = ae^{\psi J} e^{\tau K} \binom{1}{0} \qquad (8)$$

where

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \quad \text{and} \quad K = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix} . \qquad (9)$$

Thus, any arbitrary polarization can be written as two rotation operators, $e^{\psi J}$ and $e^{\tau K}$, operating on the horizontal polarization. The first rotation $e^{\tau K}$ is a complex rotation which gives the proper ellipticity of the polarization. The second rotation $e^{\psi J}$ is a real rotation which gives the proper orientation to the ellipitcal polarization (proper orientation of major axis with respect to horizontal). Any polarization state can thus be represented as a point on a unit sphere, called the Poincaré sphere, generated by these two successive rotations from the point representing horizontal polarization.

As mentioned above, τ can range from -45^o to 45^o. The sign of τ gives the "sense" of the polarization, i.e., right-hand or left-hand elliptically polarized ($\tau = -45^o$ or $+45^o$ is circularly polarized; $\tau = 0^{o}$ is linearly polarized). As might be expected, there is no concensus of opinion on what sign convention to adopt. The optics convention is

> "Right-hand elliptical polarization is that polarization in which the $\vec{E}$ -field rotates in a clockwise direction at a fixed point in space as seen by an observer toward whom the wave is propagating."

Adoption of this convention makes positive τ correspond to right-hand elliptical polarization.

The Institute of Electrical and Electronics Engineers (IEEE) has adopted a sign convention that is opposite to that of the optics convention. Adoption of the IEEE convention makes positive τ correspond to left-hand elliptical polarization.

A final word of caution is in order. Specification of the sign convention adopted does not completely specify whether an arbitrary polarization given by Equations (3), (5), (7), or (8) is "right-hand" or "left-hand" elliptically polarized. This is due to the fact that the sign of the phase, Θ , in the time harmonic factor is arbitrary, i.e., some choose to write the time harmonic factor as $e^{-i\Theta}$. Reversal of the sign of Θ changes the polarization sense. This is a problem only when an $\vec{E}$ -field is written in the form given by Equations (3), (5), (7), or (8) since the time harmonic factor, $e^{i\Theta}$, is not explicitly given.

The two most common basis sets used in polarization theory are the linear (H, V) basis and the circular (R, L) basis. Circular polarization is given by $\tau = \pm 45^{o}$, i.e., from Equation (7)

$$E_{\pm} = e^{i(\alpha \mp \psi)} \frac{a}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm i \end{pmatrix} \qquad (10)$$

To construct a circular, normalized basis set from $E_{\pm}$, one must (1) normalize $E_{\pm}$, i.e., $|E_{+} \cdot E_{+}^{*}| = |E_{-} \cdot E_{-}^{*}| = 1$, which makes a = 1; (2) choose a "base direction", i.e., choose a value for ψ , and (3) choose a convention for right-hand and left-hand circular polarization. Normally, the +x (horizontal) axis is chosen as the base direction, i.e., $\psi = 0$. Therefore, dropping the absolute phase factor,

$$E_{\pm} = \frac{1}{\sqrt{2}} \binom{1}{\pm i} \tag{11}$$

Finally, whether E_+ is right-hand or left-hand circular polarization depends on the sign convention chosen (optics or IEEE) and whether the implicit time harmonic factor is $e^{i\Theta}$ or $e^{-i\Theta}$, where $\Theta = \omega t - kz$. These choices are summarized in Table 1.

2.3 SCATTERING MATRIX THEORY

When a target is illuminated by a plane wave transmitted from an antenna with a transmit polarization, $\vec{a}$, the backscattered complex voltage, V, collected at the terminals of the receiver antenna with receive polarization, $\vec{b}$, may be expressed as*

$$V = S\vec{a} \cdot \vec{b} \tag{12}$$

where S is the 2x2 complex scattering operator, or matrix, that characterizes the target's scattering properties.

*The scalar product between two complex vectors $\vec{x} = (x_1, x_2)$ and $\vec{y} = (y_1, y_2)$ is defined here as $\vec{x} \cdot \vec{y} = x_1 y_1 + x_2 y_2$.

TABLE 1. RIGHT-HAND AND LEFT-HAND CIRCULAR POLARIZATION CONVENTIONS.

$\vec{E}_+ = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}$		CONVENTION	
		OPTICS	IEEE
TIME HARMONIC FACTOR	$e^{i\theta}$	RHC	LHC
	$e^{-i\theta}$	LHC	RHC

$\vec{E}_- = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-i\end{bmatrix}$		CONVENTION	
		OPTICS	IEEE
TIME HARMONIC FACTOR	$e^{i\theta}$	LHC	RHC
	$e^{-i\theta}$	RHC	LHC

$\theta = \omega t - kz$
RHC = Right-Hand Circular
LHC = Left-Hand Circular

The units of the scattering matrix are determined when the units of $\vec{a}$ and $\vec{b}$ in Equation (12) are defined. The units of S vary from user to user, and various systems of units have been employed. However, one of the more common systems employed is the following: Let

$$\vec{a} = a_o \hat{a} \tag{13}$$

$$\vec{b} = b_o \hat{b}$$

where $\hat{a}$ and $\hat{b}$ are the normalized, unitless polarization vectors that represent the transmit and receive antenna polarization, respectively, and a_o and b_o are scalars that are defined such that the scattering matrix can now be defined by the equation

$$\sigma_{ab} = \left| S\hat{a} \cdot \hat{b} \right|^2 \tag{14}$$

where σ_{ab} is the radar cross section (RCS) that appears in the radar range equation and has the units of square meters. (The subscripts a and b appear on the symbol for RCS, σ, as a reminder that RCS does indeed depend on the polarizations of the transmit and receive antennas.) The product $a_o b_o$, therefore, has the units of volts/meter and includes all radar-target range dependencies. Adopting this definition, the scattering matrix has the units of meters.

The vectors $\hat{a}$ and $\hat{b}$ and the scattering matrix S are expressible in terms of a two-dimensional complex basis, usually linear

$$\hat{x} = \binom{1}{0}; \; \hat{y} = \binom{0}{1} \tag{15}$$

or circular. If a linear basis is used, then S is given by

$$S = \begin{bmatrix} HH & VH \\ HV & VV \end{bmatrix} \tag{16}$$

where, for example, HV is the complex scattering amplitude received from the target with a vertically polarized antenna when a horizontally polarized wave was transmitted.

An eigenvalue analysis of the scattering matrix yields physical insight into the scattering process. The characteristic eigenvalue problem for the scattering matrix is given by*

$$S\hat{a} = s\hat{a}^* \tag{17}$$

where * denotes complex conjugation. There are two solutions (eigenvectors) to Equation (17), $\hat{a}_1$ and $\hat{a}_2$, with corresponding eigenvalues s_1 and s_2. The orthonormal eigenvectors of Equation (17) can be written as

$$\hat{a}_1 = e^{\psi J} e^{\tau K} \hat{x}$$

$$\hat{a}_2 = e^{(\psi+\pi/2)J} e^{-\tau K} \hat{x} \tag{18}$$

As indicated above, the parameter τ determines the "ellipticity" of the polarization (0° for linear, $\pm 45^\circ$ for circular) and has the range $-45^\circ \leq \tau \leq 45^\circ$. It is a measure of

---

*The complex conjugate appears in Equation (17) due to the fact that the relevant eigenvalue problem here is to find the transmit polarization which, when scattered from the target, will be proportional to the optimum receive polarization of the transmitting antenna.

target symmetry with respect to right and left circular polarization (0° for symmetric, $\pm 45^\circ$ for totally non-symmetric). The parameter ψ determines the angle which the major axis of the elliptical polarization makes with respect to $\hat{x}$ and has the range $-90^\circ \leqslant \psi \leqslant 90^\circ$. It is a measure of the orientation of the target.

The associated eigenvalues can be expressed as

$$s_1 = me^{i2\nu} \tag{19}$$

$$s_2 = m\tan^2\gamma e^{-i2\nu}$$

where the parameter ν is related to the number of bounces of the reflected signal and has the range $-45^\circ \leqslant \nu \leqslant 45^\circ$. The parameter γ is the target polarizability angle and has the range $0^\circ \leqslant \gamma \leqslant 45^\circ$. It is a measure of the target's ability to polarize incident unpolarized radiation (0° for fully polarized, 45° for unpolarized). Finally, the parameter m provides an overall measure of target size or radar cross section. It is the amplitude of the maximum return from the target, i.e., the amplitude of the optimum polarization that maximizes the radar cross section of the target.

The relative scattering matrix (equivalent to the scattering matrix to within a phase factor) can thus be expressed in terms of the five physically relevant parameters $(m, \psi, \tau, \nu, \gamma)$, as

$$S = U^* \begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix} U^+ \tag{20}$$

where + denotes the Hermitian adjoint and U is the unitary matrix given by

$$U = [\hat{a}_1, \hat{a}_2] \tag{21}$$

The scattering matrices (in the H,V basis) and their associated five physically relevant parameters are shown in Table 2 for some simple targets.

TABLE 2. SCATTERING MATRICES AND PARAMETERS OF SOME SIMPLE TARGETS.

TARGET	SCATTERING MATRIX	ψ	τ	ν	γ
FLATPLATE, TRIHEDRAL, SPHERE	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	arbitrary	0^0	0^0	45^0
DIPLANE AT $\psi = \psi_a$	$\begin{bmatrix} \cos 2\psi_a & \sin 2\psi_a \\ \sin 2\psi_a & -\cos 2\psi_a \end{bmatrix}$	ψ_a	0^0	$\pm 45^0$	45^0
HELIX	$1/2 \begin{bmatrix} 1 & \pm i \\ \pm i & 1 \end{bmatrix}$	arbitrary	$\pm 45^0$	arb.	0^0

SECTION 3
POLARIMETRIC REQUIREMENTS CONSIDERATIONS FOR SCATTERING MATRIX MEASUREMENTS

3.1 INTRODUCTION

In this section, polarimetric requirements for the 35 GHz Test Bed SAR are discussed. Transmit and receive antenna polarizations are considered and a simple polarization switching network enabling polarization agility is presented. Polarization channel isolation requirements, measurement time scales, and bandwidth contraints are also considered. Finally, scattering matrix data formats and calibration targets are discussed.

3.2 TRANSMIT AND RECEIVE ANTENNA POLARIZATIONS

The optimum transmit and receive antenna polarizations for measuring scattering matrices are those that give strong signal-to-noise ratios in all channels. If the radar receiver is not sensitive enough to measure a small return in one or more channels, then the measured signal in those channels will be zero or noise-corrupted, depending on the setting of the receiver threshold. An accurate signal measurement in all channels is critical to target discrimination/identification performance.

Since a polarization transmit-receive (TR) pair should be chosen such that, for the target being measured, a strong signal is obtained in all channels, polarization TR pairs that are eigenvectors of the target scattering matrix should be avoided. These polarization TR pairs will produce a null in the cross-polarization channel, i.e., a "cross-pol" null. Also, those polarization TR pairs that produce nulls in the co-polarized channel, i.e., "co-pol" nulls, should be avoided.

An example of how using co-pol or cross-pol nulls for the polarization TR pair can produce problems in target measurements is given in radar meteorology. In polarimetric meteorological radars, measuring the canting angle of raindrops is of interest. Since raindrops are nearly spherical objects, the horizontal and vertical polarizations are nearly cross-pol nulls, and the right-hand circular and left-hand circular polarizations are nearly co-pol nulls of the raindrops. Signals in the cross-polarized channel for the H,V pair and the co-polarized channel for the R,L pair may be 30 dB or more down from the signals in corresponding orthogonal channel. This can be a serious problem, since an accurate measurement of signals in these channels is crucial for raindrop canting-angle determination.

The most obvious choice for a polarization TR pair for measuring scattering matrices might seem to be the horizontal, vertical (H,V) polarization pair. However, this pair may not be an optimum choice for measuring scattering matrices from man-made targets. Some man-made targets tend to be symmetric ($\tau = 0^{\circ}$) with scatterers oriented horizontally and vertically ($\psi = 0^{\circ}, \pm 90^{\circ}$). Thus, the eigenvectors of the resulting scattering matrices will be nearly the H,V polarization pair. This results in the cross-polarized channel (HV) return being significantly less than the co-polarized channel (HH or VV) returns. Shown in Table 3 are the average radar cross sections (RCSs) at 35 GHz for a military vehicle for six polarization channels. The RCSs were averaged over 360° of aspect angle. As can be seen from this table, the HV return is more than 12 dB down from the HH or VV return.

The R,L polarization TR pair would be more optimum in measuring the scattering matrices from man-made targets. For the military vehicle (as evidenced in Table 3), the signal in the cross-polarized channel (RL) is now the dominant signal (being approximately equal to the signals in the HH or VV channels), and the signals in the co-polarized channels are only approximately 5 dB down from it. Still, the R,L polarization pair is less than optimal in many cases, especially for simple scatterers.

TABLE 3. 35 GHZ RADAR CROSS SECTIONS OF A MILITARY VEHICLE AVERAGED OVER 360° OF ASPECT ANGLE.

$\|HH\|^2 = 24.8$	$\|RR\|^2 = 18.9$
$\|VV\|^2 = 24.5$	$\|LL\|^2 = 19.0$
$\|HV\|^2 = 12.3$	$\|LR\|^2 = 24.1$

(ALL VALUES IN dBsm)

The R,L polarizations are co-pol nulls for spheres, flat plates, and trihedral corner reflectors, while they are cross-pol nulls for a dihedral corner reflector. The H,V polarizations are cross-pol nulls for spheres, flat plates, trihedrals, and (horizontally or vertically oriented) dihedrals. Therefore, for these scatterers (or targets made up of these type scatterers), a more optimal polarization TR scheme would be to mix polarization pairs, i.e., transmit R and L polarizations and receive H and V polarizations. This polarization scheme results in equal signal amplitudes in all four channels (RH, RV, LH, LV) for the simple scatterers above.

The best polarization TR configuration for a radar that is to measure scattering matrices is a polarization agile on transmit and receive configuration. This way, a polarization adaptable radar system becomes feasible. In such a radar system, all polarization channels could be monitored, and the transmit and receive polarizations could be adapted to optimize the return in the channels. To obtain any arbitrary transmit polarization desired, one must be able to arbitrarily vary the power ratio and relative phase between the two basis polarization channels. An example of a simple polarization switching network that accomplishes this and therefore permits polarization agility on transmit (with co-polarized and cross-polarized channels on receive) is shown in Figure 2. The signal from the transmitter is first sent through a low-loss variable power splitter. This power splitter consists of two hybrid ("magic tee") junctions, a variable phase shifter (No. 1), and an attenuator to account for any phase shifter insertion loss. The signal from the transmitter is introduced into one port of the first hybrid junction, and the setting of the variable phase shifter determines the power ratio of the signals out of the second hybrid junction. Another variable phase shifter (No. 2) in one of the output channels (with a loss-matching attenuator in the other channel) provides for the desired relative phase shift

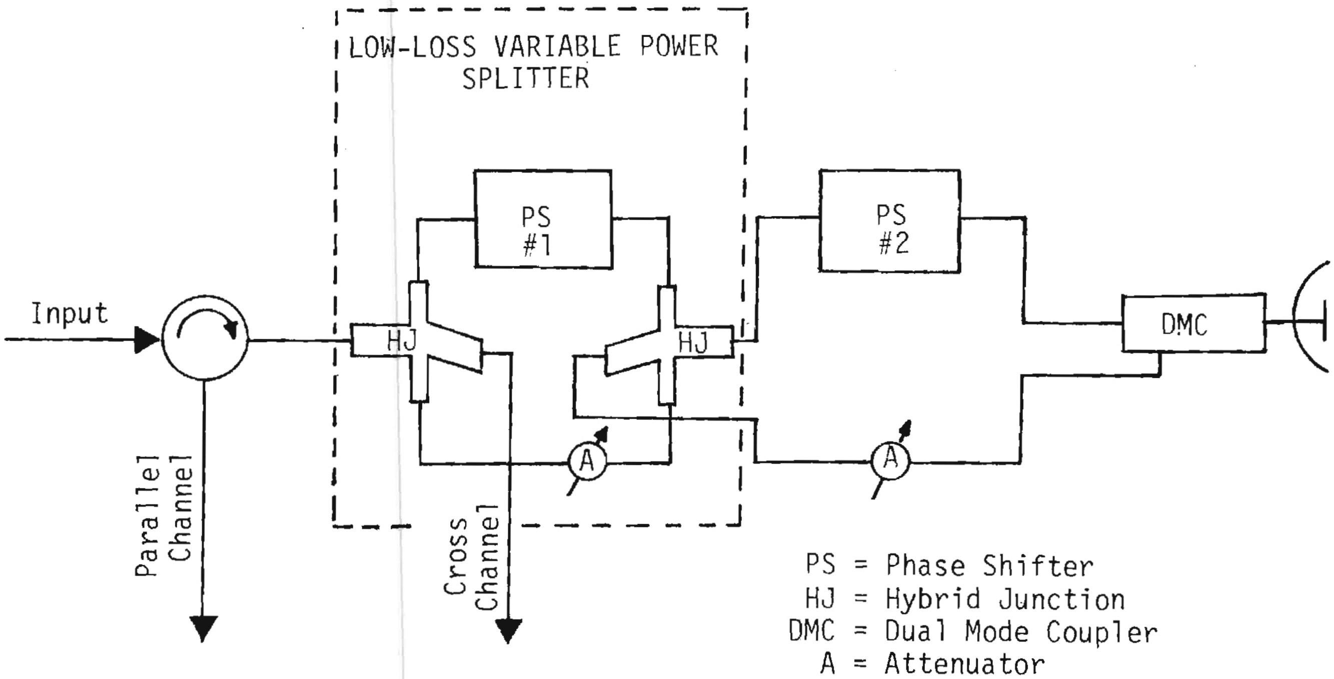


Figure 2. Polarization Switching Network.

between channels. The return signal from the target is automatically split into a co-polarized (parallel) channel and a cross-polarized (cross) channel, unless a change is made in the phase shifters before reception of the signal.

3.3 POLARIZATION CHANNEL ISOLATION

Sufficient isolation between polarization channels is required to make accurate scattering matrix measurements. The amount of isolation needed before a significant degradation in the performance of scattering matrix discrimination/identification algorithms is realized, however, is not known. This is due to the immaturity in the current state of the art of the scattering matrix discrimination/identification algorithm technology.

An analytic method to determine the isolation required for accurate scattering matrix measurements is an follows: A given relative scattering matrix can be represented as a point in a five-dimensional space, each point representing a different scattering matrix "value." A five-dimensional neighborhood can be defined around that point. The four-dimensional surface of this neighborhood is defined (by some criterion to be determined) such that all points within the "interior" of the surface represent acceptable approximations to the true "value" for the scattering matrix. Next, inter-polarization-channel leakage is permitted, which will cause the measured scattering matrix point to wander from the actual scattring matrix point. The maximum allowable leakage (minimum allowable isolation) is determined by the minimum amount of leakage that causes the measured point to wander outside of the neighborhood. The performance dependence of polarimetric discrimination/identification algorithms on this neighborhood is unknown at this time, thus preventing implementation of this analytic solution.

In radar meteorology where polarimetric radars have been in use for some time, polarization channel isolations in excess of 30 dB are required in some applications. Some radar meteorological researchers have even claimed that isolations in excess of 40 dB are required.[3]

A probable absolute minimum level of polarization channel isolation required for scattering matrix measurements of ground targets and clutter is 20 dB. An isolation of 30 dB would probably be enough to guarantee no significant degradation in scattering matrix discrimination/identification algorithm performance due to inter-channel leakage.

3.4 MEASUREMENT TIME SCALES

For a non-stationary target (or non-stationary radar sensor), the scattering matrix measurement should be taken "instantaneously." If reciprocity is assumed, a minimum of three measurements, e.g., HH, VV, VH, must be made to determine the scattering matrix. This requires that two separate polarization transmissions be made. Thus, an "instantaneous" scattering matrix measurement is not possible. However, an adequate "near-instantaneous" measurement can be made.

An adequate "near-instantaneous" scattering matrix measurement time is one that is much less than the decorrelation time of the target's signal, which is a function of target/sensor motion, target type, and transmit frequency. As an example of decorrelation times, the radar return from a wind blown tree (as measured by a stationary sensor) decorrelates in approximately 200 ms or greater (at X-band) for a tree in a gentle breeze (< 2 MPH) and in less than 1 ms (at 95 GHz) for a tree in a 15 MPH wind.[4]

Scattering matrix measurements can be made with a pulsed radar using a pulse-pair, assuming that the radar has inter-pulse polarization agility. The measurement time will thus be the inverse of the pulse repetition frequency (PRF), which can be made arbitrarily high (subject to other design contraints such as maximum unambiguous range requirements, duty cycle limitations, etc.). With an intra-pulse polarization agile radar (IPAR) scattering matrix measurements can be made using a single pulse; the measurement time is essentially the radar's pulse width.

The 35 GHz Test Bed SAR will be a pulsed radar system with inter-pulse polarization agility. Therefore, a scattering matrix sample can be taken with a pulse-pair. Since the radar is on a moving platform, there will be a platform-induced phase shift in the signal between the pulses of the pulse-pair used to sample the scattering matrix. Indeed, it is this phase shift that allows the SAR to achieve a high cross-range resolution. However, this phase shift must be accounted for to ensure accurate scattering matrix measurements. In addition, the target Doppler frequency as measured in one polarimetric channel will differ slightly from the target Doppler frequency as measured in another polarimetric channel when the two channels are measured on different pulses of the pulse-pair, e.g., HH and VV. However, with a long enough aperture time, this frequency difference between channels will be much less than the frequency resolution of the SAR. For example, given the current parameters envisioned for the Test Bed SAR, this frequency difference is estimated to be approximately 1/6 of the Test Bed SAR's frequency resolution.

Sometimes it becomes necessary to make a scattering matrix measurement over an extended period of time (hundreds to thousands of milliseconds) such that the target return has partially or totally decorrelated during the measurement time. This may be necessary to enhance signal-to-noise ratios (by integrating many pulses) achieve high range resolution (by pulse-to-pulse frequency stepping), or achieve high cross-range resolution (by SAR techniques). In the case of the 35 GHz Polarimetric Test Bed SAR, long aperture times will be necessary to realize the desired cross-range resolution. This aperture time may be longer than the decorrelation times of some of the return signals. However, as long as each scattering matrix sample, e.g., each pulse-pair, is measured "instantaneously," valid scattering matrix data will be obtained. The scattering matrix measurement in this instance does not provide "instantaneous" target data, but "time-averaged" target data, i.e., data of a partially or totally decorrelated target, which are still useful data. It is a matter of perception. The human eye, for example, perceives the wings of a Hummingbird in flight as a continum, whereas a high-speed camera perceives them as discrete wings. Both perceptions are valid and useful.

3.5 BANDWIDTH CONSIDERATIONS

The scattering matrix is defined for a monochromatic (single frequency) signal, and the scattering matrix theory developed in Section 2 is based on such signals. However, all real signals have a finite bandwidth. The effect of using real finite bandwidth signals instead of the idealized zero-bandwidth signals should be negligible as long as the bandwidth of the real signal is a small percentage of the signal's center frequency.

A target made up of discrete scatterers has two basic effects on a finite bandwidth signal when scattering that signal. The first effect, which is due to (and is a function of) the different spatial locations of the scatterers, is an interference effect among the spectral components of the signal. The second effect is due to any possible frequency dependence of the individual scatterers themselves.

The interference effect is a desirable effect, since it is this effect that produces range and cross-range resolution; the resolution obtainable is dependent on signal bandwidth. Signal bandwidth is obtained by transmitting a pulse or frequency-coded waveform (for range resolution) and/or by receiving a band of Doppler-shifted signals (for cross-range resolution). In any event, here the finite bandwidth of the signal is used for resolution, and if the scatterers themselves are relatively frequency independent, then the signal is essentially measured at the center frequency (RF) and bandwidth has little effect.

As an example, consider a transmitted pulse of pulse width τ. The magnitude of the frequency spectrum of the pulse is the familiar (sin x)/x curve centered at the RF with a bandwidth approximately equal to $1/\tau$. The return signal from a single scatterer is also a rectangular pulse, whose amplitude (corrected for antenna gain, range, etc.) is equal to the scattering amplitude of the scatterer at the center frequency (RF) of the transmitted waveform. If a synchronous (I/Q) detector is employed, the amplitudes of the returned pulses in the two (I/Q) channels are the rectangular components of one of the complex elements of the scattering matrix. Therefore, by sampling in the center region of the return pulses, finite bandwidth effects are negligible.

If the individual scatterers themselves have a frequency dependence, then the primary effect of this frequency dependence on a finite bandwidth signal will be to reduce resolution. However, this frequency dependence could also produce results obtained with a finite bandwidth signal that vary from those that would be obtained with an idealized zero-bandwidth signal. If the bandwidth-to-RF ratio, β, of the signal is small though, then these frequency dependence effects should be small. For example, a trihedral corner reflector's RCS varies as the square of the frequency. Thus, the change in RCS of a trihedral over the bandwidth of the signal is well approximated by 2β, which in all practical examples will be a fraction of a decibel. Therefore, these RCS variations due to the trihedral's frequency dependence can be neglected in most cases.

3.6 SCATTERING MATRIX DATA FORMAT REQUIREMENTS

The output of the 35 GHz Polarimetrtic Test Bed SAR will be a scattering matrix for each resolution cell or pixel. A resolution cell is defined by the SAR's range and cross-range resolutions. For target discrimination/identification purposes, only the relative scattering matrix (equivalent to the scattering matrix to within a phase factor) is required. The relative scattering matrix can be specified (assuming matrix symmetry) by measuring three amplitudes and two relative phases of the four complex numbers that make up the scattering matrix. Therefore, these five parameters would be the only ones required <u>if only data taken at the SAR's range and cross-range resolutions is of interest</u>.

However, interest does exist within the data-user community in obtaining full polarimetric data at range and cross-range resolutions less than that of the Test Bed SAR. Therefore, the data need to be "resolution degradable" so that scattering matrices can be obtained at any resolution less than the Test Bed SAR's. Providing <u>full</u> scattering matrix data for each SAR resolution cell will allow for this capability. This requires providing the amplitude and phase data for all four polarimetric channels (three if reciprocity is assumed).

3.7 POLARIMETRIC CALIBRATION TARGETS

Polarimetric calibration targets will be required in order to check the calibration of the Test Bed SAR. Either active or passive targets could be used. However, passive targets are recommended since they permit a true two-way calibration check of the radar system. In addition, passive calibration targets are much easier to maintain than active calibration targets.

A calibration target is one of known RCS for the polarimetric channel being tested or calibrated, and it should produce a strong signal in that channel. Therefore, the types of calibration targets chosen will depend on the polarization transmit-receive pair chosen for the Test Bed SAR. For simplicity, only the H,V polarization pair and the R,L polarization pair will be considered here.

No one calibration target will produce a maximum signal in all four polarization channels (although a target can be made to produce equal (sub-maximum) signals in all four channels). Calibration targets can be made that produce a maximum signal in two of the four channels while producing a null signal in the other two channels. Checking the calibration of the Test Bed SAR with such calibration targets will thus require two calibration runs with two separate calibration targets.

For the H,V polarization pair and the R,L polarization pair, the recommended calibration targets are the trihedral corner reflector and the dihedral corner reflector. The maximum RCS for a triangular-sided trihedral is given by

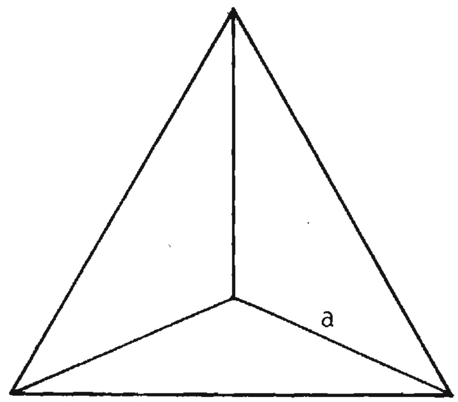
$$\sigma_{max} = \frac{4\pi a^4}{3\lambda^2} \quad \text{(trihedral)} \qquad (22)$$

where the dimension a is shown in Figure 3, and λ is the wavelength of the transmitted signal. The maximum RCS for a dihedral is given by

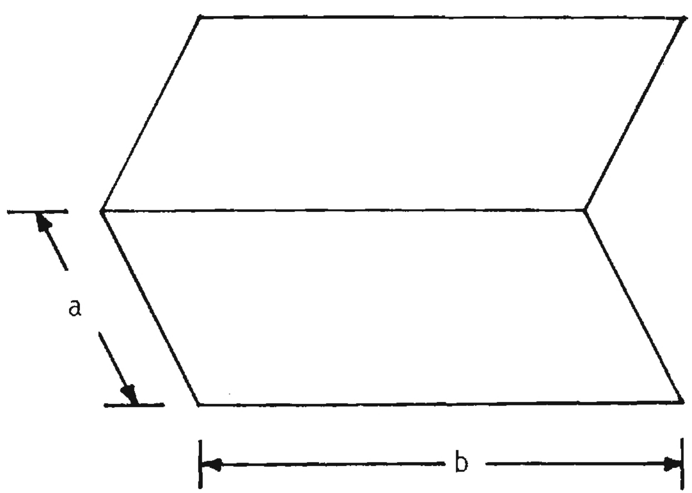
$$\sigma_{max} = 8\pi\left(\frac{ab}{\lambda}\right)^2 \quad \text{(dihedral)} \qquad (23)$$

where the dimensions a and b are shown in Figure 3.

For the H,V polarization transmit-receive pair, the trihedral gives maximum signals in the HH and VV channels and minimum (theoretically null) signals in the VH and HV channels. The same results are obtained for the dihedral when it is oriented horizontally (the b dimension in Figure 3) or



(A)



(B)

Figure 3. (A) Trihedral Corner Reflector, and
(B) Dihedral Corner Reflector.

vertically. If the dihedral is oriented at a 45^{o} angle, then maximum signals are obtained in the VH and HV channels and minimum signals are obtained in the HH and VV channels.

For the R,L polarization transmit-receive pair, the trihedral gives maximum signals in the LR and RL channels and minimum signals in the RR and LL channels. The dihedral gives (independent of orientation angle) maximum signals in the RR and LL channels, and minimum signals in the LR and RL channels.

A summary of the polarization properties of the tridedral and dihedral corner reflectors is given in Table 4.

3.8 SUMMARY

In summary, the optimal transmit and receive antenna polarizations for the 35 GHz Test Bed SAR can be obtained by employing a polarization switching network as shown in Figure 2 to obtain polarization agility. For a fixed polarization system, the best polarization configuration is to transmit R and L and to receive H and V. The transmit and receive H and V configuration is not the optimum choice for measuring scattering matrices from man-made objects due to the resulting small return signals in the cross-polarization channels. Of course, this will not be a problem if enough receiver sensitivity is available.

A polarization isolation of 30 dB is probably enough to guarantee no significant degradation in scattering matrix discrimination/identification algorithm performance due to inter-polarization-channel leakage.

The only mesurement time restriction on the Test Bed SAR is that scattering matrix samples, i.e., pulse-pairs of data, should be collected in times much less than the decorrelation times of the target and clutter. A phase correction must be applied to correct for sensor platform motion between pulses of the pulse-pair.

TABLE 4. SIGNAL STRENGTHS IN POLARIZATION CHANNELS FOR VARIOUS CALIBRATION TARGETS.

<table>
<tr><th rowspan="3">POLARIZATION CHANNEL</th><th colspan="3">CALIBRATION TARGET</th></tr>
<tr><th rowspan="2">TRIHEDRAL</th><th colspan="2">DIHEDRAL</th></tr>
<tr><th>HORIZONTAL/ VERTICAL</th><th>45^{o} ANGLE</th></tr>
<tr><td>HH</td><td>MAX</td><td>MAX</td><td>MIN</td></tr>
<tr><td>VV</td><td>MAX</td><td>MAX</td><td>MIN</td></tr>
<tr><td>VH</td><td>MIN</td><td>MIN</td><td>MAX</td></tr>
<tr><td>HV</td><td>MIN</td><td>MIN</td><td>MAX</td></tr>
<tr><td>RR</td><td>MIN</td><td colspan="2">MAX</td></tr>
<tr><td>LL</td><td>MIN</td><td colspan="2">MAX</td></tr>
<tr><td>LR</td><td>MAX</td><td colspan="2">MIN</td></tr>
<tr><td>RL</td><td>MAX</td><td colspan="2">MIN</td></tr>
</table>

MAX = MAXIMUM STRENGTH
MIN = MINIMUM STRENGTH

The finite bandwidth signals of the Test Bed SAR used to measure the scattering matrices will not have any substantial detrimental effect on the collected data if the bandwidth-to-RF ratio is small.

The scattering matrix data format should consist of amplitude and phase data for all four polarization channels for each resolution cell so that the data can be "resolution degradable."

Polarimetric calibration targets should be passive, and trihedral and dihedral corner reflectors are recommended for the H,V and R,L polarization transmit-receive pairs.

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