A Convenient Technique For Polarimetric Calibration of Single-Antenna Radar Systems

KAMAL SARABANDI AND FAWWAZ T. ULABY, FELLOW, IEEE

Abstract—**This paper introduces a practical technique for calibrating single-antenna polarimetric radar systems. With this technique, only a single calibration target, such as a conducting sphere or a trihedral corner reflector, is needed to calibrate the radar system, both in amplitude and phase, for all linear polarization configurations. By using a metal sphere, which is orientation independent, error in calibration measurement is minimized while simultaneously calibrating the cross-polarization channels.**

The antenna system and two orthogonal channels (in free space) are modeled as a four-port passive network. Upon using the reciprocity relations for the passive network and assuming the cross-coupling terms of the antenna to be equal, the cross-talk factors of the antenna system and the transmit and receive channel imbalances can be obtained from measurement of the backscatter from a metal sphere. For an *X*-band radar system with cross-polarization isolation of 25 dB, comparison of values measured for a sphere and a cylinder with theoretical values shows agreement within 0.4 dB in magnitude and 5° in phase. Also, an effective polarization isolation of 50 dB is achieved using this calibration technique.

I. Introduction

Accurate knowledge of the scattering matrix of a target is an important ingredient for extracting biophysical information about the target. The scattering matrix of a target can be measured by using a set of orthogonal polarization. In practice, however, it is very difficult, if not impossible, to design an antenna system with perfect isolation between the orthogonal polarization channels, which leads to contamination of the measurements.

In recent years, considerable effort has been devoted to the development of techniques for calibrating polarimetric radar systems. Calibration techniques available in the literature can be categorized into two major groups: 1) calibration techniques for imaging radars, and 2) calibration techniques for point-target measurement systems, which may also be appropriate for imaging radars. In the first group, the scattering properties of clutter are usually employed to simplify the calibration problem [5]. van Zyl [6] and Klein [3] developed a method for estimating the cross-talk contamination of the antenna by assuming that the like- and cross-polarized responses of natural targets with azimuthal symmetry are uncorrelated. Among the point-target calibration techniques, the generalized calibration technique (GCT) by Whitt *et al.* [7] characterizes the distortion matrices (channel imbalances and antenna cross-talk) of the receive and transmit antenna by using three calibration targets. An eigenvalue approach is employed to solve for the distortion matrices. In a similar technique by Barnes [1], the distortion matrices are obtained by using targets with specific scattering matrices. This technique is referred to by Whitt *et al.* [7] as the constrained calibration technique (CCT). Although, in principle, GCT and CCT can fully characterize the distortion matrices, they are very sensitive to target alignment and to the knowledge of the theoretical values of the scattering matrices of the calibration targets. A third calibration technique for point targets by Sarabandi *et al.* [4] uses a sphere and any other depolarizing calibration target (scattering matrix of this target need not to be known), and is therefore immune to errors caused by target orientation and lack of precise knowledge of the theoretical values of the calibration targets' scattering matrices. However, the drawback of this method, which is called the isolated-antenna calibration technique (IACT), is that it does not account for cross-talk contamination in the antenna. The isolated antenna assumption can lead to significant errors in the cross-polarized terms when the ratio of cross- to like-polarized terms is small and/or cross-talk contamination is large.

To remove the drawback of the IACT while maintaining insensitivity to orientation of the calibration targets, we introduce in this paper a technique for calibrating single-antenna radar systems using a four-port network approach. The antenna system and two orthogonal directions in free space are modeled as a four-port network, and channel imbalances as well as the antenna cross-talk contamination are determined by measuring the backscatter from a single calibration target, namely, a conducting sphere. This technique will henceforth be referred to as STCT, or single-target calibration technique. Like IACT, STCT is insensitive to target orientation, but it also accounts for the antenna cross-talk contamination. If the antenna cross-talk contamination is very small (≈ 0), the STCT is not appropriate and the IACT should be used instead.

The validity and accuracy of this technique were tested using *X*-band and *L*-band scatterometers, both in an anechoic chamber and under field conditions. Cylinders and spheres were used as test targets. Excellent agreement was

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The authors are with the Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122.

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obtained between the measured and theoretical values of the test target. Also, the effective cross-polarization isolation obtained in this method was on the order of 50 dB.

II. Theoretical Formulation

By defining a set of orthogonal directions in a plane perpendicular to the direction of propagation, the field components of the wave scattered by a given point target can be related to the components of the incident plane wave through the scattering matrix of the target s. The antenna structure of a polarimetric radar system must be designed in such a way that the transmit and receive polarizations are parallel to the specified orthogonal directions. In practice, however, it is not possible to construct antennas that are totally free of polarization contaminations; i.e., coupling between the orthogonal polarization ports of the antenna. Polarization contamination (antenna cross-talk) takes place in the orthogonal mode transducer (OMT) and in the antenna structure itself.

Suppose the two orthogonal directions in free space are viewed as two ports of a four-port passive device that includes the OMT and the antenna structure (see Fig. 1). This four-port network can be characterized by a scattering matrix $\mathcal{S}$ which relates the incident wave vector $\boldsymbol{V}^+$ to the reflected wave vector $\boldsymbol{V}^-$

$$\boldsymbol{V}^- = \mathcal{S}\boldsymbol{V}^+$$

where

$$\mathcal{S} = \begin{bmatrix} \mathcal{S}_{11} & \mathcal{S}_{12} & \mathcal{S}_{13} & \mathcal{S}_{14} \\ \mathcal{S}_{21} & \mathcal{S}_{22} & \mathcal{S}_{23} & \mathcal{S}_{24} \\ \mathcal{S}_{31} & \mathcal{S}_{32} & \mathcal{S}_{33} & \mathcal{S}_{34} \\ \mathcal{S}_{41} & \mathcal{S}_{42} & \mathcal{S}_{43} & \mathcal{S}_{44} \end{bmatrix}. \tag{1}$$

Since the four-port device is passive, its scattering matrix must be symmetric. Thus,

$$\mathcal{S}_{ij} = \mathcal{S}_{ji} \qquad i, j \in \{1, 2, 3, 4\}.$$

If the reference plane of the nth port is translated outward by distance l_n, the new scattering matrix for the device becomes [2]

$$\mathcal{S}' = \Theta \mathcal{S} \Theta \tag{2}$$

where the translation matrix Θ is given by

$$\Theta = \begin{bmatrix} e^{-i\beta_1 l_1} & 0 & 0 & 0 \\ 0 & e^{-i\beta_2 l_2} & 0 & 0 \\ 0 & 0 & e^{-i\beta_3 l_3} & 0 \\ 0 & 0 & 0 & e^{-i\beta_4 l_4} \end{bmatrix}. \tag{3}$$

In (3), β_n is the propagation constant of the nth port transmission line. In this case, since ports 3 and 4 are two ports in free space, $\beta_3 = \beta_4 = k_0$, and the translation matrix must be modified to account for spherical propagation. If the target is located at a distance r from the radar system and the reference planes at ports 3 and 4 are translated to

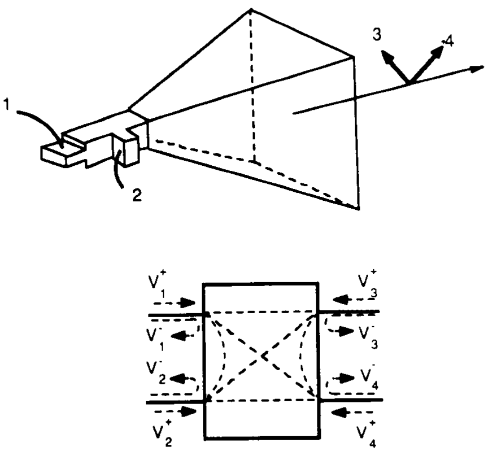

Fig. 1. Antenna system and its equivalent circuit four-port representation.

the target location, then the translation matrix becomes

$$\Theta = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \dfrac{e^{-ik_0 r}}{r} & 0 \\ 0 & 0 & 0 & \dfrac{e^{-jk_0 r}}{r} \end{bmatrix}$$

The scattering matrix, after translation of the reference planes of ports 3 and 4 by distance r, takes the following form:

$$\mathcal{S}' = \begin{bmatrix} \mathcal{S}_{11} & \mathcal{S}_{12} & \mathcal{S}_{13}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{14}\dfrac{e^{-ik_0 r}}{r} \\ \mathcal{S}_{21} & \mathcal{S}_{22} & \mathcal{S}_{23}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{24}\dfrac{e^{-ik_0 r}}{r} \\ \mathcal{S}_{31}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{32}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{33}\dfrac{e^{-2ik_0 r}}{r^2} & \mathcal{S}_{34}\dfrac{e^{-2ik_0 r}}{r^2} \\ \mathcal{S}_{41}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{42}\dfrac{e^{-ik_0 r}}{r} & \mathcal{S}_{43}\dfrac{e^{-2ik_0 r}}{r^2} & \mathcal{S}_{44}\dfrac{e^{-2ik_0 r}}{r^2} \end{bmatrix}. \tag{4}$$

Note that here we have ignored the gain and effective area of the transmit and receive antennas which will be included in the channel imbalances. The signal flow chart of the antenna system and free space ports is shown in Fig. 2. Suppose the radar is equipped with a space discriminating filter (range gating filter) which is tuned at r. The filtered scattering matrix ($\mathcal{S}''$) is then given by

$$\mathcal{S}'' = \begin{bmatrix} 0 & 0 & \mathcal{S}_{13} & \mathcal{S}_{14} \\ 0 & 0 & \mathcal{S}_{23} & \mathcal{S}_{24} \\ \mathcal{S}_{31} & \mathcal{S}_{32} & 0 & 0 \\ \mathcal{S}_{41} & \mathcal{S}_{42} & 0 & 0 \end{bmatrix} \frac{e^{-ik_0 r}}{r}.$$

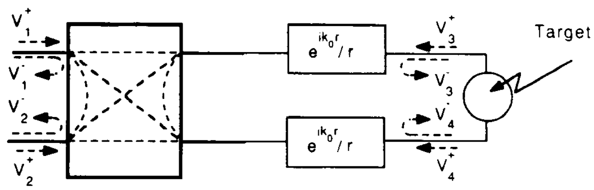

Fig. 2. Signal flow chart of the antenna system, free space, and the target.

Basically, short-range reflections from the antenna system and multiple bounces between the antenna and the target have been gated out. The incident and reflected waves at each port can now be represented by two uncoupled matrix equations as follows:

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \frac{e^{-ik_0 r}}{r} \begin{bmatrix} \mathcal{S}_{13} & \mathcal{S}_{14} \\ \mathcal{S}_{23} & \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} V_3^+ \\ V_4^+ \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} V_3^- \\ V_4^- \end{bmatrix} = \frac{e^{-ik_0 r}}{r} \begin{bmatrix} \mathcal{S}_{31} & \mathcal{S}_{32} \\ \mathcal{S}_{41} & \mathcal{S}_{42} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}. \tag{6}$$

On the other hand, the incident and reflected waves at ports 3 and 4 are the scattered and incident waves, respectively, of the target, which is represented by a two-port network, and are thus related to each other by the scattering matrix of the target s. That is,

$$\begin{bmatrix} V_3^+ \\ V_4^+ \end{bmatrix} = \begin{bmatrix} s_{vv} & s_{vh} \\ s_{hv} & s_{hh} \end{bmatrix} \begin{bmatrix} V_3^- \\ V_4^- \end{bmatrix}. \tag{7}$$

Note that the scattering matrix used here is defined in the backscattering alignment convention since the orthogonal directions are specified independent of the incident and scattering directions. After rearranging (5)–(7) in order to relate the reflected waves to the incident waves at ports 1 and 2, in addition to employing the reciprocity property of the four-port network, we get:

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \frac{e^{-2ik_0 r}}{r^2} \begin{bmatrix} \mathcal{S}_{13} & \mathcal{S}_{14} \\ \mathcal{S}_{23} & \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} s_{vv} & s_{vh} \\ s_{hv} & s_{hh} \end{bmatrix} \cdot \begin{bmatrix} \mathcal{S}_{13} & \mathcal{S}_{23} \\ \mathcal{S}_{14} & \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}. \tag{8}$$

Upon normalizing with respect to the like-polarized channels, (8) becomes

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \frac{e^{-2ik_0 r}}{r^2} \begin{bmatrix} \mathcal{S}_{13} & 0 \\ 0 & \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} 1 & C_1 \\ C_2 & 1 \end{bmatrix} \begin{bmatrix} s_{vv} & s_{vh} \\ s_{hv} & s_{hh} \end{bmatrix} \cdot \begin{bmatrix} 1 & C_2 \\ C_1 & 1 \end{bmatrix} \begin{bmatrix} \mathcal{S}_{13} & 0 \\ 0 & \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \tag{9}$$

where $C_1 = \mathcal{S}_{14}/\mathcal{S}_{13}$ and $C_2 = \mathcal{S}_{23}/\mathcal{S}_{24}$ are the antenna cross-talk factors.

So far, we have modeled the antenna system, free space channel, and the target by a two-port network. To account for the effects of active circuits on the performance of the overall radar system, let us consider the block diagram depicted in Fig. 3. The transmit (V_{tv}, V_{th}) and receive

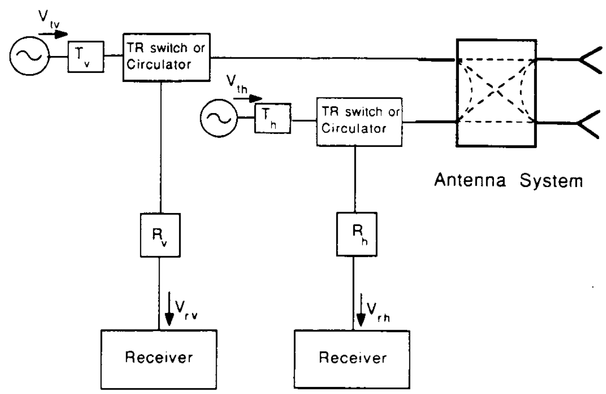

Fig. 3. Simplified block diagram of a typical polarimetric radar.

(V_{rv}, V_{rh}) voltages are the quantities measured by the radar. The channel imbalance quantities (T_v, T_h, R_v, R_h), which relate the transmit/receive voltages to the incident/reflected waves at port 1 and 2, account for variations (in both amplitude and phase) of the active circuits and the antenna gains. The transmit and receive channels of the radar system are separated by a transmit–receive switch (TR switch) or a circulator. These components can be assumed ideal because any leakage that may occur will not be sampled by the range gating process. Therefore the transmit and receive voltages can be related to the incident and reflected voltages of ports 1 and 2 by

$$\begin{bmatrix} V_{rv} \\ V_{rh} \end{bmatrix} = \begin{bmatrix} R_v & 0 \\ 0 & R_h \end{bmatrix} \begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} = \begin{bmatrix} T_v & 0 \\ 0 & T_h \end{bmatrix} \begin{bmatrix} V_{tv} \\ V_{th} \end{bmatrix}. \tag{11}$$

Using (9) in (10) and (11) results in

$$\begin{bmatrix} V_{rv} \\ V_{rh} \end{bmatrix} = \frac{e^{-2ik_0 r}}{r^2} \begin{bmatrix} R_v \mathcal{S}_{13} & 0 \\ 0 & R_h \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} 1 & C_1 \\ C_2 & 1 \end{bmatrix} \begin{bmatrix} s_{vv} & s_{vh} \\ s_{hv} & s_{hh} \end{bmatrix} \cdot \begin{bmatrix} 1 & C_2 \\ C_1 & 1 \end{bmatrix} \begin{bmatrix} T_v \mathcal{S}_{13} & 0 \\ 0 & T_h \mathcal{S}_{24} \end{bmatrix} \begin{bmatrix} V_{tv} \\ V_{th} \end{bmatrix} \tag{12}$$

which may be written in matrix notation as

$$V_r = \frac{e^{-2ik_0 r}}{r^2} \boldsymbol{R C s C^T T} V_t. \tag{13}$$

The matrix $\boldsymbol{M} = \boldsymbol{RCsC^T T}$ represents the measured (uncalibrated) scattering matrix of the target under observation. If the matrices $\boldsymbol{C}$, $\boldsymbol{R}$, and $\boldsymbol{T}$ are known, the actual scattering matrix s can then be obtained. To determine $\boldsymbol{C}$, $\boldsymbol{R}$, and $\boldsymbol{T}$, we note that these matrices depend on the choice of the orthogonal channels in free space. So far, we have made no assumption on the direction of the orthogonal channels (v and h) except that they are perpendicular to the direction of propagation. Once the v and h directions are specified, the scattering matrix of the target can, in principle, be determined. A radar system with linear polarization configurations usually is oriented such that for a given polarization most of the transmitted energy falls into the desired channel; i.e., an orientation for which the antennas' cross-talk factors (C_1 and C_2) are minimal. With available design techniques, it is easy to achieve the conditions $|C_1| \leq 0.1$ and $|C_2| \leq 0.1$, which correspond to a polarization isolation level of 20 dB, but achieving much greater isolation level is difficult. For accurate polarimetric measurements, the effective isolation level should be on the order of 40 dB. Hence the factors C_1 and C_2 may not be ignored, but should instead be determined by the calibration technique.

To demonstrate how the choice of the coordinate frame affects the antennas' cross-talk factors, we obtain a relationship for the cross-talk factors when the coordinate frame is rotated by an angle ψ. Suppose s represents the scattering matrix of a target for a particular coordinate frame, and s' denotes the scattering matrix of the same target when the coordinate frame is rotated around the incidence direction by an angle ψ. It is a trivial matter to show that

$$s' = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} s \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix}. \tag{14}$$

Let us indicate the imbalance and cross-talk matrices in the rotated coordinate system by a prime sign. Since the relative orientation of the antenna system and target have not been changed, the measured scattering matrices for two coordinate systems are identical. That is, $M' = M$. Therefore,

$$M = RCsC^T T = R'C's'C'^T T'. \tag{15}$$

Using (14) in (15) results in

$$M = R'PsP^T T' \tag{16}$$

where

$$P = \begin{bmatrix} \cos\psi + C_1' \sin\psi & -\sin\psi + C_1' \cos\psi \\ \sin\psi + C_2' \cos\psi & \cos\psi - C_2' \sin\psi \end{bmatrix}. \tag{17}$$

Again, by normalizing the diagonal elements of the matrix P to 1 and then comparing the resultant matrices to C, R, and T, it can easily be inferred that

$$C_1 = \frac{-\sin\psi + C_1' \cos\psi}{\cos\psi + C_1' \sin\psi} \tag{18}$$

$$C_2 = \frac{\sin\psi + C_2' \cos\psi}{\cos\psi - C_2' \sin\psi} \tag{19}$$

$$\mathcal{S}_{13} = (\cos\psi + C_1' \sin\psi)\mathcal{S}_{13}'$$

$$\mathcal{S}_{24} = (\cos\psi - C_2' \sin\psi)\mathcal{S}_{24}'.$$

If it is required that maximum energy falls into the v channel when port 1 (v port of the OMT) is energized, the condition $C_1 = 0$ should be enforced, which is equivalent to setting $\psi = \arctan C_1'$. This condition, however, does not maximize the energy transfer into the h channel when the h port of the OMT is energized. Moreover, the cross-talk terms usually are complex quantities, and the above condition may not be achievable. In order to maximize the energy transfer for both channels and simplify the calibration procedure, we look for a rotation angle such that $C_1 = C_2 << 1$; i.e.,

$$\frac{-\sin\psi + C_1' \cos\psi}{\cos\psi + C_1' \sin\psi} = \frac{\sin\psi + C_2' \cos\psi}{\cos\psi + C_2' \sin\psi}$$

which requires that

$$\psi = \frac{1}{2} \arctan \frac{C_1' - C_2'}{1 + C_1' C_2'}. \tag{20}$$

This can be accomplished if both C_1' and C_2' are real quantities. It is relatively easy to design the antenna such that $C_1' \approx C_2'$ to begin with, and then by adjusting the rotation angle using (20), the cross-talk factors can be made even more similar. Therefore, from here on, we shall assume that the antennas' cross-talk factors are identical, and the error associated with this assumption is on the order of the difference in the imaginary parts of the cross-talk factors. In view of this approximation, the measured scattering matrix is given by

$$M = R \begin{bmatrix} 1 & C \\ C & 1 \end{bmatrix} s \begin{bmatrix} 1 & C \\ C & 1 \end{bmatrix} T. \tag{21}$$

III. Calibration Procedure

The relationship between the measured scattering matrix M and the actual scattering matrix of an unknown target is given by (21). If the elements of the imbalance and cross-talk matrices are known, the scattering matrix of the target can be obtained from

$$s = C^{-1} R^{-1} M T^{-1} C^{-1}.$$

The matrices R and T are diagonal, and C is symmetric with known diagonal elements; therefore there is a total of five unknowns that need to be determined. The standard approach is to measure targets with known scattering matrices to establish a set of equations for the unknown elements of the R, T, and C matrices. By measuring each calibration target, four nonlinear equations are obtained, so it seems that at least two targets are needed to find all the five unknowns. But, as will be shown, a sphere or a target with similar scattering matrix (such as a trihedral) is sufficient to characterize the scattering matrix of the unknown target. In fact, it is not required to find all the five unknowns to obtain the scattering matrix of the unknown target.

Upon expanding (21), and noting that for backscattering the scattering matrix is symmetric ($s_{12} = s_{21}$), we get

$$M = R \begin{bmatrix} s_{vv} + 2Cs_{vh} + C^2 s_{hh} & (1 + C^2)s_{vh} + C(s_{vv} + s_{hh}) \\ (1 + C^2)s_{vh} + C(s_{vv} + s_{hh}) & s_{hh} + 2Cs_{vh} + C^2 s_{vv} \end{bmatrix} T. \tag{22}$$

For the sake of simplicity, the diagonal elements of $\boldsymbol{R}$ and $\boldsymbol{T}$ will be denoted by R_i and T_i ($i = 1, 2$), respectively. Measuring a sphere with radar cross section $\sigma^o = 4\pi |s^o|^2$, (22) provides the following set of equations:

$$R_1 T_1 (1 + C^2) = \frac{m_{11}^o}{s^o} \tag{23}$$

$$2 R_1 T_2 C = \frac{m_{12}^o}{s^o} \tag{24}$$

$$2 R_2 T_1 C = \frac{m_{12}^o}{s^o} \tag{25}$$

$$R_2 T_2 (1 + C^2) = \frac{m_{22}^o}{s^o} \tag{26}$$

where m_{ij}^o denotes the ijth elements of the measured scattering matrix of the sphere. The cross-talk term can be obtained by multiplying (23) by (26), and (24) by (25), and then eliminating the term $R_1 T_1 R_2 T_2$ from the resultant equations. Thus,

$$\frac{4C^2}{(1 + C^2)^2} = \frac{m_{12}^o m_{21}^o}{m_{11}^o m_{22}^o} \triangleq a$$

which is a biquadratic equation with four possible solutions given by

$$C = \pm \frac{1}{\sqrt{a}} \pm \sqrt{\frac{1}{a} - 1}.$$

Requiring C to be a small number, two of these solutions can be discarded (note that $|a| << 1$); therefore,

$$C = \pm \frac{1}{\sqrt{a}} (1 - \sqrt{1 - a}). \tag{27}$$

To meet the condition $|C| < 1$, the branch cut for $\sqrt{1 - a}$ is chosen such that Re $[\sqrt{1 - a}] > 0$. Therefore, C is determined from the sphere measurement within a $\pm$ sign.

By denoting the measured scattering matrix elements of the unknown target by m_{ij}^u and using (23)–(26) to find the products of $R_i T_j$, we obtain

$$s_{vv} + C(s_{vh} + s_{hv}) + C^2 s_{hh} = \frac{m_{11}^u}{m_{11}^o} (1 + C^2) s^o \tag{28}$$

$$C^2 s_{vv} + C(s_{vh} + s_{hv}) + s_{hh} = \frac{m_{22}^u}{m_{22}^o} (1 + C^2) s^o \tag{29}$$

$$C(s_{vv} + s_{hh}) + s_{vh} + C^2 s_{hv} = \frac{m_{12}^u}{m_{12}^o} (2C) s^o. \tag{30}$$

$$C(s_{vv} + s_{hh}) + s_{hv} + C^2 s_{vh} = \frac{m_{21}^u}{m_{21}^o} (2C)\, s^o \tag{31}$$

Solving these equations simultaneously, the unknown scattering matrix elements can be obtained and are given by

$$s_{vv} = \frac{1}{(1 - C^2)^2} \left[-2C^2 \left(\frac{m_{12}^u}{m_{12}^o} + \frac{m_{21}^u}{m_{21}^o} \right) + (1 + C^2) \left(\frac{m_{11}^u}{m_{11}^o} + C^2 \frac{m_{22}^u}{m_{22}^o} \right) \right] s^o \tag{32}$$

$$s_{hh} = \frac{1}{(1 - C^2)^2} \left[-2C^2 \left(\frac{m_{12}^u}{m_{12}^o} + \frac{m_{21}^u}{m_{21}^o} \right) + (1 + C^2) \left(\frac{m_{22}^u}{m_{22}^o} + C^2 \frac{m_{11}^u}{m_{11}^o} \right) \right] s^o \tag{33}$$

$$s_{vh} = \frac{C}{(1 - C^2)^2} \left[2 \frac{m_{12}^u}{m_{12}^o} + 2C^2 \frac{m_{21}^u}{m_{21}^o} - (1 + C^2) \left(\frac{m_{11}^u}{m_{11}^o} + \frac{m_{22}^u}{m_{22}^o} \right) \right] s^o \tag{34}$$

$$s_{hv} = \frac{C}{(1 - C^2)^2} \left[2 \frac{m_{21}^u}{m_{21}^o} + 2C^2 \frac{m_{12}^u}{m_{12}^o} - (1 + C^2) \left(\frac{m_{11}^u}{m_{11}^o} + \frac{m_{22}^u}{m_{22}^o} \right) \right] s^o \tag{35}$$

It should be pointed out that there is no ambiguity in s_{11} and s_{22} since the branch of $\sqrt{1 - a}$ is defined, but there is a 180° phase ambiguity in s_{12} and s_{21}. Expressions (32)–(35) give the elements of the scattering matrix when the calibration and the unknown targets are at the same range from the radar. If the range of the calibration target (r_0) is different from the range of the unknown target (r_u), (32)–(35) must be modified by a multiplying factor $(r_u / r_0)^2 e^{-2ik_0(r_0 - r_u)}$.

The complex quantity C is an inherent characteristic of the antenna system and does not change with variations in the performance of the active devices in the radar system, and therefore is less affected by environmental changes. The ambiguity in the sign of C for an antenna system may be easily resolved once by measuring a target with a known phase relationship between the elements of its scattering matrix (such as a tilted cylinder).

To investigate the accuracy of the measurement of C, we use the fact that $|a| << 1$, and therefore (27) becomes $C \approx \frac{1}{2} \sqrt{a}$. If the uncertainty in measurement of a is represented by Δ and $|\Delta| << |a|$, then

$$C + \delta C = \frac{1}{2} \sqrt{a + \Delta} \approx \frac{1}{2} \sqrt{a} \left(1 + \frac{\Delta}{2a} \right)$$

from which we get

$$\frac{\delta C}{C} = \frac{1}{2} \frac{\Delta}{a}.$$

It is concluded that the uncertainty in C is about 50% of the uncertainty in measuring a.

Using a sphere as the calibration target not only simplifies calculation of the unknowns significantly, but also

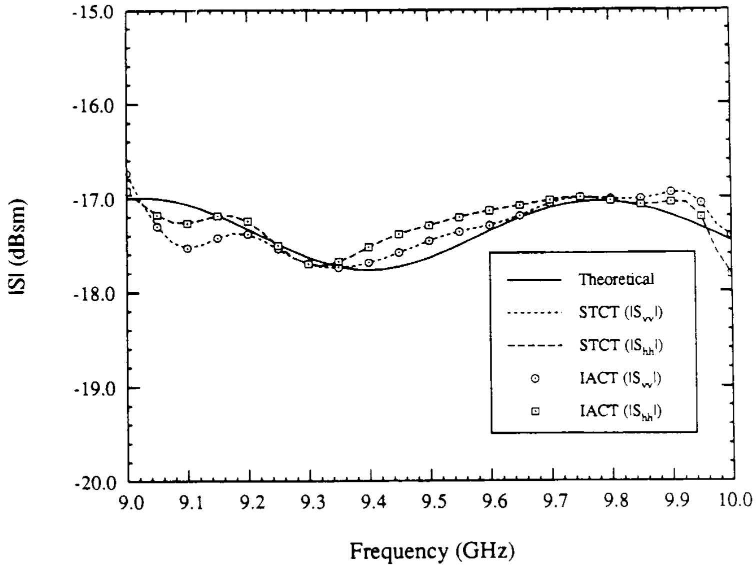

Fig. 4. Magnitude of the diagonal elements of the scattering matrix of a 6-in sphere.

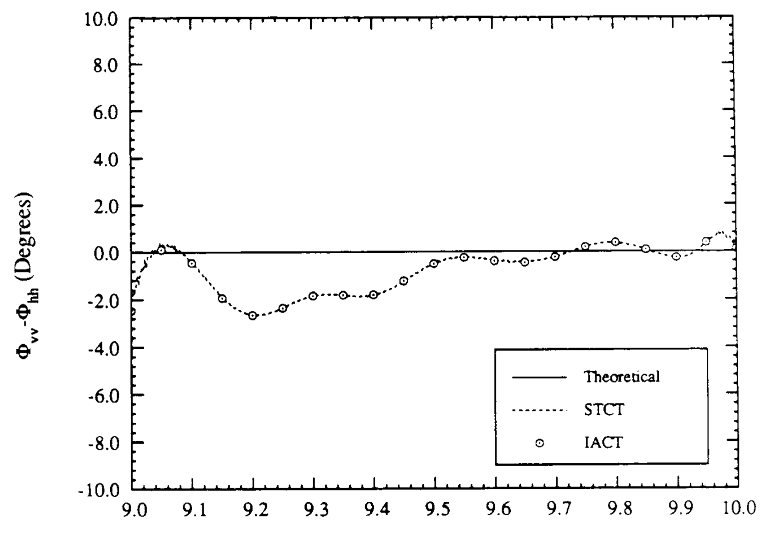

Fig. 5. Phase difference between the diagonal elements of the scattering matrix of a 6-in sphere.

offers two more advantages. One advantage is that the scattering matrix of a sphere is insensitive to orientation, and therefore no error will be incurred because of target orientation. The second advantage stems from the fact that spheres are the only three-dimensional structures for which an exact theoretical scattering matrix is known.

IV. Comparison to Measured Data

The validity of the STCT is now examined by measuring scattering matrices of cylinders and spheres as test targets employing a polarimetric X-band scatterometer. The results based on the IACT are also included for comparison. The measurements were performed in a 13-m-long anechoic chamber, and the target orientation was facilitated by a very-fine-tuned azimuth over elevation stepper motor positioner. Detailed description of the scatterometer and measurement setup is given in [3].

The analysis given in Section II does not take into account the effect of noise and disturbances. In reality, the measured scattering matrix includes an additive noise fac-

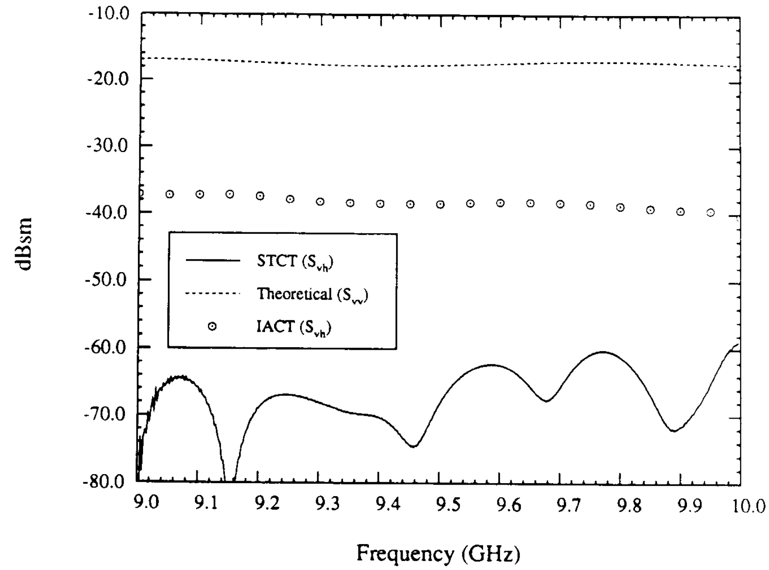

Fig. 6. Magnitude of the off-diagonal element of the scattering matrix of a 6-in sphere compared to one of the diagonal elements.

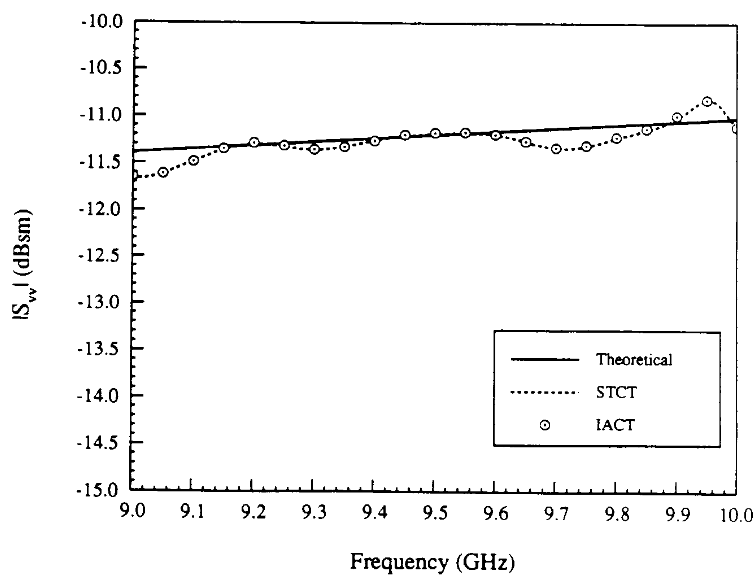

Fig. 7. Magnitude of the diagonal element (s_{vv}) of the scattering matrix of the vertical cylinder.

tor, and therefore (21) becomes

$$M = RCsCT + N \tag{36}$$

where N is a matrix representation of disturbances. In order to measure s accurately, all the elements of N must be much smaller than the elements of M. The disturbances for a typical radar system may include thermal and background noise. Thermal noise is a zero-mean random process with power proportional to the product of the system bandwidth and noise temperature. This effect can be minimized using an averaging process. The background noise includes the signal returns from objects at ranges comparable to that of the test target or the short-range multiple reflections within the system. This problem can be eliminated using background subtraction from the target and background response. Another source of error in the measurement of s is the interaction of the target with its sup-

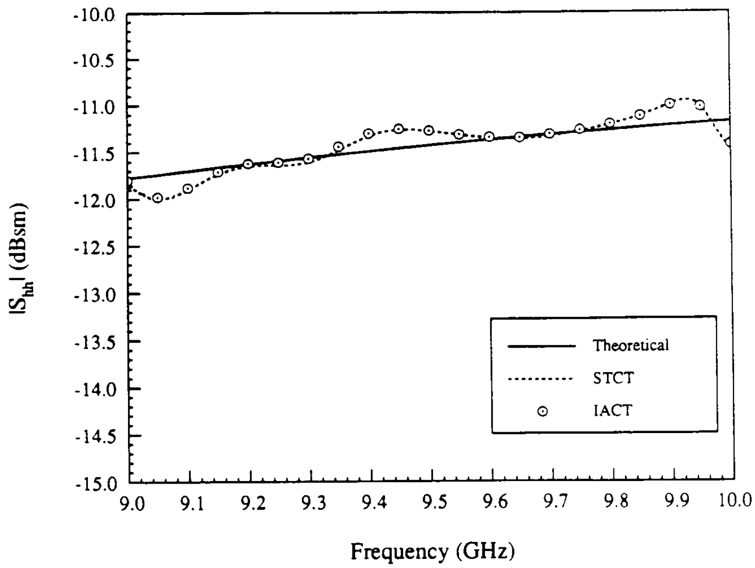

Fig. 8. Magnitude of the diagonal element (s_{hh}) of the scattering matrix of the vertical cylinder.

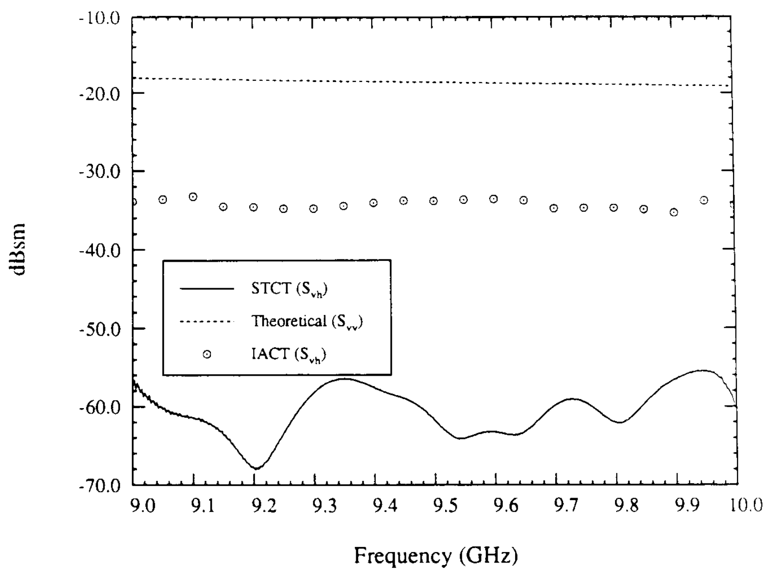

Fig. 9. Magnitude of the off-diagonal element (s_{vh}) of the scattering matrix of the vertical cylinder compared to s_{vv}.

port structure (pedestal). This interaction is not linear and hence cannot be subtracted out.

A 12-in-diameter sphere was used as the calibration target, and test targets included a 6-in sphere, an 8-in sphere, and a conducting cylinder with a diameter of 0.8 cm and length of 27.2 cm observed at three different orientations (vertical, horizontal, and 45°). The calibrated elements of the scattering matrix were then compared to the theoretical values computed using the exact Mie-series solution for the spheres and using a semiexact solution for the cylinder. The semiexact solution is based on the assumption that the current induced on the surface of the cylinder is identical to that of an infinite cylinder with the same radius. This solution is accurate in the specular direction and when the cylinder length is much larger than the wavelength.

Using averaging and background subtraction, a signal-to-noise ratio of better than 40 dB was achieved in mea-

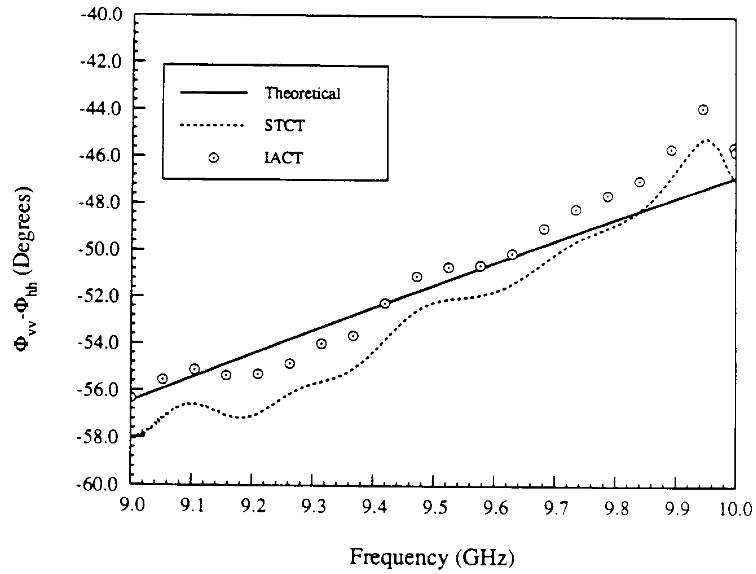

Fig. 10. Phase difference between the diagonal elements of the scattering matrix of the vertical cylinder.

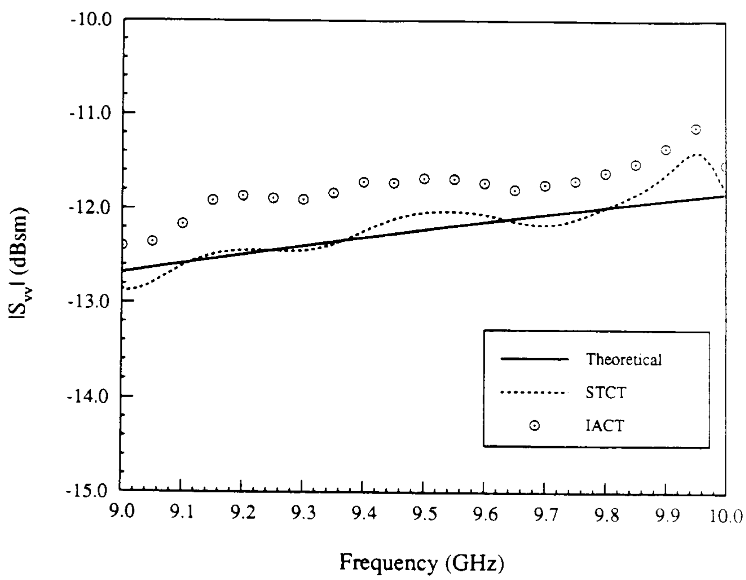

Fig. 11. Magnitude of the diagonal element (s_{vv}) of the scattering matrix of the 45° tilted cylinder.

suring the elements of $\boldsymbol{M}$. For targets with $s_{12} = 0$ (such as sphere and vertical cylinder), the signal-to-noise ratio for the off-diagonal elements of $\boldsymbol{M}$ was better than 25 dB.

Figs. 4–6 compare the theoretical and measured scattering matrix elements of the 6-in sphere. The error in the like-polarized terms is less than 0.3 dB, and the results based on the IACT and STCT are exactly identical. It is also shown that the error in the phase is less than 2°. Fig. 6 shows the cross-polarized component of the sphere (theoretical value $= -\infty$ in dB scale) where there is a significant disagreement between STCT and IACT. An effective polarization isolation of 50 dB is obtained using STCT. It should be pointed out that the minimum noise-equivalent cross section of the radar system is -65 dBsm. Therefore, the cross-polarization isolation is limited by the system noise in this case. Similar results were also obtained for the 8-in sphere. Figs. 7–10 depict the results for the vertical cylinder, and excellent agreement between

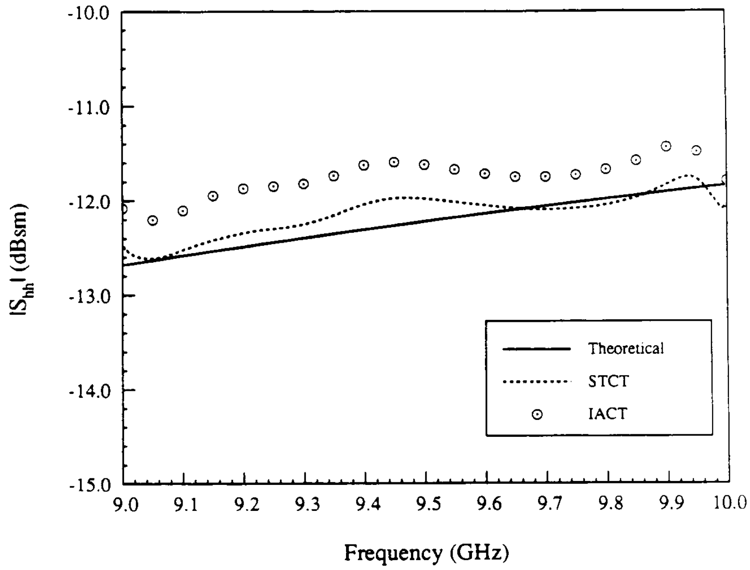

Fig. 12. Magnitude of the diagonal element (s_{hh}) of the scattering matrix of the 45° tilted cylinder.

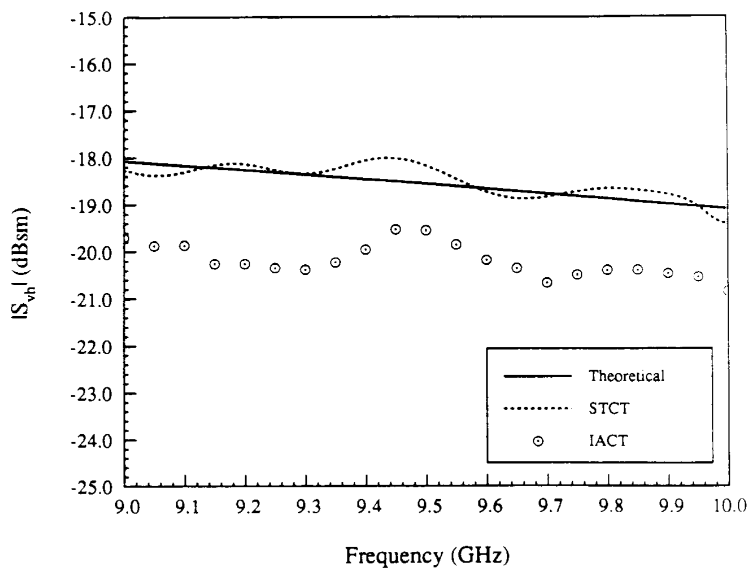

Fig. 13. Magnitude of the off-diagonal element (s_{vh}) of the scattering matrix of the 45° tilted cylinder.

the measured data and theory is achieved. As shown in Fig. 9, the measured effective polarization isolation for the vertical cylinder is -50 dB. Results for the 45° tilted cylinder are shown in Figs. 11–15, where the accuracy of the STCT is within ± 0.4 dB in magnitude and $\pm 5°$ in phase. These plots demonstrate the superiority of the STCT over the IACT.

V. Concluding Remarks

A convenient calibration technique for single-antenna polarimetric radar system with range-gating capability has been developed. The radar cross-talk contamination and channel imbalances are obtained by measuring the backscatter from a single calibration target whose scattering

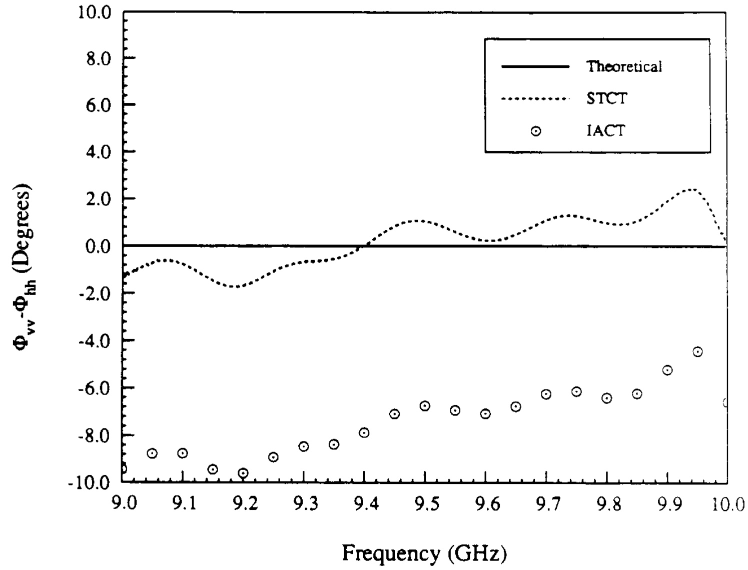

Fig. 14. Phase difference between the diagonal elements of the scattering matrix of the 45° tilted cylinder.

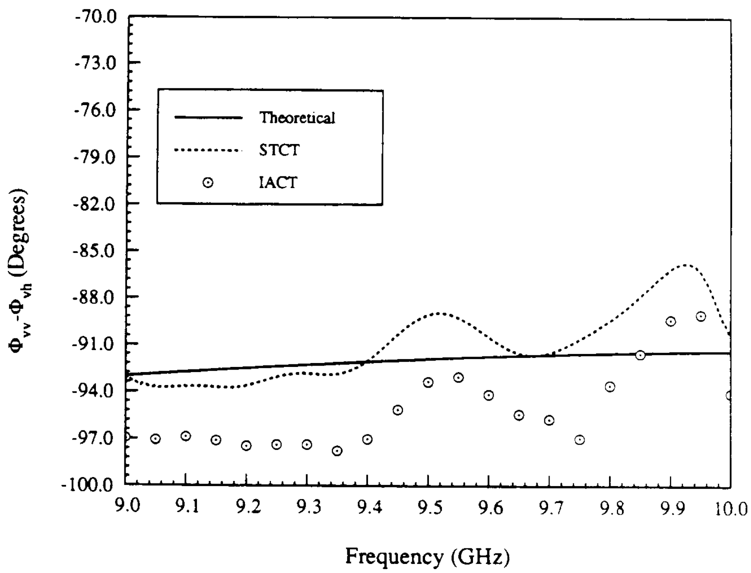

Fig. 15. Phase difference between the diagonal and the off-diagonal elements of the scattering matrix of the 45° tilted cylinder.

matrix is diagonal with equal diagonal entries. The insensitivity to alignment of calibration target offered by this technique makes it particularly useful for field operation.

Using a four-port network approach, it is shown that the cross-talk contamination factor is a feature of the antenna system only, and hence is not affected by instability of active devices in the radar system. Excellent agreement between measurements and theory was obtained when a sphere was used as the calibration target, and cylinders and other spheres were used as test targets. A minimum effective polarization isolation of 50 dB was achieved using this technique.

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Kamal Sarabandi was born in Tehran, Iran, on November 4, 1956. He received the B.S. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1980. He entered the graduate program at The University of Michigan in 1984 and received the M.S.E. degree in electrical engineering in 1986, the M.S. degree in mathematics, and the Ph.D. degree in electrical engineering in 1989.

From 1980 to 1984 he worked as a Microwave Engineer in the Telecommunication Research Center in Iran. He is presently an Assistant Research Scientist in the Department of Electrical Engineering and Computer Science at the University of Michigan. His research interests include electromagnetic scattering and microwave remote sensing.

Dr. Sarabandi is a member of the Electromagnetics Academy.

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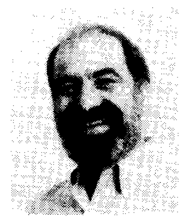

Fawwaz T. Ulaby (M'68-SM'74-F'80) is Professor of Electrical Engineering and Computer Science at The University of Michigan, Ann Arbor. His current research interests involve microwave propagation and active and passive microwave remote sensing.

Dr. Ulaby served as Executive Editor of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING from 1984 to 1988 and was the Geoscience and Remote Sensing (GRS) Society's Distinguished Lecturer for 1986-1987. He received the GRS Society's Outstanding Service Award in 1982 and its Distinguished Service Award in 1983, and the IEEE Centennial Medal in 1984.