Calibration of Polarimetric Radar Systems With Good Polarization Isolation

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Abstract—A practical technique is proposed for calibrating single-antenna polarimetric radar systems using a metal sphere plus any second target with a strong cross-polarized radar cross section. This technique assumes perfect isolation between antenna ports. It is shown that all magnitudes and phases (relative to one of the like-polarized linear polarization configurations) of the radar transfer function can be calibrated without knowledge of the scattering matrix of the second target. Comparison of the values measured (using this calibration technique) for a tilted cylinder at X-band with theoretical values shows agreement within ± 0.3 dB in magnitude and $\pm 5°$ in phase. The radar overall cross-polarization isolation was 25 dB. The technique is particularly useful for calibrating a radar under field conditions, because it does not require the careful alignment of calibration targets.

I. Introduction

A POLARIMETRIC radar is a phase-coherent instrument used to measure the polarization scattering matrix S of point or distributed targets. The matrix S relates the field E^s scattered by the target to the field E^i of a plane wave incident upon the target [1, p. 1087]:

$$E^s = \frac{e^{-ikr}}{r} SE^i \tag{1}$$

where r is the distance from the center of the target to the point of observation, and k is the wave number. For a plane-wave incident upon the particle in the direction $\hat{k}_i$, its electric field vector may be written in terms of vertical and horizontal polarization components E_v^i and E_h^i, using the coordinate system $(\hat{v}_i, \hat{h}_i, \hat{k}_i)$ shown in Fig. 1:

$$E^i = (E_v^i \hat{v}_i + E_h^i \hat{h}_i) e^{-ik\hat{k}_i r} \tag{2}$$

where

$$\hat{v}_i = \cos\theta_i \cos\phi_i \hat{x} + \cos\theta_i \sin\phi_i \hat{y} - \sin\theta_i \hat{z} \tag{3}$$

$$\hat{h}_i = -\sin\phi_i \hat{x} + \cos\phi_i \hat{y} \tag{4}$$

$$\hat{k}_i = \sin\theta_i \cos\phi_i \hat{x} + \sin\theta_i \sin\phi_i \hat{y} + \sin\theta_i \hat{z}. \tag{5}$$

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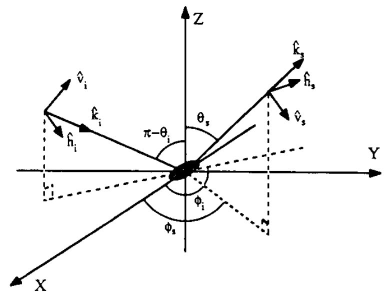

Fig. 1. Geometry of the scattering of a plane wave from a particle.

In (2), a time dependence of the form $e^{+i\omega t}$ is assumed and suppressed.

The far-field wave scattered in the direction $\hat{k}_s$ is a spherical wave given by

$$E^s = E_v^s \hat{v}_s + E_h^s \hat{h}_s \tag{6}$$

where $(\hat{v}_s, \hat{h}_s, \hat{k}_s)$ are defined by the same expressions given in (3) to (5) except for replacing the subscript i with the subscript s. For the backscattering case, $\theta_i + \theta_s = \pi$, $\phi_i + \phi_s = \pi$, $\hat{k}_s = -\hat{k}_i$, $\hat{v}_s = \hat{v}_i$, and $\hat{h}_s = -\hat{h}_i$.

In matrix form, (1) may be rewritten as

$$\begin{bmatrix} E_v^s \\ E_h^s \end{bmatrix} = \frac{e^{-ikr}}{r} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E_v^i \\ E_h^i \end{bmatrix} \tag{7}$$

where

$$S = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \tag{8}$$

is defined in terms of the scattering amplitudes S_{mn}, with m and n denoting the polarization (v or h) of the scattered and incident fields, respectively. The scattering amplitude S_{mn} is, in general, a complex quantity comprised of a magnitude $s_{mn} = |S_{mn}|$ and a phase angle ψ_{mn},

$$S_{mn} = s_{mn} e^{i\psi_{mn}}, \qquad m, n = v \text{ or } h \tag{9}$$

and it is related to the radar cross section (RCS) of the target σ_{mn} by

$$\begin{aligned} \sigma_{mn} &= 4\pi |S_{mn}|^2 \\ &= 4\pi s_{mn}^2, \qquad m, n = v \text{ or } h. \end{aligned} \tag{10}$$

Interest in measuring S stems from the fact that if the elements of S are known, we can compute the RCS of the

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target which would be observed by a radar with any specified combination of transmit and receive antenna configuration, including elliptical and circular polarizations [2]. In fact, we do not need to know all four magnitudes and four phases of S in order to synthesize the desired RCS; it is sufficient to know the four magnitudes and any three of the phase angles, measured with respect to the fourth as reference. Thus, if we choose ψ_{vv} as reference, we can write (8) in the form:

$$S = e^{i\psi_{vv}} \begin{bmatrix} s_{vv} & s_{vh} e^{i\psi'_{vh}} \\ s_{hv} e^{i\psi'_{hv}} & s_{hh} e^{i\psi'_{hh}} \end{bmatrix} = e^{i\psi_{vv}} S' \tag{11}$$

where

$$\psi'_{mn} = \psi_{mn} - \psi_{vv}, \qquad m, n = v \text{ or } h. \tag{12}$$

For backscattering, the reciprocity theorem mandates that $S_{hv} = S_{vh}$, which further reduces the number of unknown quantities from 7 to 5.

The formulation given above is equally applicable to a distributed target. If the effective area illuminated by the radar antenna is A, the polarimetric scattering behavior of the distributed target is characterized by the differential scattering matrix $S^0 = S/\sqrt{A}$.

In principle, S_{vv} and S_{hv} can be determined by measuring E_v^s and E_h^s with the target illuminated by a pure vertically polarized wave $E^i = E_v^i \hat{v}_i$, and, similarly, S_{vh} and S_{hh} can be determined by measuring the same quantities when the target is illuminated by $E^i = E_h^i \hat{h}_i$. Such a procedure requires that: 1) the transmit and receive antennas of the measurement system each have excellent isolation between its v- and h-ports, and 2) the receive–transmit transfer functions of the measurement system be known for all four polarization combinations (vv, vh, hv, and hh). Design techniques are currently available to achieve antenna polarization isolation on the order of 30 dB. For a radar scatterometer system intended to measure the differential scattering matrices of distributed targets such as ground surfaces and vegetation canopies, such a level of isolation is sufficient to insure good measurement accuracy of the magnitudes and phases of all four scattering amplitudes. The error associated with measuring the like-polarized components S_{vv} and S_{hh} is negligibly small, and for S_{hv} (and S_{vh}) the error also is less than 0.85 dB if $|S_{hv}|/|S_{vv}| \geq 0.31$, which corresponds to $\sigma_{hv}/\sigma_{vv} \geq 0.1$ (or -10 dB). For natural targets, the like- and cross-polarized components S_{hv} and S_{vv}, for example, are uncorrelated, and for $\sigma_{hv}/\sigma_{vv} \geq 0.01$ the associated error would be less than 0.4 dB.

If the radar antennas do not individually have good polarization isolation between their v- and h-ports, it is necessary to characterize each antenna by a polarization distortion matrix that accounts for the coupling between the two ports, and to use at least two, and preferably three, targets of known scattering matrices in order to calibrate the radar completely [3]. This case is outside the scope of this paper and will be the subject of future papers. Instead, we will now focus our attention on the problems associated with measuring the receiver–transmitter transfer function for a radar with reasonably good overall cross-polarization isolation using suitable external calibration targets.

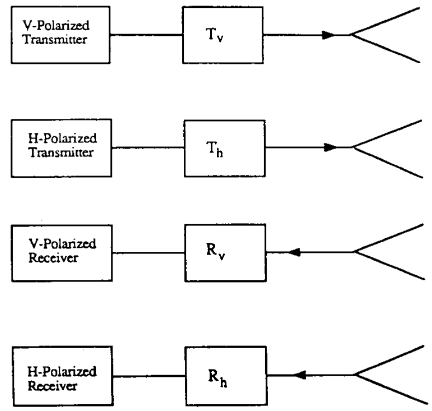

Fig. 2. Simplified block diagram of a dual-polarized radar system.

II. System Transfer Function

Although a radar may use a single antenna to provide both transmit and receive functions and may also use a polarization switching network capable of exciting either v- or h-polarized waves in the antenna, we shall use the block diagram shown in Fig. 2 to represent the general case of a two-pole transmitter and a two-pole receiver. Assuming perfect isolation between antenna ports, the voltage received by the v-polarized receive antenna due to illumination of a target at range r by a v-polarized wave is given by

$$E_{vv} = \left[\frac{P_t G_t G_r \lambda^2}{(4\pi)^3 r^4}\right]^{1/2} e^{-i2kr} R_v T_v \sqrt{4\pi} S_{vv} = \frac{K}{r^2} e^{-i2kr} R_v T_v S_{vv} \tag{13}$$

where

$$K = \left[\frac{P_t G_t G_r \lambda^2}{(4\pi)^2}\right]^{1/2} \tag{14}$$

and S_{vv} is the scattering amplitude of the target, P_t is the transmitted power, and G_r and G_t are the nominal gains of the transmit and receive antennas. The quantities R_v and T_v are the field transfer function for the receive and transmit antennas, respectively, which account for the deviation in both amplitude and phase from the nominal condition described by $G_t G_r$. Similarly, for any receive–transmit polarization configuration, we have

$$E_{mn} = \frac{K}{r^2} e^{-i2kr} R_m T_n S_{mn}, \qquad m, n = v \text{ or } h. \tag{15}$$

III. Calibration

The standard calibration approach involves the use of one reference target of known scattering matrix. Upon measuring E_{mn} with S_{mn} known, the quantity $(KR_m T_n)$ can be determined in amplitude and phase, with the latter being relative to some reference distance time delay.

In principle, the procedure is simple and straightforward. The problem arises when we need to select a reference target of known scattering matrix. The metal sphere is the easiest target to align, and its scattering matrix can be computed exactly [4, p. 297]. Unfortunately, it can only be used to calibrate the vv- and hh-channels because its $S_{hv}^{sp} = S_{vh}^{sp} = 0$. Targets that exhibit significant cross-polarized scattering include the dihedral corner reflector, tilted cylinders, and others, but scattering from such targets is inherently sensitive to the orientation of the target relative to the $(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{h}}_i, \hat{\boldsymbol{k}}_i)$ coordinate system. This, and other factors such as edge scattering, may lead to significant errors between the calculated values of the scattering amplitudes and their actual values. The orientation problem may be reduced down to an acceptable level when operating in an anechoic chamber under controlled laboratory conditions, but it poses a difficult problem when it is necessary to calibrate a truck-mounted scatterometer, for example, under field conditions.

To solve this problem, we propose to use two reference targets; namely, a sphere and any target with a strong cross-polarized RCS. As will be shown below, it is not necessary to know the RCS of the second reference target in order to calibrate the radar system.

First, let us use a metal sphere of known size and place it at a distance r_0 from the radar. The scattering amplitudes of a metal sphere are $S_{hh} = S_{vv} \equiv S_0$, and $S_{hv} = S_{vh} = 0$. The received fields for vv and hh polarizations are

$$E_{vv}^0 = \frac{K}{r_0^2} e^{-i2kr_0} R_v T_v S_0 \tag{16}$$

$$E_{hh}^0 = \frac{K}{r_0^2} e^{-i2kr_0} R_k T_h S_0 \tag{17}$$

where the subscript and superscript "0" denote quantities associated with the metal sphere. For a test target with the <u>unknown</u> scattering matrix S^u, placed at a distance r_u from the radar, the received field is

$$E_{vv}^u = \frac{K}{r_u^2} e^{-i2kr_u} R_v T_v S_{vv}^u \tag{18}$$

$$E_{hv}^u = \frac{K}{r_u^2} e^{-i2kr_u} R_h T_v S_{hv}^u \tag{19}$$

$$E_{hh}^u = \frac{K}{r_u^2} e^{-i2kr_u} R_h T_h S_{hh}^u \tag{20}$$

$$E_{vh}^u = \frac{K}{r_u^2} e^{-i2kr_u} R_v T_h S_{vh}^u. \tag{21}$$

From (16) and (18), and similarly from (17) and (20), we obtain the following expressions for the unknown like-polarized scattering amplitudes:

$$S_{vv}^u = \left(\frac{E_{vv}^u}{E_{vv}^0}\right)\left(\frac{r_u}{r_0}\right)^2 e^{-i2k(r_0 - r_u)} S_0 \tag{22}$$

$$S_{hh}^u = \left(\frac{E_{hh}^u}{E_{hh}^0}\right)\left(\frac{r_u}{r_0}\right)^2 e^{-i2k(r_0 - r_u)} S_0. \tag{23}$$

All the quantities on the right-hand side of the above two expressions can be measured directly except for S_0, which can be precisely computed by using the standard Mie expressions. Small errors in the measurements of the ranges r_u and r_0 will have a minor effect on the magnitude of S_{hh}^u, but may cause a large error in the measurement of the phase angle of S_{hh}^u if the error $\Delta(r_0 - r_u)$ is comparable to λ. However, the phase ψ_{hh}' of S_{hh}^u relative to that of S_{vv}^u is independent of $(r_0 - r_u)$.

Next, let us use any point target that exhibits strong cross-polarized scattering, and let us measure the received field for hv and vh polarizations,

$$E_{hv}^c = \frac{K}{r_c^2} e^{-i2kr_c} R_h T_v S_{hv}^c \tag{24}$$

$$E_{vh}^c = \frac{K}{r_c^2} e^{-i2kr_c} R_v T_h S_{vh}^c \tag{25}$$

where the subscript and superscript "c" refers to the cross-polarization calibration target. The reciprocity theorem states that in the backscattering direction, the cross-polarized scattering amplitudes are always equal. Hence,

$$S_{hv}^c = S_{vh}^c \tag{26}$$

and consequently

$$K_1 \equiv \frac{E_{hv}^c}{E_{vh}^c} = \frac{R_h T_v}{R_v T_h}. \tag{27}$$

If we define the additional quantity K_2 as

$$\begin{aligned} K_2 &= E_{vv}^0 E_{hh}^0 \\ &= \frac{K^2}{r_0^4} e^{-i4kr_0} R_v T_v R_h T_h S_0^2 \end{aligned} \tag{28}$$

and use it in combination with (19), (21), and (27), we can obtain the following expressions for the cross-polarized scattering amplitudes of the test target:

$$S_{hv}^u = \frac{E_{hv}^u}{\sqrt{K_1 K_2}} \left(\frac{r_u}{r_0}\right)^2 e^{-i2k(r_0 - r_u)} S_0 \tag{29}$$

$$S_{vh}^u = \sqrt{\frac{K_1}{K_2}} E_{vh}^u \left(\frac{r_u}{r_0}\right)^2 e^{-i2k(r_0 - r_u)} S_0. \tag{30}$$

Equations (22), (23), (29), and (30) provide expressions for the four scattering amplitudes in terms of: 1) The like-polarized received voltages for the metal spheres E_{vv}^0 and E_{hh}^0, 2) the ratio of the cross-polarized received voltages for the second calibration target $K_1 = E_{hv}^c / E_{vh}^c$, 3) the like-polarized scattering amplitude of the sphere S_0, and 4) the ranges to the sphere and the test target r_0 and r_u. Note that knowledge of the scattering amplitude of the second calibration target is not required.

IV. Comparison With Measured Data

To verify the validity of the proposed calibration technique summarized by (22), (23), (29), and (30), we measured the scattering matrix of a tilted cylinder with an X-band radar. The radar is an HP 8753-based dual-polarized scatterometer operating in continuous chirped mode (9–10 GHz). The antenna of the scatterometer is a square horn with an orthogonal mode transducer (OMT). The overall cross-polarization isolation of the system is better than 25 dB. The scattering measurements were performed in a 13-m-long anechoic chamber using the setup diagrammed in Fig. 3. A similar system with an operating frequency of 35 GHz is described in [5].

Although an exact theoretical solution for a finite-length conducting cylinder does not exist, the solution based on the assumption that the current along the axis of the cylinder is constant provides accurate results in the specular direction, if the length of the cylinder (L) is much larger than the wavelength [6]. In order to minimize the edge effects caused by scattering by the ends of the cylinder, the diameter of the cylinder (D) must also be chosen to be much smaller than the wavelength. Hence, we selected a cylinder with L = 30.48 cm and D = 1.625 mm.

Correct positioning of the test target with respect to the antenna coordinates is very important. First, the target must be placed at the center of the antenna beam in order to avoid phase variations of the incident field along the axis of the target. This was accomplished using a pair of two laser beams. Another alignment parameter that has to be carefully controlled is the angle ϕ between the incidence direction ($\hat{k}_i$) and the projection of the cylinder axis onto the horizontal plane (Fig. 4). The elements of the scattering matrix are very sensitive to variations in the azimuth angle, and the rate of change is proportional to the length of the cylinder. This angle was set to 90° with a fine-control stepper motor (steps of a fraction of a tenth of a degree) by maximizing the received power. The third alignment parameter is the tilt angle θ, which is the angle between the axis of the cylinder and the vertical direction ($\hat{v}_i$). Accurate setting of this angle is very difficult. The sensitivity due to misalignment in θ is shown in Fig. 5 for amplitude and in Fig. 6 for the relative phase (to vv) of the elements of the scattering matrix using theoretical expressions [6]. This angle was set to 50° by using an inclinometer.

Under the mentioned conditions, a signal-to-noise ratio of 25 dB was achieved for the test cylinder, and after background subtraction the signal-to-noise ratio was improved to 40 dB. To eliminate short-range reflections from the antenna circulators, the returned signal was time-gated, as a result of which the frequency response around the beginning and end of the frequency band was distorted and discarded.

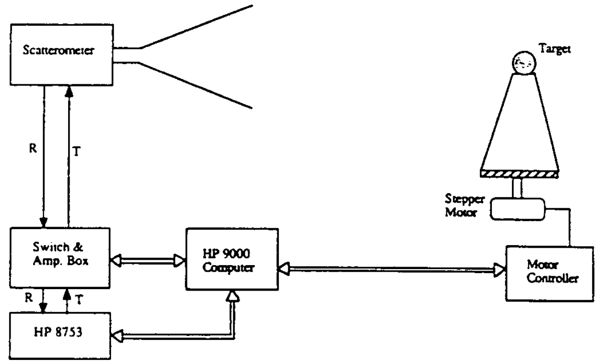

Fig. 3. Automatic radar cross-section measurement setup.

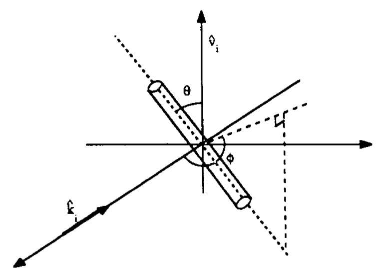

Fig. 4. Geometry of the scattering of a plane from a long, thin cylinder.

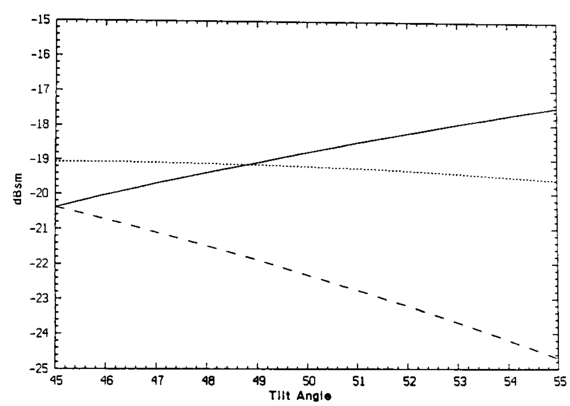

Fig. 5. Theoretical values for the radar cross section versus the tilt angle of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) hh, (— —) vv, and (- - -) hv.

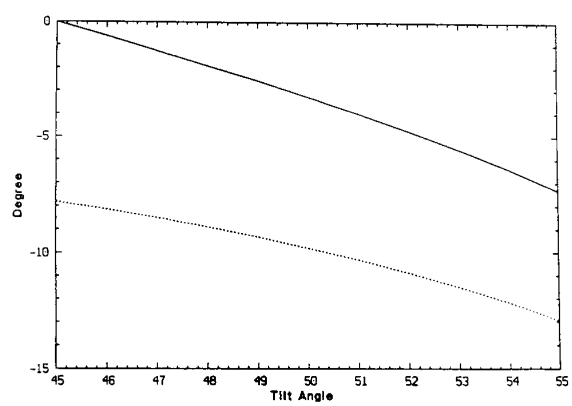

Fig. 6. Theoretical values for relative phase (to vv) of the elements of the scattering matrix versus the tilt angle of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) hh, and (- - -) hv.

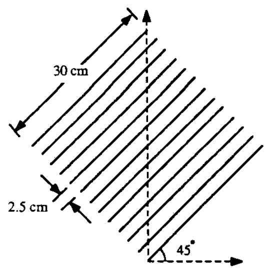

Fig. 7. Geometry of a wire mesh.

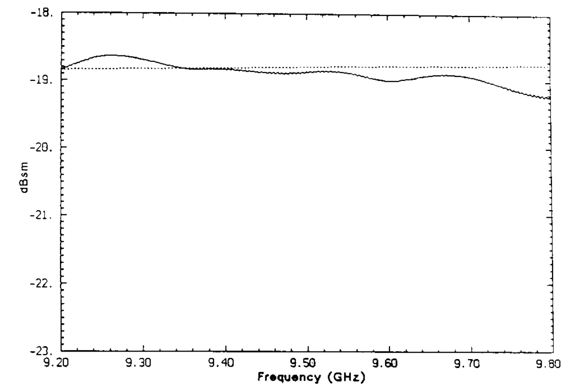

Fig. 8. Radar cross section (hh) versus the frequency of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) measured, and (---) theory.

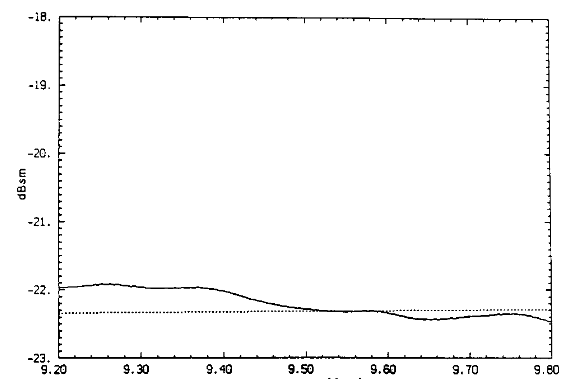

Fig. 9. Radar cross section (vv) versus the frequency of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) measured, and (---) theory.

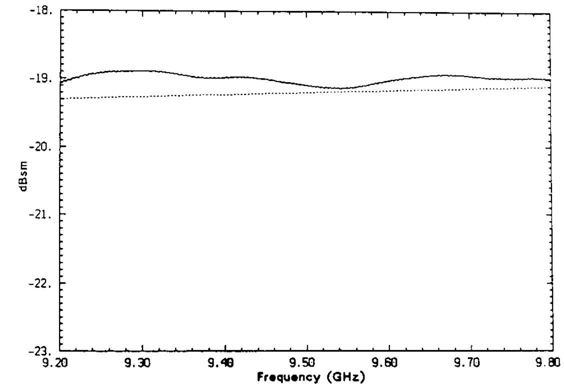

Fig. 10. Radar cross section (hv) versus the frequency of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) measured, and (---) theory.

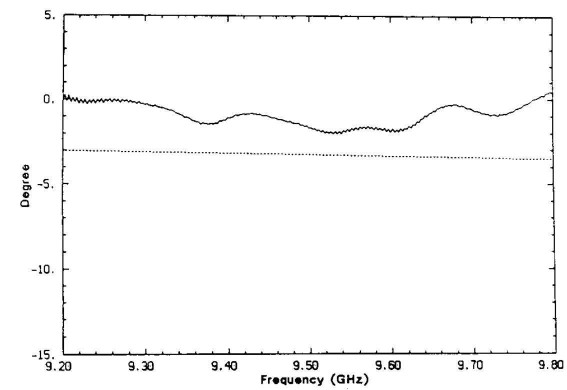

Fig. 11. Relative phase S_{hh} (to S_{vv}) versus the frequency of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) measured, and (---) theory.

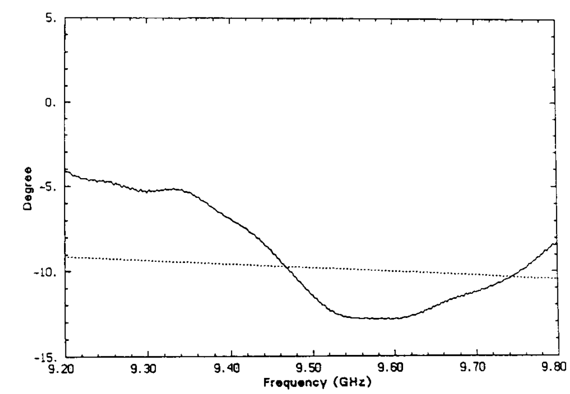

Fig. 12. Relative phase S_{hv} (to S_{vv}) versus the frequency of a cylinder, with L = 30.48 cm and D = 1.625 mm: (——) measured, and (---) theory.

A 15-cm sphere was used for sphere calibration and a 45° wire-mesh (Fig. 7) was employed as the cross-polarization target. The distances of all the targets from the scatterometer, which were accurately measured using the time-domain feature of the HP 8753 Vector Network Analyzer, were arranged such that $r_0 = r_c = r_u$. The measured amplitudes of the scattering matrix elements of the cylinder are compared with theoretical values in Figs. 8–10. The measured values are within ±0.3 dB of the theoretical results. For the relative phase, the measured values (Figs. 11 and 12) are within ±5° of the theoretical predictions. These deviations are attributed to alignment errors and the imperfect polarization isolation of the antenna.

V. Conclusions

The excellent agreement between measurements and theory demonstrates that the calibration technique proposed in this paper is an effective approach for calibrating single-antenna polarimetric radar systems. The technique is particularly useful for field operations because it does not require accurate alignment of calibration targets or knowledge of the radar cross section of the depolarization target.

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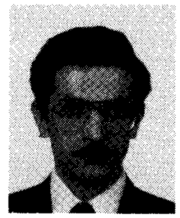

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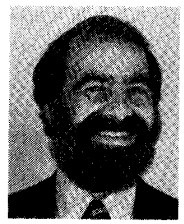

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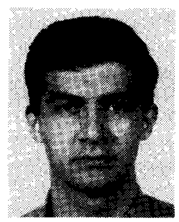

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