An Investigation of Bistatic Calibration Objects

Christopher J. Bradley, Member, IEEE, Peter J. Collins, Senior Member, IEEE, Joaquim Fortuny-Guasch, Member, IEEE, Michael Larkin Hastriter, Senior Member, IEEE, Giuseppe Nesti, Andrew J. Terzuoli, Jr., Member, IEEE, and Kelce S. Wilson

Abstract—Several popular metallic bistatic calibration objects are investigated, including a sphere, long and short cylinders, dihedral, trihedral, circular disk and wire mesh. Comparisons are made between the advantages and disadvantages of various objects for calibration. The analysis addresses sensitivity to object alignment error, availability of accurate radar cross section (RCS) calculations and bistatic RCS levels. Both theoretical concepts and practical considerations are discussed based on measurements accomplished at the European Microwave Signature Laboratory (EMSL) of the EC Joint Research Center (JRC) in Ispra, Italy. This facility has the capability to produce far-field fully polarimetric precision bistatic measurements in a 30 cm diameter quiet zone, suitable for comparing different calibration objects.

Index Terms—Bistatic, calibration, radar cross section (RCS), scattering.

I. INTRODUCTION

FULLY polarimetric, bistatic radar systems possess additional complexity and therefore additional systemic error sources above those for single-polarization, monostatic systems [1], [2]. These additional error sources can significantly affect the requirements of the calibration procedure and include cross-polarization leakage, crosstalk between the transmitter and receiver apertures, channel dissimilarities, and the unsuitability of test objects to bistatic configurations or polarization changes. Polarization is one source of the additional complexity. Radar systems that operate on a single polarization may only need a single transmit (Tx) channel and a single receive (Rx) channel. However, fully polarized systems duplicate both the Tx and Rx channels. This is a four-fold increase in potential Tx/Rx channel pairings, each of which requires calibration [3]. Bistatic configurations are a second source of additional complexity. Fig. 1 depicts both monostatic and bistatic radar configurations. A monostatic system uses a single location for both transmit and receive, whereas a bistatic system locates the transmitter and receiver at separate locations. Monostatic radars operating on only a single polarization may employ either a single antenna that is switched between transmit (Tx) and receive (Rx) modes, or two separate, but colocated antennas. The use of separate antennas in a monostatic system affects antenna design, due to the need to minimize crosstalk between the Tx and Rx channels. The addition of a receiver in a second location introduces new error sources involving antenna placement, increased sensitivity to misplacement of the calibration objects, and the suitability of particular objects for bistatic measurements.

Several considerations arise in the selection of objects for bistatic calibration [4]–[6]: the variability of the bistatic scattering pattern across the angular region of interest, the intensity of the scattering across the angular region of interest, the availability of a reliable reference dataset such as calculations, and polarization-changing phenomena. As a result, reference objects that are quite suitable for monostatic calibration, such as dihedrals and trihedrals, are not always desirable for bistatic measurements.

Since the purpose of this paper is to investigate the suitability of several existing and proven bistatic calibration objects, and to document the specific problems and benefits of using a particular calibration object, the objects are evaluated on the basis of the factors previously listed. Not of interest were calibrators of several existing and proven bistatic calibration objects, and to document the specific problems and benefits of using a particular calibration object, the objects are evaluated on the basis of the factors previously listed. Not of interest were calibrators...
A reference calibration object, for instance, nearly always requires a precise calculation of the exact scattering coefficients' amplitude and phase. Reference objects that are more complicated than a canonical set of spheres, disks, or small cylinders require computationally intense numerical electromagnetic solutions. Such solutions are sometimes impractical, depending on the complexity and electrical size of the object. All of these factors are considered in selecting objects for the calibration of a bistatic radar system, depending on the unique capabilities and deficiencies of a given measurement environment. In this study, the main figure of merit of the calibration objects will be the magnitude of the bistatic radar reflectivity (i.e., the bistatic RCS).

In order to provide for a meaningful evaluation of bistatic calibration objects that is still applicable to a generalized measurement environment, the ideal measurement facility should possess: 1) the capability to precisely align the reference objects; 2) good antenna polarization purity of at least 30 dB; 3) a large signal-to-noise ratio capable of producing reliably repeatable measurements; 4) the capability to perform fixed angle bistatic or swept angle bistatic measurements; 5) the capability to perform measurements on a wide variety of objects; and 6) relative ease in object mounting and system configuration.

The European Microwave Signature Laboratory (EMSL) [7] at the European Commission’s Joint Research Centre (Ispra, Italy) was chosen because it fits all of these criteria. An auxiliary capability was also available for limited duplication of the EMSL measurements at an instructional RCS lab at the Air Force Institute of Technology (AFIT). The latter facility did not have the capability to efficiently collect fully polarimetric data, nor does it have the measurement flexibility of the EMSL. These factors make the difference between the facilities sufficient enough to justify its use in extending the applicability of these results to a wide range of measurement environments.

This paper is organized as follows. Section II gives the basics of calibration of a polarimetric bistatic radar. Section III presents the methodology followed to assess the performance of the calibration objects used in the subsequent indoor RCS measurements. The results of the measurements and the discussion on the selection of the calibration objects are given in Section IV. The conclusions of this study are summarized in Section V.

II. BACKGROUND

A. Definition of Terms

1) Scattering Matrix: A polarimetric measurement gathers four complex scattering coefficients at a single bistatic angle and frequency. These values are arranged in a 2 x 2 complex scattering matrix. Scattering matrices usually take the form of [2]

\[ S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{bmatrix} \]

where the elements of the matrix \( S \) denote the complex scattering coefficients of each respective measurement. The scattering matrix is also referred to as the Sinclair matrix [2]. The matrix representation is useful in performing calculations for analysis and calibration, as seen in the following sections.

2) Subsystem Distortion Matrix: The errors introduced as a result of nonideal hardware can be calculated using two different 2 x 2 complex matrices called subsystem distortion matrices. These two matrices correspond to the distortion of the receiver subsystem and the transmitter subsystem, as given by

\[ R = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{HV} & R_{VV} \end{bmatrix} \quad T = \begin{bmatrix} T_{HH} & T_{HV} \\ T_{HV} & T_{VV} \end{bmatrix}. \]

\( R \) and \( T \) are the receiver and transmitter subsystem distortion matrices, respectively. The matrices operate on the theoretically pure object scattering matrix, thereby distorting the actual scattering coefficients, to yield the same value as the measurement obtained with the system to be calibrated. Therefore, the measured scattering matrix as given by the real-world system can be expressed as [2]

\[ M = RST \]

where \( M \) is the measured 2 x 2 scattering matrix and \( S \) is the theoretically pure, actual scattering matrix. This paper focuses on the effect of the measured and theoretical scattering matrices (\( M \) and \( S \), respectively) on the overall calibration equation.

B. Basic Calibration Relation

For a given measurement, more than one type of calibration can be used. The determination of the calibration type is dependent on the quality and sophistication of the measurement facility, the measurement conditions, and the degree of accuracy required. Radar calibration can be of three basic types: Amplitude and phase (Type-1), simple polarimetric (Type-2), and full polarimetric (Type-3). These techniques are evaluated in our companion paper [8]. All calibration methods, however, have in common a basic relationship that provides an interpretation of the raw measurement of the object under test, based on the relationship between the calibration object measurement and its theoretical value. This fundamental relationship can be expressed as [1]

\[ S_{\text{cal}} = \frac{S_{\text{tar}} - S_{\text{tar,kg}}}{S_{\text{cal,tar}} - S_{\text{cal,tar,kg}}} S_{\text{cal,tar,th}} \]

where \( S_{\text{cal}} \) is the calibrated response of the object. \( S_{\text{cal,tar}} \) and \( S_{\text{tar}} \) are, respectively, the responses of the calibration object and the object under test. \( S_{\text{cal,tar,kg}} \) and \( S_{\text{tar,kg}} \) denote the corresponding background responses. \( S_{\text{cal,tar,th}} \) is the theoretical response of the calibration object. This assumes that the object–mount interaction is negligible.

III. EXPERIMENTAL METHODOLOGY

A. Calibration Object Selection

There is a range of objects that have been used as a canonical set for calibration. Monostatic calibration objects are often similar, but some objects used for monostatic calibration are not suitable in a bistatic scenario. Some popular objects for monostatic calibration are trihedrals, dihedrals, disks and plates, spheres, and cylinders. All objects are usually metallic with a brushed or polished finish.
TABLE I
TEST MATRIX

<table>
<thead>
<tr>
<th>Object</th>
<th>Orientation</th>
<th>Measurement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic sphere</td>
<td>swept bistatic</td>
<td>monostatic</td>
</tr>
<tr>
<td>Short cylinder</td>
<td>axis parallel to x-axis</td>
<td>bistatic: 4.6 deg</td>
</tr>
<tr>
<td></td>
<td>axis 45° from horizontal</td>
<td>monostatic</td>
</tr>
<tr>
<td></td>
<td>axis 67.5° from horizontal</td>
<td></td>
</tr>
<tr>
<td>Dihedral</td>
<td>one face: 380 mm, a=155 mm</td>
<td>bistatic: 4.6 deg</td>
</tr>
<tr>
<td></td>
<td>Seam oriented vertical</td>
<td>monostatic</td>
</tr>
<tr>
<td></td>
<td>Seam oriented vertical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seam 45° from vertical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seam 45° from vertical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seam 22.5° from vertical</td>
<td></td>
</tr>
<tr>
<td>Circular disk</td>
<td>20 cm diameter</td>
<td>bistatic: 4.6 deg</td>
</tr>
<tr>
<td></td>
<td>Specular orientation</td>
<td>monostatic</td>
</tr>
<tr>
<td>Wire mesh</td>
<td>19 cm x 20 cm</td>
<td>bistatic: 4.6 deg</td>
</tr>
<tr>
<td></td>
<td>Wire mesh spaced 1 cm</td>
<td>monostatic</td>
</tr>
<tr>
<td></td>
<td>Wire mesh oriented</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tilted 45° counter-clockwise</td>
<td></td>
</tr>
<tr>
<td>Trinocular</td>
<td>one face: 102 mm, c=145 mm</td>
<td>bistatic: 4.6 deg</td>
</tr>
<tr>
<td></td>
<td>Specular orientation</td>
<td>monostatic</td>
</tr>
</tbody>
</table>

TABLE II
AVERAGE ALIGNMENT ERROR AND STANDARD DEVIATION FOR TYPE-1 CALIBRATION USING SMALL DISK

<table>
<thead>
<tr>
<th>Object Misalignment</th>
<th>VV-error</th>
<th>HH-error</th>
<th>VH level</th>
<th>HV level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.17 ± 0.01 dB</td>
<td>0.10 ± 0.01 dB</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1°</td>
<td>0.32 ± 0.04 dB</td>
<td>0.35 ± 0.01 dB</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2°</td>
<td>1.24 ± 0.04 dB</td>
<td>1.28 ± 0.01 dB</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE III
AVERAGE ALIGNMENT ERROR AND STANDARD DEVIATION FOR CALIBRATION USING SPHERE

<table>
<thead>
<tr>
<th>Object Misalignment</th>
<th>VV-error</th>
<th>HH-error</th>
<th>VH level</th>
<th>HV level</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>0.79 ± 0.15 dB</td>
<td>0.28 ± 0.03 dB</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE IV
AVERAGE ALIGNMENT ERROR AND STANDARD DEVIATION FOR CALIBRATION USING DIHEDRAL (TILTED 22.5°)

<table>
<thead>
<tr>
<th>Object Misalignment</th>
<th>VV-error</th>
<th>HH-error</th>
<th>VH level</th>
<th>HV level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.38 ± 0.04 dB</td>
<td>0.95 ± 0.01 dB</td>
<td>-39.3 dBsm</td>
<td>-39.3 dBsm</td>
</tr>
<tr>
<td>1°</td>
<td>2.76 ± 0.10 dB</td>
<td>3.68 ± 0.06 dB</td>
<td>-36.8 dBsm</td>
<td>-36.0 dBsm</td>
</tr>
<tr>
<td>2°</td>
<td>7.01 ± 0.13 dB</td>
<td>8.46 ± 0.43 dB</td>
<td>-32.5 dBsm</td>
<td>-31.5 dBsm</td>
</tr>
</tbody>
</table>

B. Measurement Procedures and Conditions

A systematic alignment error was introduced for each measurement of Table I, with the exception of the sphere measurement. The alignment error ranged from 0° to 2°, with increments of 0.5°. The error was added in either azimuth or elevation, based upon which misalignment axis would provide the worst case measurement error for the specific object under test.

A frequency band of 5–15 GHz was chosen for the measurement of all objects, where the subset of 6–14 GHz was used in the analysis. A 1-GHz region was trimmed from either side of the measurement to mitigate the effects of frequency lobes introduced by windowing of the measurement.

The EMSL provides a fully polarimetric indoor anechoic environment with a distance between the radar and object of 10 m, yielding a quiet zone of 30 cm at the highest selected frequency. The antennas used in the EMSL consist of two dual-polarized quad-ridged horns with isolation about 28 dB within the frequency range of 5–15 GHz. At 10 GHz, these antennas showed a gain of 15.8 dBi (decibels with respect to isotropic), and beamwidths in the E and H planes of 27.5° and 23°, respectively.

For each object and orientation listed in the test matrix, measurements were performed for each of the two Tx/Rx combinations. All measurements were fully polarimetric, i.e., HH, VH, HV, andVV polarization were all collected. Finally, in the selected frequency range and the measurement setup used in the EMSL, the edge effects observed in the measurements of the dihedral and trihedral were negligible.

IV. RESULTS

For each object, measurements were taken and calibrated with the EMSL’s standard two-object polarimetric calibration technique at nearly monostatic angles. The scattering coefficients were predicted using a suitable analytic or numerical technique for comparison with the calibrated measurement.

A. Dihedral (Quasi Monostatic)

In a monostatic configuration, a dihedral provides an excellent reference object for the purpose of cross-polarization calibration. The theoretical prediction can be realized using a method of moments (MoM) solver. However, cross-polarization
calibration can be accomplished with two measurements with the same dihedral in different orientations, without knowledge of the exact theoretical RCS prediction. This is done in the EMSL simple polarimetric (Type 2) calibration technique described herein.

The scattering matrix of the dihedral with the seam oriented parallel to the vertical polarization unit vector is

\[ S_0 = \sqrt{S_{\text{vert}}} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}. \]  

(3)

For a dihedral composed of two identical faces at right angles to each other, with face dimensions \( a \) and \( b \), the maximum monostatic scattering coefficient \( (S_{\text{vert}}) \) is

\[ S_{\text{vert}} = \frac{16\pi a^2 b^2}{\lambda^2}. \]  

(4)

As explained in [9], the scattering matrix of the same dihedral rotated in the plane defined by the direction of the wave propagation can be found by a rotation of the scattering matrix of (3). At a rotation through angle \( \theta \), the scattering matrix becomes

\[ S(\theta) = S_0 \begin{bmatrix} -\cos(2\theta) & \sin(2\theta) \\ \sin(2\theta) & \cos(2\theta) \end{bmatrix} \]

\[ = \sqrt{S_{\text{vert}}} \begin{bmatrix} -\cos(2\theta) & \sin(2\theta) \\ \sin(2\theta) & \cos(2\theta) \end{bmatrix}. \]  

(5)

If \( \theta = 22.5^\circ \), then

\[ S(\theta = 22.5) = \frac{\sqrt{S_{\text{vert}}}}{\sqrt{2}} \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix}. \]  

(6)

The advantages of using the dihedral in an orientation such that the scattering matrix reduces to the values in (6) are twofold. First, the absolute amplitude need not be known if the amplitude in the \( \theta = 0^\circ \) orientation is known \( (S_{\text{vert}}) \) is known. Second, the elements of the scattering matrix are equal in magnitude, yielding strong cross-polarization response, as well as being linearly independent from all copolarizing scatterers.

The disadvantage of using the dihedral as a calibrator is its alignment sensitivity. For measurement systems which use two closely separated antennas for monostatic measurements, such as the EMSL, this antenna separation can be significant enough so that the power of each polarization channel is not balanced as assumed by (3) and (6). In the case of the EMSL, the antennas on each sled are separated by 1.7\(^\circ\). Fig. 2 is the MoM calculation of a measurement in this configuration. The difference in the copolarization channels is up to 1 dB. The RCS level of the cross-polarization channel is on the order of \(-60\) dBsm (decibels with respect to a square meter).

These results indicate that the dihedral is best suited for monostatic cross-polarization calibration of a radar system that has a single Tx/Rx antenna, rather than two closely separated antennas.

For a polarimetric calibration, the ratio of the scattering coefficients of the vertical dihedral to the tilted dihedral is important.

Fig. 2. MoM simulation of an EMSL monostatic measurement of the vertical dihedral.

Fig. 3. Calibrated RCS ratios of measurement of dihedral in two orientations—performed in the EMSL.

Using (3) and (6), one can predict the trend versus frequency of this ratio by

\[ S_0 \times S^{-1}(\theta = 22.5) = \sqrt{2S_{\text{vert}}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \]  

(7)

If a dihedral measurement such as this were to be used in a polarimetric calibration, such as one for which the exact scattering matrices of the cross-polarizing reference objects is not known, the ratio of the scattering coefficient of the copolarizing orientation to that of the cross-polarizing orientation would be similar to the trend of the RCS ratios versus frequency that are shown in Fig. 3.

The variations in Fig. 3 can be contrasted with the expectation of relatively constant ratios in the truly monostatic scenario. The rippling and variations due to the small separation between the Tx and Rx antennas in the EMSL create uncertainties that make these measurements inappropriate for calibration of the copolarization channels in a polarimetric technique. The scattering coefficient of the tilted dihedral relative to that of the vertical dihedral for each polarization channel shows a smooth trend versus frequency, as indicated by (6).
A dihedral measured with a similar angular separation between the antennas may be suitable when used as a depolarizing calibrator—a calibration object that is used to calibrate the cross-polarization channels. This gives reverse-diagonal elements of $\mathbf{R}$ and $\mathbf{T}$. For depolarization calibration, it is only necessary that the depolarizing object has a high cross-polarization RCS. A tilted dihedral meets this requirement, even at small bistatic angles.

B. Dihedral (Bistatic)

As can be predicted, dihedral measurements at larger bistatic angle, such as 6° or greater, create even larger deviations from the ideal monostatic response. The tilted dihedral still yields a large cross-polarization RCS, which makes it suitable for a Type-3 calibration, but the vertical dihedral begins to show a higher RCS in the cross-polarization channels. This phenomenon creates problems for calibration, since it is no longer a good approximation to set the cross-polarization scattering coefficient to zero in the theoretical prediction. Rather, the cross-polarization coefficients must be calculated. Unfortunately, low levels of the cross-polarization scattering coefficient lead to numerical noise issues with an iterative MoM solver code. This is seen in Fig. 2, specifically the HV-polarization channel. This effect will not just degrade the cross-polarization calibration capability of a Type-3, but will degrade the overall performance of the calibration. These results indicate that in the absence of extraordinary measures to precisely align the object and predict its RCS via a MoM solver, the dihedral is not suitable for bistatic measurements beyond the nearly monostatic configuration of 2° to 3° of angular separation. A dihedral of reduced electrical size would be preferable.

C. Cylinders

Cylinders can be classified by the ratio of length to diameter. A long cylinder, one with a length to diameter ratio greater than two, offers a higher specular RCS than a sphere of the same diameter, but has more alignment sensitivity than a short cylinder. Also, the design of the pedestal can be problematic for a long cylinder. It is difficult to manufacture a pedestal that allows precise alignment of a long cylinder, but does not interfere with the measurements. Since the long cylinder yields no improvement over the short cylinder, it will not be discussed further.

A short cylinder, one with a length to diameter ratio less than one half, has a higher monostatic RCS than a long cylinder having the same maximum dimension. This is an important feature, since the maximum dimension of the object defines a bounding box that must fit within the measurement facility’s quiet zone. This is often a critical, limiting factor in far-field measurements. Additionally, the short cylinder provides much less cross-polarization RCS when tilted off of the axis of rotation, as seen in Fig. 4. The RCS of the short cylinder in Fig. 4 is approximately 7 dB higher than that of the long cylinder, and the cross-polarization RCS component is low enough to be indistinguishable from the ambient noise. The cross-polarization response shown in the plot is comparable to the cross-polarization isolation of the antennas.

The short cylinder is used successfully in the calibration of the BICOMS system [10] and takes advantage of the flat end-cap of the cylinder for bistatic phase calibration. This particular usage illustrates each of the strengths of this cylinder as a bistatic reference object. The RCS in the copolarization channels is higher than a sphere of the same diameter. Additionally, the short cylinder is largely insensitive to alignment error, and the flat, circular surface on the end-caps provides a scattering pattern with a distinct phase peak. From Fig. 5, the MoM prediction of the short cylinder in both monostatic and bistatic configurations also demonstrates that the short cylinder is predicted more easily than the long cylinder when using a combined electric and magnetic field integral equation and an iterative matrix solver. In this study, the MoM code used employed a multilevel fast multipole algorithm as the matrix solver, and an electric field integral equation formulation.

D. Trihedral

Trihedrals are popular monostatic calibration objects due to high peak RCS and ease of alignment. The cross-polarization return is nonzero, because of diffraction from the edges. Two of
the three edges are aligned diagonally with respect to the horizontal and vertical directions, giving a high cross-polarization RCS.

The RCS of the trihedral becomes highly rippled and dramatically lower as the bistatic angle is increased beyond 6°. The high degree of rippling makes the trihedral extremely difficult to align such that the RCS is unpredictable. Thus, the trihedral is not suitable at all for bistatic calibration, only for monostatic, copolarization amplitude calibration.

For the trihedral, the cross-polarization monostatic RCS is low enough to be indiscernible from the clutter and polarization channel crosstalk. The cross-polarization RCS levels are the result of edge diffraction from the forward edges that are oriented diagonally with respect to the antenna. The low levels of the cross-polarization RCS make it hard to predict, and thus unsuitable for any Type-3 calibration. Alternatively, the use of a square dihedral (where the edges are all parallel or perpendicular with respect to the antenna) would alleviate this problem.

As seen in Fig. 6, the comparison of the trihedral measurement to the MoM calculation is on the average less than 1 dB. The lobing in the frequency domain makes the trihedral sensitive to misalignment; however, it is shallow enough so that the copolarization RCS remains highly predictable.

E. Circular Disk

The combination of high copolarization RCS and a readily available theoretical prediction via physical optics makes the circular disk an obvious choice for monostatic or quasi-monostatic calibration. However, the disk is extremely alignment-sensitive, and alignment verification can add time to a calibration procedure. In the EMSL, which uses a precise laser alignment system, the circular disk has shown to be a very valuable object. The cross-polarization RCS due to diffraction from the disk’s edge is very low relative to the copolarization RCS, giving the scattering matrix a nearly pure copolarization response.

F. Sphere

The rotational symmetry of the sphere alleviates alignment problems normally associated with a calibration measurement. However, since the sphere needs to be fairly large to produce an RCS high enough to calibrate, object positioning can become a problem. Using a large sphere measured at a small bistatic angle will necessitate the mitigation of the creeping wave contribution. The creeping wave for a sphere that occupies all, or exceeds the dimensions of, the quiet zone will not interact with the specular return in a manner characteristic of a far-field measurement. The magnitude of this creeping wave decreases in proportion to the size of the sphere, and is further reduced when measured at small bistatic angles. Then only the specular RCS return will remain, which is from the front of the sphere, allowing a far-field nearly monostatic measurement to be performed on a sphere for which the dimensions exceed the dimensions of the chamber’s quiet zone.

As seen from Fig. 7, the RCS of the sphere in the optics region is relatively constant versus frequency in a nearly monostatic configuration. This fact illustrates another possible advantage of using the sphere calibration. As seen in the figures for both polarizations, the signal level of the measurement is not large enough to be able to discern the lobing pattern of the RCS in the frequency domain. For this frequency band, the lobing pattern is essentially inconsequential. In creating a theoretical prediction, it is reasonable to use a single complex constant for this entire band, rather than the vector that represents the true scattering coefficient. This would save memory and computational time in calibrating with the sphere over this bandwidth.

G. Wire Mesh

Though not considered a canonical object, the wire mesh has also proven to be a good object for polarimetric calibration. The wire mesh is a simple arrangement of parallel wires, in this case separated from each other by a distance of 1 cm. The mesh consists of 19 wires, each of length 20 cm, thus yielding a square mesh. It acts as a polarization filter, where only the polarization component of the incident wave parallel to the length of the wires will be reflected—all other components are transmitted through the mesh. This assumes that the wires are thin enough such that the specular return from the other polarization is negligible.

Under the assumption that the wires are both long and thin with respect to the incident wavelength, and further that the main lobe of the RCS is wide relative to the bistatic angle being
considered, the scattering characteristic of the wires in the vertical orientation is approximated by the following relationship [7]:

$$S_{\text{mesh,vert}} = S_{\text{mesh}} \begin{bmatrix} 0 & 0 \\ 0 & \cos^2 \left( \frac{\theta}{2} \right) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ S_{\text{VV,mesh,vert}} \end{bmatrix}. \quad (8)$$

In the tilted configuration, the vector takes the form [7]

$$S_{\text{mesh,tilt}} = \frac{S_{\text{mesh}}}{2} \begin{bmatrix} 1 \\ -\cos \left( \frac{\theta}{2} \right) \\ -\cos \left( \frac{\theta}{2} \right) \\ \cos^2 \left( \frac{\theta}{2} \right) \end{bmatrix} = \begin{bmatrix} S_{\text{HH,mesh,tilt}} \\ S_{\text{VH,mesh,tilt}} \\ S_{\text{HV,mesh,tilt}} \\ S_{\text{VV,mesh,tilt}} \end{bmatrix}. \quad (9)$$

In Fig. 8, the measurement of the mesh for which the wires are aligned vertically, the high flat response of the VV channel is immediately apparent. Like the sphere, this is also a good characteristic for a calibration object. The HH-polarization component in this measurement is due to the mounting foam, which is oriented such that it produces a direct specular return to the radar. This may be overcome by a more thoughtful design of the mesh mounting. Surface wave effects within the wires may also contribute to this anomaly, which could potentially be mitigated by cutting the wires into 2–5-cm segments.

Fig. 9 shows the same wire mesh measured at an orientation 45° from vertical. As expected, the RCS of each polarization channel is nearly identical. The ratio of the RCS versus frequency for the vertical and tilted orientations is not constant. However, the major benefit in selecting this object is not to create an amplitude correction factor similar to the copolarization channel compensation, but to isolate the distortion terms of the antenna’s polarization distortion matrix.

The mesh of long, thin cylinders (wires) also gives this object exceptional bistatic scattering characteristics. The wide main lobe of the RCS response of each polarization channel allows it to be used as a good polarizing/depolarizing object for bistatic angles wider than 2°. This cannot be said of the dihedral, or any other object with a high, predictable cross-polarization RCS. In the calibrations performed in the EMSL, the calibration objects are measured at a bistatic angle of about 5°, and the resulting cross-polarization isolation is quite good.

V. Conclusion

In order to select an object with high RCS and minimal sensitivity to alignment error in a given bistatic configuration, several results have been shown to be of primary importance. Objects can be chosen whose scattering matrices are diagonal, or quasi diagonal, in both monostatic and bistatic configurations. This may alleviate the need for some time-consuming simulations to be done in order to accurately predict the bistatic RCS. Indeed, these objects are more accurately predicted using relatively simple analytical methods. This is the case for objects such as the sphere and disk.

It has further been shown that the parallel wire mesh offers promise as a versatile bistatic cross-polarization calibration reference object. It offers high and smooth cross-polarization RCS at a much greater bistatic angular range than any other object evaluated in this work.

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Christopher J. Bradley (M’96) received the B.S.E.E. degree from the Rose-Hulman Institute of Technology, Terre Haute, IN, and the M.S.E.E. degree in the area of bistatic radar polarimetry and computational electromagnetics from the Air Force Institute of Technology, Wright-Patterson AFB, OH, in 1999 and 2001, respectively. He currently serves the U.S. Air Force as an Engineering Program Manager with current duty as an executive officer in Las Vegas, NV. Mr. Bradley is a member of Tau Beta Pi andEta Kappa Nu engineering honor societies.

Giuseppe Nesti was born in Piteglio, Italy, in 1957. He received the laurea degree in physics from the University of Florence, Florence, Italy, in 1983, with a thesis on remote sensing of natural surfaces by means of microwave radiometry. In 1985, he joined the European Space Technology Centre, European Space Agency, Noordwijk, The Netherlands, where he was involved mainly in the specification and testing of millimeter-wave radiometers. Since 1988, he has been working at the Joint Research Centre, European Commission, Ispra, Italy, where he has been involved as the key microwave specialist in the design, construction, testing, and operation of the European Microwave Signature Laboratory (EMLS). He was Responsible of the EMLS operation and scientific program until March 2001. His main research interests concern the experimental investigation of the radar scattering properties of man-made and natural objects, in particular the signal decorrelation induced by natural changes, and the development of calibration procedures for bi- and multistatic polarimetric radar systems.

Andrew J. Terzuoli, Jr. (S’77–M’82) received the B.S. degree from the Polytechnic Institute of Brooklyn, New York, the M.S. degree from the Massachusetts Institute of Technology, Cambridge, and the Ph.D. degree from The Ohio State University (OSU), Columbus, in 1969, 1970, and 1982, respectively, all in electrical engineering. He has been on the civilian faculty of the Air Force Institute of Technology, Wright-Patterson AFB, OH, since late 1982. Prior to this, he was a Research Associate at the ElectroScience Laboratory, OSU, and a member of the technical staff at the Bell Telephone Laboratories in New Jersey. His research areas include computer model-based studies; application of parallel computation, VLSI technology, and RISC architecture to numerical and transform methods in electromagnetics; remote sensing and communication; passive radar; antennas, electromagnetics, wave scattering, radar cross section; machine vision and image processing; and automated object recognition. He has published numerous reports and articles in journals and conference proceedings in these and related areas. His research has been funded by various agencies of the U.S. Government, private industry, and research institutes.

Kelce S. Wilson received the B.S. degree in electrical engineering from the University of Arizona, Tucson, the M.B.A. degree from Chapman University, Orange, CA, the M.S. degree in electrical engineering and the Ph.D. degree in electromagnetic field theory from the Air Force Institute of Technology, Wright-Patterson AFB, OH, and the J.D. degree from Capital University, Columbus, OH, in 1988, 1993, 1994, 1998, and 2005, respectively. He is a registered patent agent with the U.S. Patent and Trademark Office, with software security, computational electromagnetics, and radar cross section calculations expertise. He has spent over 13 years in the Air Force working in both satellite control for the Consolidated Space Operation Center and signature prediction for the Sensors Directorate of the Air Force Research Laboratory. Currently he is an Associate with Fulbright and Jaworski, Dallas, TX. His research has contributed to a better understanding of novel phenomena in radar polarization, processing of digital terrain elevation data, and exploitation of synthetic aperture radar imagery. He has been an invited speaker in the fields of automatic target recognition and radar noise prediction. His current research area is in antihacking techniques for protecting software from exploitation.

From 1990 to 1992, he was a Research Assistant in the RF Division at the European Space Technology Centre of the European Commission, The Netherlands. Since 1993, he has been with the Directorate General Joint Research Centre of the European Commission, Ispra, Italy. His research interests are in the area of computational electromagnetics. His research interests include radar cross section prediction, measurement, analysis, and validation as well as scattering centers, bistatic scattering, and periodic corrugated waveguides. He was a distinguished graduate (top 10%) of AFIT and at Squadron Officer School and has completed in-residence Air Command and Staff College. He has also been named company grade officer of the quarter and field grade officer of the quarter for different organizations. He is an Eagle scout and has served as a troop committee chairman, varsity coach, assistant scoutmaster, and a webelos leader.

Dr. Larkin Hastriter was awarded the Meritorious Service Medal, Air Force Commendation Medal, Air Force Achievement Medal, and the Military Outstanding Volunteer Service Medal for his military service. He is a member of Tau Beta Pi, and Eta Kappa Nu. He was a National Collegiate Engineering Awards winner in 2001.

Peter J. Collins (S’84–M’85–SM’00) received the B.S.E.E. degree from the University of Minnesota, St. Paul, and the B.A. degree from Bethel College, St. Paul, in 1985, and the M.S.E.E. and Ph.D. degrees from the Air Force Institute of Technology, Wright-Patterson AFB, OH, in 1990 and 1996, respectively. From 1986 to 1989, he served a tour of duty at the Air Force Wright Laboratories, Wright-Patterson AFB, OH, where he performed research in electro-optic component development. In 1990, he served as Engineering Branch Chief with the Radar Target Scatter Division, 6585th Test Group, Holloman AFB, NM. He is currently a Lieutenant Colonel in the U.S. Air Force and Adjunct Associate Professor of electrical engineering at the Air Force Institute of Technology. His research interests are in the area of computational electromagnetics.

Joaquim Fortunya-Guasch (S’93–A’96–M’04) was born in Tarragona, Spain, in 1964. He received the "Ingeniero" degree in telecommunications engineering from the Polytechnic University of Catalonia, Barcelona, Spain, and the Dr.-Ing. degree in electrical engineering from the Universität Karlsruhe, Karlsruhe, Germany, in 1988 and 2001, respectively.

From 1988 to 1989, he worked on the design of microwave circuits at Ka-Band in the Electromagnetics and Photonics Engineering Group at UPC. From 1990 to 1992, he was a Research Assistant in the RF Division at the European Space Technology Centre of the European Commission, The Netherlands. Since 1993, he has been with the Directorate General Joint Research Centre of the European Commission, Ispra, Italy. His research interests are in the fields of advanced microwave remote sensing monitoring techniques, calibration techniques for polarimetric radar systems, and the retrieval of biophysical parameters using polarimetric SAR interferometry.