Fully Polarimetric Bistatic Radar Calibration With Modified Dihedral Objects

C. Beaudoin, Member, IEEE, T. Horgan, G. DeMartinis, Senior Member, IEEE, M. J. Coulombe, Senior Member, IEEE, A. J. Gatesman, and W. E. Nixon

Abstract—We introduce the design of dihedral reflectors that are used to calibrate an instrumented, dual-linearly polarized, wide-bistatic compact radar range operating at 160 GHz. The polarization scattering matrix of this bistatic calibration object may be tailored to rotate the incident linear polarization state to a slant polarization state in a fashion similar to that of the 90° dihedral that is used for calibrating monostatic polarimeters. The bistatic calibration object that we describe here is capable of introducing this polarization rotation while simultaneously steering the mainlobe of its specular reflection to the receiver. As we demonstrate, this characteristic of the mainlobe-steered dihedral (MSD) object can be achieved over a wide range of bistatic angles. The MSD object possesses a variety of desirable qualities for the calibration of bistatic polarimeters, but they are particularly useful for those systems that do not possess the capability to rotate their feed arrangement (e.g., millimeter-/submillimeter-wave waveguide-based systems). Through both computational and experimental results, we demonstrate the capability of the MSD object to calibrate and characterize the accuracy (better than 0.5 dB) and polarization purity (≥50 dB) of a 160 GHz dual-linearly polarized, bistatic compact radar range at 15°, 45°, and 75° bistatic angles.

Index Terms—Calibration, compact range, millimeter-wave (MMW) measurements, MMW radar, radar polarimetry, radar scattering, radar testing.

I. INTRODUCTION

The use of dihedral corner reflectors for the calibration of monostatic polarimetric radar systems has been documented in [1] and [2]. To the best of our knowledge, the first work documenting the modification of the dihedral object for bistatic polarimetric calibration was reported in [3] although only for the vertical seam orientation. While there are a variety of efforts that have investigated the issues and subject of bistatic calibration dihedrals a wide range of bistatic angles. With this characteristic, the MSD provides the necessary transformation of the transmit/receive bistatic antennas to produce the necessary transformation of the transmit/receive polarization states for the calibration process [2], [5]. In other cases, when the transmit/receive antennas were static, cylinders have been used to provide the necessary polarization transformation [4]. Under the same static antenna conditions, wire grid calibration objects have been investigated to calibrate a bistatic polarimeter as well though with limited polarization purity [6]. In the case of the wire grid study, the mechanical structure supporting the object was believed to be an accuracy limiting factor. Since the wire grid is transmissive to particular polarization states, the results indicate that the definition of the elements of the polarization scattering matrix (PSM) is complicated by scattering of the mechanical structure supporting (particularly behind) the wire grid.

The calibration dihedral serves an important role in instrumented millimeter-wave (MMW)/submillimeter-wave polarimetric radar systems [11]–[13] that employ a large compact range optic to satisfy the far-field requirement within a physically confined space. In this case, the mechanical support needed to rotate the feed arrangement becomes unwieldy and adds overhead to data acquisition time, so the calibration requirement to transform the polarization state of the transmit/receive signals is imposed on the calibration objects alone. As we show in Section II, the mainlobe-steered dihedral (MSD) provides the necessary transformation of the transmit/receive polarization states to apply the wideband polarimetric radar calibration algorithm [1]. In this way, the MSD circumvents the need to rotate the antenna/optic’s feed arrangement for a fully polarimetric bistatic calibration while also providing a stronger radar return than that of a cylinder of comparable size.

In our survey, the dearth of information on the subject of bistatic calibration dihedrals appears, in part, because bistatic polarimeters tend to possess the capability to rotate their transmit/receive bistatic antennas to produce the necessary transformation of the transmit/receive polarization states for the calibration process [2], [5]. In other cases, when the transmit/receive antennas were static, cylinders have been used to provide the necessary polarization transformation [4]. Under the same static antenna conditions, wire grid calibration objects have been investigated to calibrate a bistatic polarimeter as well though with limited polarization purity [6]. In the case of the wire grid study, the mechanical structure supporting the object was believed to be an accuracy limiting factor. Since the wire grid is transmissive to particular polarization states, the results indicate that the definition of the elements of the polarization scattering matrix (PSM) is complicated by scattering of the mechanical structure supporting (particularly behind) the wire grid.

The bistatic calibration cylinder is also limited in its ability to transform the incident polarization state; it may only partially transform the incident linear polarization to the cross linear polarization. As we show in Section II, the MSD does not suffer from this limitation; the object can be tailored to produce a signature that is dominantly cross polarized over a large range of bistatic angles. With this characteristic, the MSD provides the capability to more fully characterize the polarimetric measurement accuracy of a bistatic polarimeter. Other bistatic calibration objects have been reported that...
exhibit this scattering behavior [7], but the MSD possesses an arguably simpler geometry that can be fabricated by any tool and die machine shop with wire electrical discharge machining (wire EDM) capabilities. The simplicity of the MSD is also advantageous when compared with constructing/procuring a wire grid. And, unlike the wire grid, the MSD is 100% reflective to all polarization states so that its PSM is less perturbed by the mechanical structure supporting the object.

In Section II, we expand on the previous work of the modified vertical seam dihedral [3] and outline the design of a dihedral object that more generally addresses the bistatic polarimetric calibration as well as its properties. In Section III-A, we describe the wideband polarimetric calibration algorithm [1] that was developed for monostatic calibration and how it may be applied for fully polarimetric bistatic radar calibration. In Section III-B, we describe the 160 GHz fully polarimetric bistatic compact radar range (CRR) and present the hardware realizations of the MSD that were used to calibrate the system and characterize its performance. In Sections IV and V, we present the measured results and discuss their significance in terms of radar cross section (RCS) accuracy and cross-polarization isolation/purity.

II. MAINLOBE-STEERED DIHREDRAL

A. Design

As noted in Section I, the MSD design is a modified form of the 90° corner angle dihedral reflector (the 90° dihedral). This concept represents an extension of the work reported in [3] where the authors modified a corner reflector having a vertically oriented seam to support polarimetric bistatic radar calibration. We generalize this modification by not requiring a vertical seam orientation while still maintaining specular reflection from the transmitter-to-receiver within a ray-tracing framework. In this way, the MSD design may achieve a normalized PSM, henceforth simply referred to as PSM, of the form

\[
S_{msd} = \begin{bmatrix}
-\gamma \\
\sqrt{1 - \gamma^2} \\
\gamma
\end{bmatrix}
\]

where \(\gamma\) is the copolarization scattering amplitude parameter and is in the range \([-1, 1]\). To realize a PSM prescribed by (1), the face-to-face interior and seam rotation angles of the MSD are determined jointly for a specified \(\gamma\) value. As we show in the Appendix, the joint determination of these angles is derived through a ray-tracing analysis of a corner reflector that is rotated by \(\psi_{msd}\) about the bisector \(x\)-axis of the bistatic radar collection geometry and possesses an interior angle \(\phi_{msd}\), as depicted in Fig. 1. The MSD design angles \(\psi_{msd}\) and \(\phi_{msd}\) are given by (A25) and (A28), respectively, in the Appendix and are duplicated here for convenience

\[
\psi_{msd} = \cot^{-1} \left( \sqrt{\frac{1 + \gamma}{1 - \gamma}} \cos \frac{\beta}{2} \right)
\]

\[
\phi_{msd} = 90 + \cos^{-1} \left( (1 + \gamma) \cos^2 \frac{\beta}{2} - \frac{\gamma}{2} \right)
\]

where \(\beta\) is the bistatic angle of the radar collection geometry, as shown in Fig. 1.

B. Properties

In the case when \(\beta = 0\) (monostatic radar), \(\phi_{msd}\) reduces to 90° and \(\gamma\) equates to \(\cos 2\psi_{msd}\). In this case, (1) reduces to the monostatic PSM of a 90° dihedral that is rotated by \(\psi_{msd}\) [1], [2]. The simplification of (1) for this specific case demonstrates that the MSD design formulation possesses the property that it collapses to the monostatic form of the 90° dihedral’s PSM for \(\beta = 0\). This is an anticipated characteristic, since the MSD design is a generalization of the 90° dihedral.

Also, for the vertical seam orientation (\(\psi_{msd} = 0\), \(\gamma\) equates to 1. In this case, (3) collapses to the formulation of the vertical seam corner reflector’s “corner angle” as reported in [3]. This is also to be expected, since the MSD design is a generalization of their work as well.

Finally, another insightful property is observed for \(\gamma = -1\). In this case, we observe that the MSD design angles (2) and (3) are independent of \(\beta\) and both equivalent to 90°. Here, we see that the MSD design collapses to that of the 90° dihedral. This object naturally possesses the property that its specular reflection is directed at the receiver from the direction of the transmitter when its seam lies along the \(y\)-axis (see Fig. 1) for any bistatic angle in the range \([0, 180]\). Because its (normalized) PSM is independent of bistatic angle, this object may be applied usefully for any bistatic angle in this range. The absolute RCS of this object, of course, will exhibit bistatic angle dependence.

III. FULLY POLARIMETRIC BISTATIC CALIBRATION AND CHARACTERIZATION WITH THE MSD OBJECT

A. Wideband Polarimetric Calibration Algorithm

The wideband calibration algorithm [1] has been used successfully for producing calibrated, fully polarimetric monostatic radar data [11]–[13]. As formulated in [1], the polarimetric distortions of the radar transceiver are represented by the transmit \((T)\) and receive \((R)\) distortion matrices

\[
[S^m] = [I] + [R][S_{ideal}][T]
\]

where \(S^m\) is the measured fully polarimetric scattering data, \(S_{ideal}\) is the theoretical PSM of the specific object measured by the radar system, and \(I\) represents the matrix of radar background scattering observed when the target is removed from the radar range.
The wideband calibration algorithm employs three measurements of calibration objects to estimate the radar system’s \( R \) and \( T \) matrices: 1) flat plate; 2) vertical seam dihedral; and 3) a dihedral with its seam rotated by \( \theta \) degrees relative to the vertical axis. Qualitatively, the calibration measurement of the flat plate provides an absolute RCS and phase reference to correct the amplitude and phase nonlinearities (as a function of frequency) in the system, while the dihedral measurements provide a measure for the amount of cross-polarization contamination present in the radar system.

The PSM of the flat plate used to provide the absolute RCS reference takes the form

\[
S_{fp1} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}
\]

and its absolute RCS is given by

\[
\sigma_{fp} = \frac{4\pi A^2}{\lambda^2} \cos^2 \beta
\]

where \( A \) is the area of the flat plate and \( \lambda \) is the wavelength of the incident/scattered electromagnetic fields. Equation (6) is independent of the flat plate’s shape (e.g., square and circular) and can be derived through a physical optics (PO) analysis when the bisector of the bistatic angle is coincident with the normal to the plate’s surface. As a PO solution, (6) only applies to electrically large plates.

The calibration algorithm also assumes that the calibration measurements of objects 2 and 3 are of standards having a PSM described by the following:

\[
S_{90dih} = \begin{bmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{bmatrix}
\]

This basis is satisfied by the dihedral corner reflector with a 90° interior angle in a monostatic radar collection geometry as described in [1] and [2]. This algorithm is not sensitive to the absolute RCS of the dihedrals provided they are electrically large objects. Rather, the relative amplitude and phase relationship between each of the polarization channels is the critical property exhibited by (7) that is exploited by the wideband polarimetric calibration algorithm. For this reason, we need not describe the RCS of the dihedral object in the absolute sense to compute the \( R \) and \( T \) distortion matrices.

We derive in [1] that measurement of a \( \theta = 22.5^\circ \) dihedral optimizes the estimates of the \( R \) and \( T \) matrices in the presence of receiver noise where the magnitude of each element of \( S_{90dih} \) is equal to \( 1/\sqrt{2} \). For this standard, the scattering amplitudes are distributed equally among all four polarization channels.

While these PSMs are derived to calibrate a monostatic radar system [1], the \( R \) and \( T \) matrix error terms to be calibrated out of the polarimetric radar measurements are inherent to the instrumentation hardware themselves and are not strictly a function of the data collection geometry. For this reason, we are justified in applying this algorithm for a bistatic collection geometry provided the bistatic calibration objects have PSMs of the form described by (5)–(7). In Section II, we described how (1)–(3) governing the MSD object collapse to that of the monostatic 90° dihedral that is given by (7).

We now relate (1)–(3) and (7) to the bistatic data collection geometry.

To successfully apply this algorithm for the bistatic collection geometry, we require MSD objects possessing the following two PSMs:

\[
S_{msd2} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}
\]

and

\[
S_{msd3} = \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix}
\]

for the calibration measurements of objects 2 and 3. For the sake of example, assume a collection geometry having \( \beta = 75^\circ \). For \( S_{msd2} \) (8), by comparison with (1), we observe that \( \gamma = 1 \). Then, applying (2) and (3), we compute the MSD design angles and \( \check{\psi}_{msd} = 0^\circ \) and \( \check{\phi}_{msd} = 127.5^\circ \). Similarly, for \( S_{msd3} \) (9), \( \gamma = 1/\sqrt{2} \), so that \( \check{\psi}_{msd} = 27.5^\circ \) and \( \check{\phi}_{msd} = 124.22^\circ \). This example demonstrates how we may realize the dihedral PSMs (7) necessary to apply the wideband calibration algorithm for the general bistatic case by employing the MSD object. However, for the bistatic case, we may not simply rotate a single calibration object about its seam rotation axis to measure the PSMs defined in (8) and (9)—measurement of two physically different MSD objects is necessary.\(^{1}\)

B. 160 GHz Fully Polarimetric Bistatic Compact Radar Range

The University of Massachusetts Lowell (UML) Submillimeter-Wave Technology Laboratory (STL) has developed a prototype 150–170 GHz fully polarimetric bistatic compact radar range [14] to expand its radar signature acquisition capabilities. A graphic of the bistatic compact radar range is shown in Fig. 2. The 27 in compact range mirrors integrated into the system support a quiet zone size of approximately 8 in in diameter and their staging/oilics support data collection from 10° to 80° in the bistatic angle. The system's MMW transceiver is outfitted with transmit and receive chains that are sensitive to the linear horizontal and vertical polarization basis and possesses a frequency-integrated RCS noise floor of approximately –85 dBsm.

As shown in Fig. 2, the MMW bistatic compact radar range is also outfitted with a metal Ogive style calibration pylon on which each calibration object is mounted for measurement. This calibration pylon incorporates azimuth, elevation, tilt, and seam rotation axes necessary to align a calibration object within the quiet zone. The calibration pylon may be removed from the quiet zone to support the requisite background subtraction measurement [1] as well.

The MMW bistatic compact radar range also incorporates a helium–neon (He–Ne) laser alignment system. The transmitter and receiver horn feeds are outfitted with independent He–Ne lasers that are aligned coaxially with the direction of their respective boresight directions. These lasers are utilized to

\(^{1}\)If one were to fabricate an MSD object that possessed an adjustable interior angle \( \check{\phi}_{msd} \), the requirement to physically exchange these objects could be circumvented. Such a design is considered nontrivial.
C. Calibration and Characterization Methodology

To demonstrate the polarimetric performance of the MMW compact radar range as a function of bistatic angle, three sets of calibration objects were designed and fabricated for 15°, 45°, and 75° bistatic angles. These included a 1.265 in diameter flat plate standard and 1.142 in diameter MSD objects satisfying (8) and (9) for each bistatic angle.

In addition to these calibration objects, two additional objects 4 and 5 were included in the set having the following PSMs:

\[
S_{\text{msd4}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad (10)
\]

\[
S_{90\text{dih}} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \quad (11)
\]

Objects 4 and 5 are not utilized for the calibration calculations of the \( R \) and \( T \) matrices. In our methodology, calibration objects 1–3 are utilized to compute the \( R \) and \( T \) distortion matrices of the system. These distortions are then removed from the measurements of objects 4 and 5 to provide absolutely calibrated fully polarimetric RCS measurements of these two objects, which are physically independent of calibration objects 1–3. In this way, the calibrated measurements of objects 4 and 5 provide an assessment of the system’s absolute RCS accuracy and cross-polarization performance that are independent of the measurements used to compute the \( R \) and \( T \) distortion matrices. An MSD object is used to realize the PSM given in (10), while a 90° dihedral with its seam oriented (horizontal) in the plane of the bistatic angle is used to realize (11).

A summary of the objects used to calibrate and characterize the performance of the MMW compact radar range is provided in Table I, and Fig. 3 provides a photograph of the objects that were fabricated and utilized for the demonstration. In order to avoid RCS errors in excess of 0.1 dB, the FEKO analysis shows that the manufacture tolerance of the interior angles should be held better than 0.25°. The wire EDM process that
was used to manufacture the objects reported here was able to machine the interior angles to a tolerance of \(\pm 0.04^\circ\). Each of the objects shown in Fig. 3 was polished to a mirror finish to support reflection by the compact radar range’s He–Ne laser alignment system.

### IV. Measurement Results

Fully polarimetric, frequency-swept I/Q measurements of each object identified in Table I were collected using the MMW bistatic compact radar range described in Section III-B. Using the wideband calibration algorithm described in Section III-A, the \(R\) and \(T\) matrices of the transceiver were calculated, frequency-by-frequency, for each bistatic angle from measurements of objects 1–3. The resultant \(R\) and \(T\) matrices were then used to calibrate the measured data for all five objects.

For each of calibration objects 1–3, two independent measurements were taken: one for calculation of \(R\) and \(T\) and one to be calibrated by the computed distortion matrices. The second measurement differed from the first only in terms of independent receiver noise, and the object was not removed or adjusted between the two measurements.

As a basis for assessing the absolute accuracy of the calibrated performance of the MMW bistatic compact radar range, electromagnetic scattering was computed for each object using FEKO and its multilevel fast multipole method solver. The calibrated measurements and associated computational results for all 15 object/bistatic-angle measurements are reported in Figs. 4–18.

Objects 1, 2, and 5 possess PSMs that do not generate any cross polarization of the incident polarization in theory. As such, the difference between the measured copolarized and cross-polarized levels for these objects provides a metric for the system’s calibrated cross-polarization isolation. Furthermore, because these objects do not produce cross-

---

**TABLE I**

<table>
<thead>
<tr>
<th>Object</th>
<th>(\beta = 15) degrees</th>
<th>(\beta = 45) degrees</th>
<th>(\beta = 75) degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\gamma) (\phi_{\text{mid}}) (\psi_{\text{mid}}) (\gamma) (\phi_{\text{mid}}) (\psi_{\text{mid}}) (\gamma) (\phi_{\text{mid}}) (\psi_{\text{mid}})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.265 inch diameter flat plate</td>
<td>1 97.50 0.00 1 112.50 0 1 127.50 0.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(\frac{1}{\sqrt{2}}) 96.93 22.68 1 (\frac{1}{\sqrt{2}}) 110.71 24.15 (\frac{1}{\sqrt{2}}) 124.22 27.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0 95.30 45.25 0 105.70 47.27 0 115.50 51.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>90 degree horizontal seam dihedral</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.** Fully polarimetric RCS results for object 1—flat plate and \(\beta = 15^\circ\). Measurement of this object is used to estimate the system’s \(R\) and \(T\) distortion matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement. Theoretical cross-polarized scattering from this object is zero so only measured residual cross polarization is plotted.
polarized scattering terms, we plot only the measured cross-polarized RCS for objects 1, 2, and 5. The frequency-averaged measurement error relative to the FEKO computations for each object is reported for 15°, 45°, and 75° bistatic angles in Tables II–IV, respectively. The frequency-averaged cross-polarization isolation for each object and bistatic angle is summarized in Table V.

V. DISCUSSION OF MEASUREMENT ERRORS
As reported in Tables II–IV, the worst case RCS measurement error of any of the copolarized scattering objects 1, 2, and 5 is 0.30 dB. Also, the cross-polarization isolation performance of the calibrated results is at a level of ~50 dB. Both of these performance metrics are in keeping with the performance reported on other instrumented bistatic radar measurements [2]–[4], [8].

We distinguish the error/accuracy inherent to the measurements of the copolarized scattering objects 1, 2 and 5, from those of objects 3 and 4, because we were unable to identify any reports on the measurement accuracy of objects that possess strongly cross-polarized bistatic scattering behavior. Hence, there is no basis on which to make comparative assessments of the MSD’s efficacy for producing accurate cross-polarization isolation performance.

In our literature search, we identified one piece of work discussing cross-polarization accuracy of bistatic measurements [9], but the author’s accuracy metrics are based on the total integrated scattering over 4π steradians so they are not directly comparable with the single aspect angle measurements reported here.
cross-polarization measurements of strongly cross-polarized scatterers. In lieu of a drawing a comparative assessment to establish the MSD object’s effectiveness as a bistatic radar calibration object, we simply discuss the measurement error in objects 3 and 4, as reported in Tables II–IV.

As outlined in Section III-A, the scattering behavior of MSD object 3 was tailored to provide equal scattering amplitude in all four polarization channels, while that of MSD object 4 was tailored to yield an object that provides a dominantly cross-polarized signature to evaluate the accuracy of cross-polarized RCS measurements. For MSD object 3, the greatest overall measurement error is 0.4 dB, which is nearly as good as that of any of the copolarized objects 1, 2, and 5. In the case of MSD object 4, the greatest overall measurement error of the cross-polarized measurements is 0.35 dB, which is also nearly as good as that of any of the copolarized measurements objects 1, 2, 3, or 5. However, the measurement error reported in the copolarized measurements of object 4 are significantly greater than those of any other measurements, but these errors are not attributed to the MSD itself.

Relative to all the measurement errors reported in Tables II–IV, the copolarized errors in the measurements of object 4 are most sensitive to stray copolarized scattering in the compact radar range. Secondary to the object under measurement, the low-observable (LO) support pylon (refer to Fig. 2) is the strongest source of copolarized
Fig. 13. Fully polarimetric RCS results for object 5—horizontal seam 90° dihedral at $\beta = 45^\circ$. Measurement of this object is used to assess the calibrated performance of the system independently of those used to derive the $R$ and $T$ matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement. Theoretical cross-polarized scattering from this object is zero so only measured residual cross polarization is plotted.

Fig. 14. Fully polarimetric RCS results for object 1—flat plate and $\beta = 75^\circ$. Measurement of this object is used to estimate the system’s $R$ and $T$ distortion matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement. Theoretical cross-polarized scattering from this object is zero so only measured residual cross polarization is plotted.

Fig. 15. Fully polarimetric RCS results for object 2—MSD with $\gamma = 1$ (vertical seam) at $\beta = 75^\circ$. Measurement of this object is used to estimate the system’s $R$ and $T$ distortion matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement. Theoretical cross-polarized scattering from this object is zero so only measured residual cross polarization is plotted.

Fig. 16. Fully polarimetric RCS results for object 3—MSD with $\gamma = 1/\sqrt{2}$ at $\beta = 75^\circ$. Measurement of this object is used to estimate the system’s $R$ and $T$ distortion matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement.

scattering in the compact range albeit in the range of $-40$ to $-50$ dBsm. The sensitivity of the copolarized measurements of object 4 is, therefore, attributed to two characteristics of the measurements.

1) The LO pylon is an Ogive design so that its stray scatter is copolarized.

2) Relatively weak copolarized scattering cross section of object 4 as indicated by the FEKO calculations in Figs. 7, 12, and 17.

Relative to any of the other copolarized measurements of objects 1, 2, and 5, the stray scatter from the pylon is relatively weak, and because it is copolarized, it is not observed in any of the cross-polarized measurements. However, the copolarized RCS of object 4 is diminished relative to those of any of the other objects so that its contribution to the total measurement does not dominate over the contribution from the pylon. This situation gives rise to the aforementioned sensitivity. Furthermore, the leading edge of the pylon is vertically oriented so that the pylon’s stray scatter in the vertical copolarized state is expected to be enhanced relative to that in the horizontal copolarized state. In comparing the horizontal copolarized measurement errors to the vertical copolarized errors for object 4, it is clear that the latter errors are the greater of the two. It is worth noting that the LO design of this pylon is optimized for monostatic radar measurements. This pylon was
Fig. 17. Fully polarimetric RCS results for object 4—MSD with $\gamma = 0$ at $\beta = 75^\circ$. Measurement of this object is used to assess the calibrated performance of the system independently of those used to derive the $R$ and $T$ matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement.

Fig. 18. Fully polarimetric RCS results for object 5—horizontal seam 90° dihedral at $\beta = 75^\circ$. Measurement of this object is used to assess the calibrated performance of the system independently of those used to derive the $R$ and $T$ matrices. Blue trace: FEKO CEM. Red trace: calibrated CRR measurement. Theoretical cross-polarized scattering from this object is zero so only measured residual cross polarization is plotted.

Table II

<table>
<thead>
<tr>
<th>Object</th>
<th>HH</th>
<th>HV</th>
<th>VH</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01 dB</td>
<td>-</td>
<td>-</td>
<td>0.01 dB</td>
</tr>
<tr>
<td>2</td>
<td>0.14 dB</td>
<td>-</td>
<td>-</td>
<td>0.15 dB</td>
</tr>
<tr>
<td>3</td>
<td>0.12 dB</td>
<td>0.06 dB</td>
<td>0.18 dB</td>
<td>0.20 dB</td>
</tr>
<tr>
<td>4</td>
<td>3.70 dB</td>
<td>0.20 dB</td>
<td>0.35 dB</td>
<td>6.79 dB</td>
</tr>
<tr>
<td>5</td>
<td>0.10 dB</td>
<td>-</td>
<td>-</td>
<td>0.15 dB</td>
</tr>
</tbody>
</table>

Table III

<table>
<thead>
<tr>
<th>Object</th>
<th>HH</th>
<th>HV</th>
<th>VH</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02 dB</td>
<td>-</td>
<td>-</td>
<td>0.01 dB</td>
</tr>
<tr>
<td>2</td>
<td>0.07 dB</td>
<td>-</td>
<td>-</td>
<td>0.14 dB</td>
</tr>
<tr>
<td>3</td>
<td>0.11 dB</td>
<td>0.09 dB</td>
<td>0.08 dB</td>
<td>0.17 dB</td>
</tr>
<tr>
<td>4</td>
<td>0.70 dB</td>
<td>0.17 dB</td>
<td>0.10 dB</td>
<td>4.81 dB</td>
</tr>
<tr>
<td>5</td>
<td>0.22 dB</td>
<td>-</td>
<td>-</td>
<td>0.25 dB</td>
</tr>
</tbody>
</table>

Table IV

<table>
<thead>
<tr>
<th>Object</th>
<th>HH</th>
<th>HV</th>
<th>VH</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01 dB</td>
<td>-</td>
<td>-</td>
<td>0.01 dB</td>
</tr>
<tr>
<td>2</td>
<td>0.12 dB</td>
<td>-</td>
<td>-</td>
<td>0.30 dB</td>
</tr>
<tr>
<td>3</td>
<td>0.30 dB</td>
<td>0.15 dB</td>
<td>0.37 dB</td>
<td>0.41 dB</td>
</tr>
<tr>
<td>4</td>
<td>0.37 dB</td>
<td>0.17 dB</td>
<td>0.31 dB</td>
<td>2.36 dB</td>
</tr>
<tr>
<td>5</td>
<td>0.12 dB</td>
<td>-</td>
<td>-</td>
<td>0.10 dB</td>
</tr>
</tbody>
</table>

Table V

<table>
<thead>
<tr>
<th>Object</th>
<th>$\beta = 15$ deg</th>
<th>$\beta = 45$ deg</th>
<th>$\beta = 75$ deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.5 dB</td>
<td>52.0 dB</td>
<td>48.0 dB</td>
</tr>
<tr>
<td>2</td>
<td>56.0 dB</td>
<td>52.5 dB</td>
<td>47.5 dB</td>
</tr>
<tr>
<td>5</td>
<td>53.0 dB</td>
<td>49.0 dB</td>
<td>51.5 dB</td>
</tr>
</tbody>
</table>

integrated into the UML bistatic CRR for the simple reason that funds did not support the development of a new LO pylon design optimized for the bistatic case. As such, some variation in the level of stray scattering from the pylon as a function of bistatic angle is to be expected.

The source of the RCS fluctuations as a function of frequency (see Fig. 16) in the FEKO computational results is unrelated to the target support pylon, since these computations modeled the MSD in a truly freespace configuration. As such, the observed fluctuations are an inherent scattering component of the MSD and arise from the edges. In fact, it can be shown that the period of the perturbations is commensurate with the distance (along the bisector) between the edges and the seam. An analysis of the wideband calibration algorithm that ignores this edge scattering component, as we have done in our work, shows that the edge scattering from the circular MSD design introduces less than 0.3 dB of error in the calibration accuracy. The circular design of the MSD objects reported here serves to minimize stray scattering of the edges relative to a design having straight edges (e.g., square), which are coincident with the linear transmit/receive polarization states. It may be possible to further treat the edges (e.g., rolled edges) to more effectively attenuate the edge scattering component, but this paper requires further investigation.
VI. Conclusion

Using the 160 GHz fully polarimetric bistatic compact radar range at the UML STL, we have demonstrated, using the MSDs as part of a bistatic calibration routine, RCS measurement errors less than 0.5 dB over a wide range of bistatic angles. We were also able to achieve bistatic cross-polarization isolation of the order of 50 dB over a wide range of bistatic angles as well. This performance is consistent with other instrumented bistatic radars that have been reported in the literature. Based on these observations, we have confirmed that the MSD object may be used as a faithful bistatic radar calibration standard as it was applied in this paper. We have also demonstrated that the MSD object may also realize a strongly cross-polarized PSM that is useful for characterizing the cross-polarization accuracy of the measurement system (less than 0.5 dB as well).

To achieve the level of accuracy and cross-polarization isolation reported in Tables II–V, careful alignment of each calibration object was crucial. To this end, the laser alignment system is the bistatic compact radar range played an invaluable role in the measurement quality. While the MSD object provides a viable solution for polarimetric calibration of instrumented bistatic radar systems, its application in scenarios where the object’s orientation relative to the transmitter and receiver cannot be carefully controlled could present alignment/measurement errors significantly greater than those we report here.

APPENDIX
RAY-TRACING ANALYSIS OF THE MAINLOBE-STEERED DIHEDRAL

A. Coordinate Conventions

Derivation of (2) and (3) defining the MSD’s interior and seam rotation angles is carried out through a ray-tracing analysis of a 90° dihedral reflector that has had its interior angle modified by the parameter α, such that the interior angle $\phi_{msd}$ of the MSD is described by the following:

$$\phi_{msd} = 90° + \frac{\alpha}{2}.$$  \hspace{1cm} (A1)

To set up the ray-tracing problem, we consider two coordinate systems. The first coordinate system is fixed to the laboratory (lab) and defines the basis for the radar’s linear horizontal and vertical polarization unit vectors relative to the $xy$ plane containing the transmit/receive bistatic angle $\beta$. Fig. 19 outlines the lab-fixed system depicting the incident and scattered rays to/from the MSD as well as the transmit/receive horizontal polarization basis vectors. The second coordinate system is fixed to the MSD with its seam rotated in the $yz$ plane of the lab-fixed system. Fig. 20 relates the lab and MSD systems through the MSD’s seam rotation angle $\psi_{msd}$. These systems are related through the unitary matrix transformation

$$\tilde{g}' = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \psi_{msd} & -\sin \psi_{msd} \\ 0 & \sin \psi_{msd} & \cos \psi_{msd} \end{bmatrix} \tilde{g}.$$  \hspace{1cm} (A2)

where $\tilde{g}$ is a vector defined in the lab system and $\tilde{g}'$ is the associated vector defined in the MSD reflector’s system. For the remainder of this appendix, the superscript $r$ will be used to denote any geometric quantities defined in the MSD reflector’s coordinate system. The absence of such a superscript from any vector quantity denotes the vector’s definition in the lab
coordinate system. Also, the subscripts \( i \) and \( s \) are used to denote quantities associated with the incident and reflector scattered rays, respectively.

Using these coordinate definitions, a ray-tracing analysis is used to determine the scattered polarization state \( \hat{\nu}_s \) of the incident vertical polarization \( \hat{\nu}_i \) after it has undergone reflection upon the two surfaces of the MSD, based on the parameters \( \phi_{msd} \) and \( \psi_{msd} \). The resultant \( \hat{\nu}_s \) polarization state is then decomposed into the horizontal \( \hat{h} \) and vertical \( \hat{v} \) bases of the receiver. Since an arbitrary choice of \( \phi_{msd} \) and \( \psi_{msd} \) is not guaranteed to direct the scattered ray in the direction of the receiver, we require a constraint to enforce this condition. We apply the constraint

\[
\sqrt{(\hat{v}_s^T \hat{h})^2 + (\hat{v}_s^T \hat{v})^2} = 1 \tag{A3a}
\]

where

\[
\hat{h} = \begin{bmatrix}
-\sin (\frac{\phi}{2}) \\
\cos (\frac{\phi}{2}) \\
0
\end{bmatrix} \tag{A3b}
\]

and

\[
\hat{v} = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} \tag{A3c}
\]

to assert that the \( \phi_{msd} \) and \( \psi_{msd} \) parameters yield an MSD design that directs the scattered ray in the direction of the receiver. Furthermore, since \( \hat{h} \) and \( \hat{v} \) represent a receiver polarization orthonormal basis, each term under the radical in (A2) represents the components of the MSD’s PSM \( S_{msd} \) as described by the following:

\[
S_{msd} = \begin{bmatrix}
-\gamma & \delta \\
\delta & \gamma
\end{bmatrix} \tag{A4}
\]

where

\[
\gamma = \hat{v}_s^T \hat{v} \tag{A5a}
\]

\[
\delta = \hat{v}_s^T \hat{h} \tag{A5b}
\]

\[
\delta = \sqrt{1 - \gamma^2}. \tag{A5c}
\]

Using the conventions and constraints given by (A1)–(A5), we now derive the closed-form expressions for the parameters \( \phi_{msd} \) and \( \psi_{msd} \) that are given by (1) and (2).

**B. Derivation of \( \phi_{msd} \) and \( \psi_{msd} \)**

The incident vertical polarization vector \( \hat{\nu}_i \) and seam unit vectors as defined in the lab system described by Figs. 19 and 20 are written as

\[
\hat{\nu}_i = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} \tag{A6}
\]

\[
\hat{s} = \begin{bmatrix}
0 \\
\sin \psi_{msd} \\
\cos \psi_{msd}
\end{bmatrix}. \tag{A7}
\]

Converted to the MSD coordinate system, these vectors are

\[
\hat{\nu}_i^r = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \psi_{msd} & -\sin \psi_{msd} \\
0 & \sin \psi_{msd} & \cos \psi_{msd}
\end{bmatrix} \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} = \begin{bmatrix}
0 \\
-\sin \psi_{msd} \\
\cos \psi_{msd}
\end{bmatrix} \tag{A8}
\]

\[
\hat{s}^r = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}. \tag{A9}
\]

To facilitate the formulation of the reflections imparted on \( \hat{\nu}_i^r \) about the seam by the MSD, this unit vector can be decomposed into two orthogonal components in the MSD coordinate system: one parallel to the seam \( \hat{\nu}_i^r || \) and one perpendicular to the seam \( \hat{\nu}_i^r \perp \). These two components are given by

\[
\hat{\nu}_i^r || = (\hat{\nu}_i^r \cdot \hat{\nu}_i^r) \hat{\nu}_i^r \tag{A10}
\]

\[
\hat{\nu}_i^r \perp = \hat{\nu}_i^r - \hat{\nu}_i^r || \tag{A11}
\]

The ray trace double reflection properties of the MSD dictate that the parallel components of \( \hat{\nu}_i^r \) and \( \hat{\nu}_s^r \) are equal. These properties also relate the perpendicular component of \( \hat{\nu}_s^r \) to the associated incident component through a \( 180 - \alpha \) degree rotation about the seam axis, as illustrated in Fig. 21. These two properties can be written succinctly by

\[
\hat{\nu}_i^r || = \hat{\nu}_i^r || \tag{A12a}
\]

and

\[
\hat{\nu}_i^r \perp = \hat{\nu}_i^r \perp \tag{A12b}
\]

Substituting (A10) into (A12a) and (A11) in (A12b), the parallel and perpendicular components of the scattered ray from the incident vertical polarization can be written as

\[
\hat{\nu}_i^r || = \begin{bmatrix}
0 \\
0 \\
\cos \psi_{msd}
\end{bmatrix} \tag{A13a}
\]

\[
\hat{\nu}_i^r \perp = \begin{bmatrix}
-\sin \psi_{msd} \sin \alpha \\
\sin \psi_{msd} \cos \alpha \\
0
\end{bmatrix}. \tag{A13b}
\]

Transforming (A13a) and (A13b) to the lab system so they may be related to the \( h \) and \( v \) basis of the receiver, we have

\[
\hat{\nu}_i || = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \psi_{msd} & \sin \psi_{msd} \\
0 & -\sin \psi_{msd} & \cos \psi_{msd}
\end{bmatrix} \begin{bmatrix}
0 \\
0 \\
\cos \psi_{msd}
\end{bmatrix} \tag{A14a}
\]

\[
\hat{\nu}_i \perp = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \psi_{msd} & \sin \psi_{msd} \\
0 & -\sin \psi_{msd} & \cos \psi_{msd}
\end{bmatrix} \begin{bmatrix}
-\sin \psi_{msd} \sin \alpha \\
\sin \psi_{msd} \cos \alpha \\
0
\end{bmatrix} \tag{A14b}
\]
The scattered ray \( \hat{v}_s \) reflected by the MSD from the incident vertical polarization is then the sum of (A14a) and (A14b)

\[
\hat{v}_s = \begin{bmatrix} -\sin \psi_{msd} \sin \alpha \\ \cos \psi_{msd} \sin \psi_{msd} (\cos \alpha + 1) \\ \cos^2 \psi_{msd} - \sin^2 \psi_{msd} \cos \alpha \end{bmatrix}. \tag{A15}
\]

We are assured that the vector formulated in (A15) is of unit length, since vector operations carried out from (A8)–(A14) are unitary.

Having a representation of the scattered ray \( \hat{v}_s \) in terms of the MSD parameters \( \alpha \) and \( \psi_{msd} \), we can compute the fundamental quantities \( \gamma \) and \( \delta \) of the PSM described by (A4) and (A5). Substituting (A15) into (A5a) and (A5b), we have

\[
\gamma = \cos^2 \psi_{msd} - \sin^2 \psi_{msd} \cos \alpha \\
\delta = \sin \psi_{msd} \sin \alpha \sin \frac{\beta}{2} + \sin \psi_{msd} \cos \psi_{msd} (\cos \alpha + 1) \cos \frac{\beta}{2}. \tag{A16a}
\]

We can isolate \( \alpha \) in (A16a)

\[
\cos \alpha = \cot^2 \psi_{msd} - \frac{\gamma}{\sin^2 \psi_{msd}}. \tag{A17}
\]

Then, applying the trigonometric identity

\[
\sin \alpha = \sqrt{(1 - \cos \alpha) (1 + \cos \alpha)} \tag{A18}
\]

Equation (A19) is substituted into the first term of (A16b) and (A17) into the second term of (A16b); each term is simplified separately.

Equation (A19) into (A16b) (Term 1)

\[
\sin \psi_{msd} \frac{1}{\sin \psi_{msd}} \sqrt{(1 - \gamma) ((\gamma - 1) \cot^2 \psi_{msd} + \gamma + 1) \sin \frac{\beta}{2}} \\
= \sqrt{(1 - \gamma) ((\gamma - 1) \cot^2 \psi_{msd} + \gamma + 1) \sin \frac{\beta}{2}}. \tag{A20}
\]
\[
\cot \psi_{\text{msd}} = \frac{-2\delta (1-\gamma) \cos \frac{\beta}{2} \pm \sqrt{4\delta^2 (1-\gamma)^2 \cos^2 \frac{\beta}{2} + 4\delta^2 (1-\gamma)^2 [(1-\delta^2) \sin^2 \frac{\beta}{2} - \delta^2]}}{-2(1-\gamma)^2} \tag{A24}
\]

Equation (A17) into (A16b) (Term 2)
\[
\sin \psi_{\text{msd}} \cos \psi_{\text{msd}} \left( \cot^2 \psi_{\text{msd}} - \frac{\gamma}{\sin^2 \psi_{\text{msd}}} + 1 \right) \cos \frac{\beta}{2} = \left( \cos^2 \psi_{\text{msd}} \cot \psi_{\text{msd}} - \gamma \cot \psi_{\text{msd}} \right) + \sin \psi_{\text{msd}} \cos \psi_{\text{msd}} \cos \frac{\beta}{2}
\]
\[
= \left( \cos^2 \psi_{\text{msd}} \cot \psi_{\text{msd}} - \gamma \cot \psi_{\text{msd}} + \frac{\cos^2 \psi_{\text{msd}}}{\cot \psi_{\text{msd}}} \right) \cos \frac{\beta}{2}
\]
\[
= \left( \cos^2 \psi_{\text{msd}} \left( \cot \psi_{\text{msd}} + \frac{1}{\cot \psi_{\text{msd}}} \right) - \gamma \cot \psi_{\text{msd}} \right) \cos \frac{\beta}{2}
\]
\[
= \left( \cos^2 \psi_{\text{msd}} \left( \frac{1}{\cot \psi_{\text{msd}}} \right) - \gamma \cot \psi_{\text{msd}} \right) \cos \frac{\beta}{2}
\]
\[
= \left( \cot \psi_{\text{msd}} - \gamma \cot \psi_{\text{msd}} \right) \cos \frac{\beta}{2}
\]
\[
= \left( 1-\gamma \right) \cot \psi_{\text{msd}} \cos \frac{\beta}{2}. \tag{A21}
\]

Equation (A16b) is then equivalent to the sum of terms given by (A20) and (A21)
\[
\delta = \sqrt{(1-\gamma)((\gamma-1) \cot^2 \psi_{\text{msd}} + \gamma + 1) \sin \frac{\beta}{2}}
\]
\[
+ (1-\gamma) \cot \psi_{\text{msd}} \cos \frac{\beta}{2}. \tag{A22}
\]

The quantity \( \psi_{\text{msd}} \) can be isolated using the quadratic formula by rearranging (A22) into a quadratic form in \( \cot \psi_{\text{msd}} \)
\[
\sqrt{(1-\gamma)((\gamma-1) \cot^2 \psi_{\text{msd}} + \gamma + 1)} \sin \frac{\beta}{2}
\]
\[
= \delta - (1-\gamma) \cot \psi_{\text{msd}} \cos \frac{\beta}{2}
\]
\[
\sin \frac{\beta}{2} \sqrt{(1-\gamma)((\gamma-1) \cot^2 \psi_{\text{msd}} + \gamma + 1)}
\]
\[
= \delta^2 - 2\delta (1-\gamma) \cot \psi_{\text{msd}} \cos \frac{\beta}{2} + (1-\gamma)^2 \cot^2 \psi_{\text{msd}} \cos^2 \frac{\beta}{2}
\]
\[
+ \left[ -(1-\gamma)^2 \right] \cot^2 \psi_{\text{msd}} + \left[ 2\delta (1-\gamma) \cos \frac{\beta}{2} \right] \cot \psi_{\text{msd}}
\]
\[
+ \left[ (1-\gamma)^2 \sin^2 \frac{\beta}{2} - \delta^2 \right] = 0. \tag{A23}
\]

Equation (A23) is solved with the quadratic formula yielding (A24), as shown at the top of this page.

After substituting (A5c) into (A24), further simplification of the determinant shows that it equates to zero so that (A24) is reduced to the following closed-form solution for \( \psi_{\text{msd}} \):
\[
\cot \psi_{\text{msd}} = \frac{1+\gamma}{1-\gamma} \cos \frac{\beta}{2}
\]
\[
\psi_{\text{msd}} = \cot^{-1} \left[ \frac{1+\gamma}{1-\gamma} \cos \frac{\beta}{2} \right]. \tag{A25}
\]

To isolate \( \alpha \), we make use of the following trigonometric identity:
\[
\cos \psi = \cot \psi \sin \psi = \frac{\cot \psi}{\sqrt{\cos^2 \psi + 1}}. \tag{A26}
\]

Substituting (A25) into (A16a), making use of the identities in (A26), and performing some rearrangement, the closed-form solution for \( \alpha \) is given by
\[
\gamma = \frac{\sin \alpha}{\cos \beta} + \frac{\cos \alpha}{\sin \beta} \cos \frac{\beta}{2}
\]
\[
\cos \alpha = \frac{1+\gamma}{1-\gamma} \cos \beta + \frac{\gamma}{1-\gamma} \cos \beta + \gamma - 1 \quad \text{(A27)}
\]
\[
\alpha = \cos^{-1} \left[ (1+\gamma) \cos^2 \frac{\beta}{2} - \gamma \right]. \tag{A27}
\]

Finally, substituting (A27) into (A1) completes the closed-form derivation
\[
\phi_{\text{msd}} = 90 + \frac{\cos^{-1} \left[ (1+\gamma) \cos^2 \frac{\beta}{2} - \gamma \right]}{2}. \tag{A28}
\]

ACKNOWLEDGMENT

This paper was carried out at the Submillimeter-Wave Technology Laboratory.

REFERENCES

C. Beaudoin (M’11) was born in Peterboro, NH, USA, in 1977. He received the D.Eng degree in electrical engineering from the University of Massachusetts Lowell (UML), Lowell, MA, USA, in 2006, where he was involved in the research of physical scale modeling of UHF radar signatures at the Submillimeter-wave Technology Laboratory (STL).

In 2008, he joined the Research Staff at the MIT Haystack Observatory, Westford, MA, USA, as a Research Engineer. In this role, he lead the development of NASA’s next generation microwave systems for the Geodetic Very Long Baseline Interferometry (VLBI) Program, an effort with the target goal of reducing network telescope position uncertainties to 1 mm on global scales. His contributions to this effort included the design of an ultralow noise (50 K)/broadband (2–4 GHz) cryogenic front-end, electromagnetic analysis for radio telescope radio frequency interference mitigation, development of signal processing algorithms for geodetic delay extraction, and the innovation of a monitor/control infrastructure for the NASA geodetic VLBI radio telescope network. In 2015, he rejoined the UML, STL, as a Senior Radar Engineer, and a Co-Lead of the Solid-State Transceivers Group. In this role, he designs/constructs compact radar range instrumentation, conducts research in monostatic/bistatic synthetic aperture radar (SAR), and develops SAR signal processing algorithms to further the group’s radar scale modeling capabilities.

T. Horgan, photograph and biography not available at the time of publication.

M. J. Coulombe, photograph and biography not available at the time of publication.

G. DeMartinis (S’95–M’98–SM’16) received the B.M. degree (Cum Laude) in music (sound recording technology), the B.S. degree (Magna Cum Laude) in physics, and the M.S. and D.Eng. degrees in electrical engineering, all from the University of Massachusetts Lowell, Lowell, MA, USA.

He was a Senior Electrical Engineer with the Raytheon Integrated Defense Systems Antenna and Microwave Group, Tewksbury, MA, USA, in 2001, involved in a wide variety of electrical and electromagnetic engineering efforts. He was a Senior Radar Engineer with Submillimeter-Wave Technology Laboratory (STL), University of Massachusetts Lowell, joining the group in 2006 with a primary emphasis on the design and deployment of millimeter-wave/THz transceivers in support of electromagnetic scattering measurements. He is currently the Assistant Director of the STL. In this role, he supports the day-to-day operations of the laboratory and also involved to expand laboratory efforts in the design, modeling, and implementation of high-frequency electromagnetic systems, devices, and complex materials, with a focus on millimeter-wave transceiver design and applications.

Dr. DeMartinis is a member of the Tau Beta Pi and Sigma Pi Sigma Honor Societies, and also the Order of the Engineer.