A Performance Analysis of Several Bistatic Calibration Techniques

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ABSTRACT

Several popular bistatic calibration techniques are evaluated, and comparisons are made between the relative merits of various calibration objects. This analysis considers the following: sensitivity to object alignment error, sensitivity to polarization impurity, and ease of implementation. Both theoretical concepts and practical considerations are discussed, based on measurements accomplished at the European Microwave Signature Laboratory (EMSL) of the Joint Research Centre (JRC) in Ispra, Italy. This facility has the capability to produce far-field, fully polarimetric, bistatic measurements with an approximately 30 cm diameter quiet zone, with the necessary precision for comparing different calibration methods.

INTRODUCTION

Monostatic radars that employ duplexers illuminate and view scattering from objects with a single antenna, while bistatic and multistatic systems can transmit and receive signals from multiple antennas. Bistatic measurement geometry incorporates physically separated transmit and receive antennas whose relation to the test object is described through the bistatic angle $\beta$.

Here, the methods of calibrating laboratory systems designed to perform these bistatic measurements are divided into three classes. Type-1 calibration is a direct amplitude and phase compensation relating the scattered waveform to the true scattering characteristics of the object, applied separately to each polarization channel. Type-2 calibration uses additional calibration reference object(s) to make a zero-order approximation into the cross-polarization contamination characteristics of the antennas. Type-3 calibration is the most complete technique available for calibrating polarimetric radar systems. A Type-3 technique requires three independent object measurements, and a rigorous mathematical process is employed in order to model the distortion characteristics of the antennas by a 2x2 Polarization Distortion Matrix (PDM).

MEASUREMENT ERROR MODEL

The transmit and receive antennas can be individually represented by two 2x2 PDM’s:

$$R = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{HV} & R_{VV} \end{bmatrix} \quad (1) \quad T = \begin{bmatrix} T_{HH} & T_{VH} \\ T_{VH} & T_{VV} \end{bmatrix} \quad (2)$$

These 2x2 PDMs account for the zero-order polarimetric distortion due to a deviation from the nominal rotational alignment of the antenna, and first-order distortion due to non-ideal manufacture of the antenna aperture. Higher order distortions, such as that due to the off-focus positioning of the object (here assumed to be a point-object) cannot be accounted for in the PDM model.

Since the quantities $R$ and $T$ cannot be separately measured, a matrix (designated $C$) of products of these terms is defined, which accounts for the polarimetric distortion introduced by the antennas. This matrix is given as:

$$C = \begin{bmatrix} R_{HH}T_{HH} & R_{HH}T_{VH} & R_{HH}T_{IH} & R_{HH}T_{VH} \\ R_{HV}T_{IH} & R_{HV}T_{VH} & R_{IH}T_{VH} & R_{IH}T_{VH} \\ R_{IH}T_{IH} & R_{IH}T_{VH} & R_{IH}T_{VH} & R_{IH}T_{VH} \\ R_{HV}T_{IH} & R_{HV}T_{VH} & R_{IH}T_{VH} & R_{IH}T_{VH} \end{bmatrix} \quad (3)$$

The matrix is composed of eight distinct distortion terms representing the distortion due to each of the transmitter and receiver.

The Type-1 technique, requiring only a single reference object with a known theoretical prediction, solves for only the $R_{IH}T_{IH}$ and $R_{VH}T_{VH}$ components of the $C$ matrix, as:

$$C = \begin{bmatrix} R_{IH}T_{IH} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{VH}T_{VH} \end{bmatrix} \quad (4)$$

These coefficients are solved for distinctly, allowing matrices $R$ and $T$ to be determined individually as diagonal matrices.

The Type-2 technique (requiring a minimum of two reference objects with known theoretical predictions) fills the entire diagonal of the $C$ matrix, yielding:
Several test objects were designated as candidates for optimal implementation of each calibration given the measurement conditions at the European Microwave Signature Laboratory (EMSL) in Ispra, Italy. The test matrix is shown in Table 1. All measurements shown here are completed in a bistatic configuration where the bistatic angle $\beta$ was 5°. In addition, each measurement was done with varying degrees of systematic alignment error, in order to quantify how misalignment error effects each calibration technique.

Table 1: Experiment Test Matrix

<table>
<thead>
<tr>
<th>Object</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>N/A</td>
</tr>
<tr>
<td>Short Cylinder</td>
<td>Axis horizontal</td>
</tr>
<tr>
<td>Dihedral</td>
<td>Seam vertical</td>
</tr>
<tr>
<td>Circular Disk</td>
<td>Seam 22.5° from vertical</td>
</tr>
<tr>
<td>Linear Wire Mesh</td>
<td>Wires oriented vertically 45° from vertical</td>
</tr>
<tr>
<td>Trihedral</td>
<td>Peak specular</td>
</tr>
</tbody>
</table>

For each implementation of the calibrations, the sphere was used as the control object on which all calibrations are performed. The sphere was chosen because of the ease of alignment and positioning, as well as the availability of an exact analytical scattering solution. The sphere has zero theoretical cross-polarized RCS, so the measurements do not reveal the exact error in the cross-polarization channels after calibrating. It was not practical to use an object with high cross-polarized RCS as a control object (like the tilted dihedral) since the response of these objects is very sensitive to misalignment. Therefore, it was not possible to isolate the error in the calibration from the error that might be as a result of misalignment of the control object. As a result, the post-calibration cross-polarization levels in the sphere measurement are assumed to be closely related to the cross-polarization purity gained in calibration, and conclusions are based on the purity gain reflected in these numbers.

As a baseline calibration, the Type-1 technique was performed with the circular disk as the reference object.

Table 2 shows the calibration with alignment error ranging from perfect alignment to $2^\circ$ misalignment. Since the theoretical solution for the disk predicts exactly zero cross-polarized RCS, the cross-polarization levels are infinitely low (in dB). The Type-1 calibration, as implemented here, is consistent with the basic heuristic typical of all calibrations of this type, and is explained in detail in [1].

Table 3: Error statistics for Type-2 calibration (T1: circular disk, T2: vertical wire mesh, T3: tilted wire mesh)

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Table 2: Error statistics for Type-1 calibration (circular disk)

The Type-2 technique (Table 3) is the same as implemented in the EMSL, and is described in [2]. Objects T2 and T3 (the wire mesh) acts like a polarizing filter with the polarization reflection and transmission a function of the rotation of the mesh. To quantify the cross-polarization purity in this case, we subtract the calibrated cross-polarization levels of the sphere from the co-polar levels. The co-polarized levels of the sphere (30.5 cm diameter) are very close to –11 dBsm for the entire measurement bandwidth (13-14 GHz). With the wire mesh as a cross-polarization calibrator, a cross-polarization purity value of about 31 dB can be attained. As seen from the table, misalignment of the wire mesh has no effect on the error in the co-polar channels.
Table 4: Error statistics for Type-3 calibration (T1: circular disk, T2: vertical dihedral, T3: tilted dihedral)

<table>
<thead>
<tr>
<th>Object Misalignment</th>
<th>VV-error</th>
<th>VH-error</th>
<th>VH level</th>
<th>HV level</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1=0°, T2=0°, T3=0°</td>
<td>0.17 ± 0.01 dB</td>
<td>0.10 ± 0.03 dB</td>
<td>-49.2 dBsm</td>
<td>-51.5 dBsm</td>
</tr>
<tr>
<td>T1=1°, T2=1°, T3=1°</td>
<td>0.32 ± 0.04 dB</td>
<td>0.35 ± 0.01 dB</td>
<td>-48.8 dBsm</td>
<td>-51.5 dBsm</td>
</tr>
<tr>
<td>T1=2°, T2=0°, T3=0°</td>
<td>1.24 ± 0.04 dB</td>
<td>1.28 ± 0.01 dB</td>
<td>-47.8 dBsm</td>
<td>-50.6 dBsm</td>
</tr>
<tr>
<td>T1=0°, T2=2°, T3=0°</td>
<td>0.17 ± 0.01 dB</td>
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</tr>
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</tr>
</tbody>
</table>

Table 4 shows the results obtained implementing the Type-3 technique as explained in [3]. The resulting co-polarized RCS error is very similar to that of the Type-2 technique, since the absolute amplitude calibrator is the same for both. The cross-polarization purity, however, has increased to about 38 dB—a gain of 7 dB over the Type-2 technique. As noted in [3], this technique assumes that the scattering matrices be symmetric, i.e., the cross-polar components of the calibration reference object are equal, which requires that the reference measurements be monostatic or near-monostatic. The bistatic angle of 5° used in these measurements violates this assumption, but good calibration results are still achievable. The technique can be implemented using monostatic measurements [4], which will tend to decrease the error introduced by the bistatic measurements.

CONCLUSIONS

Three calibration techniques, each with varying degrees of complexity and completeness in the polarization distortion model, have been categorized and evaluated. It has been shown that the gain in cross-polarization purity has been the most significant advantage in using a full-polarimetric (Type-3) technique versus its simpler counterparts. The polarization purity of this technique reaches about 40 dB, depending on the system-specific parameters of the transmitter and receiver. The sensitivity of each calibration reference object is a major factor in the overall precision of the calibration. It has further been shown that the relative insensitivity to misalignment that is displayed by the wire mesh makes it an excellent candidate for cross-polarization calibration and worthy of further study.

REFERENCES


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