ABSTRACT

The purpose of this research is to quantitatively determine the limits of Falconer’s Monostatic to Bistatic Equivalence Theorem (MBET). Falconer developed two extensions to Kell’s MBET, one applicable to near zone data and one valid in the far zone region. This work encompassed collecting and analyzing both monostatic and bistatic radar cross section (RCS) data for perfect electric conducting (PEC) objects. Specifically, this research analyzes the effects of varying the parameters of transmission frequency, object shape complexity, and receiver bistatic angle. Objects range in geometric complexity from canonical objects comprised of simple scatterers to multifaceted composites that sustain numerous interactions.

Empirical data collected in the far zone are compared to analytical predictions produced by commercially available electromagnetic computer codes, both a method of moments (MoM) code and a near-field Physical Optics code. The codes ran at X-band through K-band frequencies for a comparison with object data. Further, the empirical bistatic data are compared to the estimate produced by the MBET, to ascertain the region in which the MBET approximation is applicable. Finally, electromagnetic computer codes are used to produce near-field scattering predictions to facilitate validation of Falconer’s near-field MBET.

INTRODUCTION

Monostatic radars that employ duplexer stimulate and view scattering from objects with a single antenna, while bistatic and multistatic systems can transmit and receive signals from multiple antennae. Bistatic measurement geometry incorporates physically separated transmit and receive antennae whose relation to the test article is described through the bistatic angle \( \beta \).

This work analyzes the bistatic scattering from a representative PEC object comprised of simple canonical shapes, i.e. corner reflectors, open and closed cylinders, and a shadowing plate. Far-field bistatic scattering predictions generated with two commercially available electromagnetic scattering codes are evaluated against the empirical data for their accuracy. Finally, Falconer’s Monostatic-to-bistatic scattering conversion formulae for far-field and near-field \( \theta \).

DEVELOPMENT

This paper presents a five phased research project as follows: 1) collection of far-field empirical data, 2) validation of Falconer’s far-field MBET with the empirical data, 3) validation of computer prediction codes with empirical data, 4) generation of near-field scattering with computer codes, 5) validation of Falconer’s near-field MBET with computer generated scattering data. Objects A and B, shown in Fig. 1, were chosen for their ability to highlight various scattering phenomena at different look angles, such as traveling waves, creeping waves, multi-bounce, and shadowing effects. Co-polarized (VV, HH) monostatic and bistatic waterline pattern cut and imaging data was collected according to the matrix in Table 1 at the European Microwave Signature Laboratory (EMSL) of the EC Joint Research Centre in Ispra, Italy.

<table>
<thead>
<tr>
<th>Object</th>
<th>RF (GHz)</th>
<th>TX illumination aspect angle ( \theta_T ) (deg)</th>
<th>RX look angle ( \theta_R ) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7.15</td>
<td>0</td>
<td>0-180</td>
</tr>
<tr>
<td>B</td>
<td>7.15</td>
<td>45</td>
<td>-20 - 225</td>
</tr>
</tbody>
</table>

Fig. 1: Test objects (adapted from [3])
Fig. 2 shows a typical measurement orientation as a function of transmitter illumination angle $\theta_T$ and receiver look angle $\theta_R$. These angles are referenced to the flat plate's outward pointing surface normal in Objects A and B. In the azimuth plane, bistatic estimated data is generated from the monostatic far field measurements through Falconer's CW monostatic-to-bistatic equivalence theorem given by \cite{2}

$$\sigma_d(\theta_r, \theta_z, \phi) \equiv \sigma_m \left( \theta = \arcsin\left( \frac{\sin(\theta_r) + \sin(\theta_z)}{2} \right) f \right)$$

where

- $\sigma_d =$ Estimated Bistatic RCS in dBsm
- $\sigma_m =$ Monostatic RCS in dBsm
- $\theta =$Equivalent Monostatic Azimuth Angle
- $\theta_r =$ Bistatic Receiver Angle (azimuth)
- $\theta_z =$ Bistatic Transmitter Angle (azimuth)
- $f =$ Transmitter Frequency

The above CW MBET is valid both in the near and far-fields. Falconer's MBET, similar to Crispin's, approximates the bistatic return by using the monostatic signal at the same transmission frequency but at a reduced look angle. While the structure of the formula appears similar to Crispin's formulation of the MBET given by \cite{4}

$$\sigma_d(\theta_r, \theta_z, f) \equiv \sigma_m \left( \theta = \frac{\theta_r + \theta_z}{2} f \right).$$

Falconer employed the discrete scattering center model of the object radiation pattern for his formulation. This is the same model used by Kell to construct his MBET given by \cite{5}

$$\sigma_d(\theta_r, \theta_z, f) \equiv \sigma_m \left( \theta = \frac{\theta_r + \theta_z}{2} f_m = f \cos\left( \frac{\theta_r - \theta_z}{2} \right) R_w \right).$$

Simulation data are generated for the far-field test set by two different electromagnetic scattering prediction codes. The near-field code is a high frequency prediction code, utilizing a combination of ray tracing and physical optics (PO) while the far field code utilizes the more rigorous, and computationally intensive, method of moments (MoM) approach.

Fig. 3 shows excellent agreement between the measurements and MoM simulation data. While all MBETs perform well up to about a 30\(^\circ\) bistatic angle, Kell’s and Falconer’s show continued agreement out to about 55\(^\circ\). Note that Kell’s MBET is limited by the frequency of the monostatic data collected.

For the near-field MBET evaluation, we use analytical codes to achieve two objectives: 1) study and quantitatively delineate limits of Falconer’s near field monostatic-to-bistatic equivalence theorem (MBET), 2) evaluate the performance of the computer prediction codes. Falconer’s near zone statement \cite{2}, defined in terms of scattered electric field is

$$E_s(\theta_r, \theta_z, f, R) \equiv e^{\frac{2\pi}{\lambda} \cos \left( \frac{\theta_r - \theta_z}{2} \right) R_w} E_m(\theta, f_m, R_w)$$

where

- $\theta = \left( \frac{\theta_r + \theta_z}{2} \right)$, Monostatic Angle
- $f_m = f \cos \left( \frac{\theta_r - \theta_z}{2} \right)$, Reduced frequency
- $R_w = R \cos \left( \frac{\theta_r - \theta_z}{2} \right)$, Reduced Range

Evaluation of objects in the middle of their radiating near field, defined in \cite{6}, is governed by...
where $\lambda$ refers to the transmitting signal's wavelength, and $l$ designates the longest dimension of the object bisected by the waterline cut. For Object A, $l = 240$ mm, and for Object B, $l = 380$ mm. We analyzed the objects at 8 GHz and 14 GHz, which is $\lambda = 37.5$ mm and 21.43 mm, respectively. The variable $R$ designates the limits of the near field radiating region. We calculated the bistatic return, and its corresponding monostatic return, in the region $R$'s midpoint.

Eigel [3] empirically determined the angular limits for Kell’s far-field MBET for Object A (the flat plate) to be 30°, and for the complex Object B to be 10°. Using these data points as inputs into our evaluation process, we calculate the near-field bistatic, and Falconer’s equivalent monostatic, returns from each object illuminated at 45° with $R_f$ equal to 10 meters and $R_N$ equal to the midpoint of $R$. The PO near-field prediction code results are shown in Table 2.

As the data in Table 2 illustrates, Falconer’s near-field MBET produces reasonably accurate results. The majority of points lie within a 3dBsm difference. The 6.23dBsm point appears as an outlier and could be caused by null misalignment. The data plotted in Fig. 4 depicts the near-field bistatic scattering from the complex Object B. Maintaining a constant angular separation between the transmitter and receiver antenna of 10° and rotating this system around the object generates the data in Fig. 4. This data illustrates reasonable null alignment between the computer generated near-field bistatic data and the MBET approximation, where the main scattering mechanism is specular return from the flat shadowing plate. Additionally, the MBET continues to track the nulls after the transmitter passes 90° and begins illuminating more complex components of Object B. Finally, the peaks of the MBET consistently remain within 3dBsm of the bistatic curve peaks throughout the azimuthal sweep.

Within maximum bistatic angles, determined by object scattering complexity, Falconer’s near-field MBET performs well throughout a range of transmitting frequencies and polarizations. Future work could entail collecting empirical near field data to validate these numerical results. Further, collection at various elevation angles would highlight how well Falconer’s formulation approximates additional scattering mechanisms.

Table 2: Near Field MBET Summary Data

<table>
<thead>
<tr>
<th>Object</th>
<th>Tx Freq</th>
<th>$\Delta R_{[\text{dBsm}]}$</th>
<th>$\Delta R_{[\text{dBsm}]}$</th>
<th>$\Delta R_{[\text{dBsm}]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8 HH</td>
<td>-31.12</td>
<td>-28.79</td>
<td>2.321</td>
</tr>
<tr>
<td>A</td>
<td>8 VV</td>
<td>-22.57</td>
<td>-28.8</td>
<td>-6.23</td>
</tr>
<tr>
<td>A</td>
<td>14 HH</td>
<td>-20.27</td>
<td>-25.19</td>
<td>-5.92</td>
</tr>
<tr>
<td>A</td>
<td>14 VV</td>
<td>-25.82</td>
<td>-25.19</td>
<td>0.63</td>
</tr>
<tr>
<td>B</td>
<td>8 HH</td>
<td>-8.84</td>
<td>-5.53</td>
<td>3.31</td>
</tr>
<tr>
<td>B</td>
<td>8 VV</td>
<td>-5.59</td>
<td>-4</td>
<td>1.59</td>
</tr>
<tr>
<td>B</td>
<td>14 HH</td>
<td>-1.49</td>
<td>-2.27</td>
<td>-0.78</td>
</tr>
<tr>
<td>B</td>
<td>14 VV</td>
<td>-1.8</td>
<td>-2.16</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

Fig. 4: Object B: Bistatic near-field scattering

REFERENCES


