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RCS Measurements, Transformations, and Comparisons Under Cylindrical and Plane Wave Illumination

Craig R. Birtcher, Constantine A. Balanis, *Fellow, IEEE*, and V. J. Vokurka

Abstract—Monostatic RCS measurements of a long bar (at *X*-band) and of a scale model aircraft (at *C*-band) were performed under the quasi-plane wave illumination produced by a dual parabolic-cylinder CATR. At Arizona State University's ElectroMagnetic Anechoic Chamber (EMAC) facility, these measurements were repeated under the cylindrical wave illumination produced by a March Microwave Single-Plane Collimating Range (SPCR). The SPCR measurements were corrected using the "reference target method." The corrected SPCR measurements are in good agreement with the CATR measurements.

I. INTRODUCTION

THE TECHNIQUES for determining far-field antenna and RCS patterns at short distances are numerous and well known. One class of techniques involves reflecting the spherical phasefront of a source antenna from one or two curved metal reflectors. These systems, referred to as Compact Antenna Test Ranges (CATRs), are used to synthesize planar phasefronts [1], [2]. Using a CATR, far-field patterns can be measured at short distances directly. Another class uses Near-Field to Far-Field (NF/FF) transformations to analytically predict far-field radiation patterns from measurements performed over a surface that is near the test antenna [3], [4], [5].

At Arizona State University's ElectroMagnetic Anechoic Chamber (EMAC) facility, a hybrid approach is used to determine far-field radiation and scattering patterns. A March Microwave Single-Plane Collimating Range (SPCR) semi-compact antenna test range generates a quiet zone comprised of cylindrical wavefronts [6]. The SPCR reflector has a parabolic curvature in the vertical plane and is flat in the horizontal plane. Fig. 1 shows the spherical phasefronts from the feed antenna collimated by the SPCR in the vertical plane while they continue to spread horizontally. Thus the virtual image of the SPCR feed is a vertical line source, as illustrated schematically in Fig. 2. For targets that are large relative to the curvature of the cylindrical wavefront, a one-dimensional analytical algorithm transforms the cylindrical wave (near-field) measurements into the desired plane wave (far-field) results.

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The impetus for utilizing this hybrid approach is three-fold: quiet zone size, NF/FF transformation efficiency, and cost. Due to the cylindrical spreading of the wavefronts, the horizontal-plane quiet zone is much larger (relative to the dimensions of the reflector) than that produced by conventional CATRs. Because the fields are collimated in the vertical plane, the NF/FF transformation is a simple and efficient one-dimensional algorithm. Additionally, a single pattern cut measured in the near-field of a cylindrical wave can be transformed to the far-field. Using other NF/FF transformations, comparatively prodigious amounts of near-field data must be measured, and a more computationally intensive algorithm is needed, to predict the far-field patterns. Because this semi-compact range has a single reflector that is curved in only one dimension, it can be manufactured to a given surface accuracy more economically than one doubly-curved reflector, or a dual-reflector, CATR.

Comparisons of measurements performed under cylindrical and plane wave illumination demonstrate the efficacy of the SPCR and the RCS correction algorithm. Two targets and their monostatic RCS measured with a dual parabolic-cylinder CATR were available. The targets, a 2.0 m long precision bar and a scale model aircraft, were measured at EMAC for the frequencies, orientations, and angular positions which correspond to the CATR measurements. The corrected cylindrical wave measurements are in very good agreement with the CATR plane wave measurements.

II. RCS TRANSFORMATION

The "reference target method" correction algorithm was originally proposed as a technique to extend the quiet zone of CATR's for antenna pattern measurements [7]. The context of the algorithm has been extended to include RCS pattern measurements in computer software developed by March Microwave [8], [9].

At the EMAC facility, the algorithm is used to 'transform' RCS patterns measured in the near-field of the cylindrical wavefront into far-field patterns; however, the algorithm is not a NF/FF transformation in the conventional sense. The algorithm corrects for all deviations of the illuminating field from that of an ideal plane wave. Correction coefficients that are related to the inverse of these deviations, in both amplitude and phase, are calculated for a region of space equal to or greater than the dimensions of the test target. Convolution of the correction coefficients with the RCS pattern of the target

Fig. 1. Artist's rendering of the production of a cylindrical-wave quiet zone by the Single-Plane Collimating Range (SPCR).

removes from the measurements errors due to the non-plane wave illumination.

To determine the field distribution in the quiet zone, the RCS of a reference target is measured as a function of aspect angle. The reference target can be any long straight metal bar or cylinder. The distribution of the illuminating field along the surface of this reference target is essentially related to its RCS by a Fourier transform. The transverse field distribution could also be obtained by probing the quiet zone directly, but the assembly and alignment of a scanner would be time consuming.

To derive the correction algorithm, consider the two-dimensional case of a bar of length L rotated about its center as shown in Fig. 3. The Physical Optics (PO) current $\vec{J}_p(x')$ along the length of the bar under some arbitrary illumination is given by

$$\vec{J}_p(x') = 2\hat{n} \times \vec{H}_i(x') \quad (1)$$

where

$\hat{n}$ = a unit vector normal to the surface of the bar

$\vec{H}_i$ = the incident magnetic field along the surface of the bar. Assume that the electric and magnetic fields are related by

$$\vec{H}_i(x') = \frac{\hat{k} \times \vec{E}_i(x')}{\eta_0} \quad (2)$$

where $\hat{k}$ is the propagation vector and η_0 is the free space wave impedance. Let the incident electric field along the surface of the bar be in the form of two complex parts:

$$\vec{E}_i(x') = \hat{e}_i [E_p(x') e^{jkx' \sin(\alpha)}] [g(x')] \quad (3)$$

where

$E_p(x') e^{jkx' \sin(\alpha)}$ = the electric field along the surface of the bar under ideal plane wave illumination

$g(x')$ = the complex distribution function which describes the deviation of the actual illumination from that of an ideal planar wavefront

$\hat{e}_i$ = the polarization vector of $\vec{E}_i$.

To determine the fields scattered by the bar, the vector potential $\vec{A}$ must be found. The vector potential is related to the PO current by

$$\vec{A} = \frac{\mu}{4\pi} \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \vec{J}_p(x') \frac{e^{-jkR'}}{R'} dx' \quad (4)$$

Using the far-field approximation, (4) reduces to

$$\vec{A} \approx \frac{\mu}{4\pi R} e^{-jkR} \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \vec{J}_p(x') e^{jkx' \sin(\alpha)} dx' \quad (5)$$

The far-field scattered electric field $\vec{E}_s$ is related to the vector potential by

$$\vec{E}_s = j\omega[\hat{k} \times (\hat{k} \times \vec{A})] \quad (6)$$

Replacing $\vec{A}$ in (6) with (5) leads to

$$\vec{E}_s(\alpha) \approx \frac{j\omega\mu}{4\pi R} e^{-jkR} \left[\hat{k} \times \left(\hat{k} \times \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \vec{J}_p(x') e^{jkx' \sin(\alpha)} dx' \right) \right] \quad (7)$$

Substituting from (1) and (2) into (7) yields

$$\begin{aligned} \vec{E}_s(\alpha) \approx & \frac{j\omega\mu}{4\pi R} e^{-jkR} \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \hat{k} \\ & \times \left(\hat{k} \times \left(2\hat{n} \times \frac{1}{\eta_0} (\hat{k} \times \vec{E}_i(x')) \right) \right) e^{jkx' \sin(\alpha)} dx' \quad (8) \end{aligned}$$

Performing the indicated vector operations assuming a linearly polarized TEM incident field and substituting from (3) reduces (8) to

$$\vec{E}_s(\alpha) \approx \frac{j2\omega\mu}{4\pi R\eta_0} e^{-jkR} \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \hat{e}_i E_p(x') e^{j2kx' \sin(\alpha)} g(x') \cos(\alpha) dx' \quad (9)$$

Translating the coordinates from along the bar to along the x -axis in (9), so that

$$\begin{aligned} x &= x' \cos(\alpha) \\ dx &= \cos(\alpha) dx' \end{aligned}$$

and letting $E_p(x)$ include the constant term C , where

$$C = \frac{j2\omega\mu}{4\pi R\eta_0} e^{-jkR}$$

yields

$$\vec{E}_s(\alpha) \approx \int_{-\frac{L}{2}}^{\frac{L}{2}} \hat{e}_i E_p(x) e^{j2kx \tan(\alpha)} g(x) dx \quad (10)$$

Substituting $u = 2k \tan(\alpha)$ into (10) and dropping the vector notation yields the complex amplitude of the electric field scattered from the bar, which can be expressed as

$$E_s(u) \approx \int_{-\frac{L}{2}}^{\frac{L}{2}} E_p(x) e^{jux} g(x) dx \quad (11)$$

When the incident illumination of the bar is an ideal plane wave,

$$g(x) = 1, \quad -\frac{L}{2} \leq x \leq \frac{L}{2} \quad (12)$$

(a)

(b)

Fig. 2. Schematic representation of the Single-Plane Collimating Range. (a) Top view: horizontal spreading. (b) Side view: vertical collimation.

Fig. 3. Geometry of two-dimensional scattering.

Then E_s reduces to E_{si} , the electric field scattered from the bar under plane wave illumination

$$E_{si}(u) \approx \int_{-\frac{L}{2}}^{\frac{L}{2}} E_p(x) e^{jux} dx \quad (13)$$

Because there are no contributions to the scattered fields outside the region $-\frac{L}{2} \leq x \leq \frac{L}{2}$, the limits of integration can be extended to infinity. Thus (11) and (13) can be expressed in the form of Fourier Transforms as

$$E_s(u) \approx \int_{-\infty}^{\infty} E_p(x) e^{jux} g(x) dx \quad (14)$$

and

$$E_{si}(u) \approx \int_{-\infty}^{\infty} E_p(x) e^{jux} dx \quad (15)$$

The electric fields scattered by the bar under nonplanar illumination E_s can be measured as the monostatic RCS of the bar. The deviations of the illumination from an ideal plane wave $g(x)$ can be deduced from the measured RCS versus angle of a long straight reference bar. By deriving a relationship between (14) and (15), the errors due to the non-ideal illumination can be removed from the measured scattering pattern of the target bar to yield E_{si} . Let a function called the "correction spectrum" be defined as

$$Q(u) = \int_{-\infty}^{\infty} \frac{1}{g(x)} e^{jux} dx \quad (16)$$

Then

$$E_{si}(u) = E_s(u) * Q(u) = \int_{-\infty}^{\infty} E_s(v) Q(u-v) dv \quad (17)$$

Rewriting $Q(u)$ as an infinite sum of delta functions, we have

$$Q(u) = \sum_{n=-\infty}^{\infty} q_n \delta\left(u - \frac{2\pi n}{L}\right) \quad (18)$$

and

$$q_n = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{1}{g(x)} e^{\frac{j2\pi nx}{L}} dx \quad (19)$$

where q_n are termed the correction coefficients. Substituting $Q(u)$ from (18) into (17) yields

$$E_{si}(u) \approx \sum_{n=-\infty}^{\infty} q_n E_s\left(u - \frac{2\pi n}{L}\right) \quad (20)$$

Thus, errors in the RCS pattern of a test target, due to deviations of the illumination in the plane of rotation of the reference target, can be removed by summing the products of the response measured under the arbitrary illumination E_s and the correction coefficients q_n 's to obtain the corrected response E_{si} as indicated in (20).

III. MEASUREMENTS AND COMPARISONS

For accurate correction, the length of the reference target and the angular span of the reference target measurement should exceed that of the test target. This accounts for the diminishing of the synthesized plane wave zone caused by the effects of the ends of the reference target. The reference target utilized to correct the SPCR measurements presented here is a 5 cm × 5 cm × 2.44 m aluminum bar with all four surfaces milled flat. The RCS of this reference bar was measured for each of the test target measurement configurations (frequency, polarization, etc.) for angles of -40° to $+40^\circ$.

The precision metal bar test target has a 5.0 cm square cross section and one highly polished broadside surface. The bar measurements were made in the frequency band 7.5–12.0 GHz for both VV and HH polarizations. The target was measured at azimuthal angles from -30° to $+30^\circ$ in steps of 0.1° , where zero degrees corresponds to broadside.

Fig. 4 is an example of the *uncorrected* RCS of the 2.0 m bar measured under the SPCR cylindrical wave illumination compared to the CATR measurement. The RCS pattern

Fig. 4. RCS of a 2.0 m long precision bar at 9.66 GHz and horizontal polarization (measured with the SPCR (uncorrected) and with a dual-parabolic CATR).

Fig. 5. RCS of a 2.0 m long precision bar at 9.66 GHz and horizontal polarization (measured with the SPCR (corrected) and with a dual-parabolic CATR).

measured under cylindrical illumination deviates considerably from that measured under essentially plane wave illumination. Applying the reference target method correction algorithm to this measurement results in the pattern shown in Fig. 5, again compared to the CATR measurement. The CATR and corrected SPCR measurements are in excellent agreement.

Measurements of a scale model aircraft demonstrate the application of the reference target method to a topologically complex target. The scale model is a 52" (132 cm) long, 36" (91 cm) wingspan silver painted fiberglass drone. Because optimum correction occurs in a small angular region centered about zero degrees azimuth, the SPCR measurements of the drone were separated into 30° segments. After correction the segments were re-assembled into the 360° pattern.

Fig. 6. RCS of a scale model drone aircraft at 5.216 GHz and horizontal polarization (measured with the SPCR (uncorrected) and with a dual-parabolic CATR).

Fig. 7. RCS of a scale model drone aircraft at 5.216 GHz and horizontal polarization (measured with the SPCR (corrected) and with a dual-parabolic CATR).

The measured patterns are of the yaw plane with zero degrees pitch and roll. The separation between the rotation center of the model and the virtual line source of the SPCR was 12.91 m: approximately 21% of the $2D^2/\lambda$ distance. The horizontal polarization case at 5.216 GHz is presented here. The CATR measurement and uncorrected SPCR measurement are compared in Fig. 6. Fig. 7 shows the CATR and *corrected* SPCR measurement. It is interesting to observe that, although the reference target method applies rigorously only along a line in cross-range, corrections occur for targets with significant down-range dimensions. Note particularly the -20° to 0° region of Figs. 6 and 7. This orientation corresponds to maximum down-range/minimum cross-range dimensions of the target, yet the correction is very apparent. This example corroborates other measurements and simulations which suggest that targets within the cylindrical volume of space swept out by the reference bar are corrected. The most obvious discrepancies between the CATR and corrected SPCR measurements occur near tail-on incidence (-180° to -135°). Significant effort was made prior to the SPCR measurements to ensure that the target support was true as a function of aspect angle. Additional measurements were performed with small changes in the pitch orientation of the model. After correction, we found that the comparison near -180° was improved over that of Fig. 7, but that the comparison near nose-on incidence (0°) was worse. We conclude from this that there was a significant wobble in the dielectric foam target support at the CATR facility. Shadowing may be another factor contributing to this discrepancy. At angles near -180° , the tail of the model aircraft shadows the wings and fuselage considerably. Shadowing represents an inherent error in NF/FF techniques, as no generalized correction or transformation exists that will account for the differences between near-field and far-field shadowing of one part of a target by another part.

IV. CONCLUSION

The Single-Plane Collimating Range has been implemented at ASU's ElectroMagnetic Anechoic Chamber facility to pro-

duce precision cylindrical wavefronts for antenna and RCS measurements. RCS measurements performed under cylindrical wave illumination exhibit considerable discrepancies from those performed under plane wave illumination; however, applying the "reference bar method" to the bar and drone SPCR measurements results in very good agreement with CATR measurements.

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Craig R. Birtcher, for a photograph and biography, see p. 1389 of the October 1993 issue of this *TRANSACTIONS*.

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