Dependence of Monopulse Radar Boresight Error on Incident E-Field Polarization

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ABSTRACT - Boresight Error (BSE), the angular difference between a target's actual and radar-indicated position, is influenced by protective radomes used on airborne platforms. Recent research results have demonstrated a reliable computer modeling technique for predicting the BSE of electrically large radar-radome systems. This technique, based on a ray-trace receive formulation using Geometric Optics (GO), was extended to investigate the dependence of radome-induced BSE on various combinations of aperture scan angle, element polarization, and incident wave polarization. Results obtained compare very well with available empirical, published, and measured data for the specific scan angles and polarization cases considered. Generally, BSE exhibits less dependence on incident wave polarization when aperture elements are linearly polarized and a higher degree of sensitivity when aperture elements are circularly polarized.

INTRODUCTION

Monopulse processing systems are capable of precisely and quickly locating sources of Radio Frequency (RF) energy. Because of their accuracy and speed, monopulse techniques are extensively used in modern military aircraft fire control radar and missile seeker/guidance systems [1]. The high speed nature of these platforms dictates environmental protection which is structurally sound and aerodynamically stable be provided for onboard sensors. For monopulse radar and seeker systems, this protection is provided by a radome.

An ideal radome would be "transparent" to the system's electromagnetic (EM) wave of interest, i.e., would introduce no amplitude, phase, or polarization variations on a wave passing through it. However, production constraints and available radome materials dictate compromises between EM transparency, structural integrity, and aerodynamics. The compromised radome design has a shape which is "less than ideal" from an EM wave propagation perspective. The radome introduces refractive and reflective distortions at the material boundaries, adversely affecting EM propagation characteristics.

Incident EM plane waves are no longer planar or uniformly polarized after propagating through curved radome surfaces. An arbitrarily polarized plane wave, incident on a radome may be divided into Transverse Electric (TE) and Transverse Magnetic (TM) components at all points of intersection with the radome surface. Since TE and TM transmission coefficients generally differ, the two components of the incident E-field become unequally weighted (different amplitudes and/or phases) while passing through the radome. Upon recombination of the TE and TM components on the transmission side of the radome, the resulting polarization differs from the incident polarization and radome-induced "depolarization" occurs. This effect varies with both incident wave initial polarization, and the relative orientation of the radome surface with respect to the incident wave propagation direction. As a result, the depolarization effect is non-uniform across the surface of a curved radome. These "non-planar" and "depolarized" transmitted waves are a principal cause of the radome-induced BSE generated by monopulse processing systems. The magnitude of BSE is dependant on both the absolute amount of distortion/depolarization and the relative asymmetry of the distortion across the system aperture.

Recent research results have demonstrated a reliable computer modeling technique for predicting the BSE of electrically large radome-radar systems [2,3]. The modeling technique employed a GO ray-trace receive formulation to investigate the effects of multi-layer tapered radome designs on system BSE. The technique provides a high degree of flexibility and possesses characteristics important to the current analysis/modeling effort, including 1) an aperture model which allows arbitrary element quantities, locations, co-polarized (CP) and cross-polarized (XP) field pattern responses, amplitude/phase weightings, and polarizations, 2) accurate tracking of E-Field amplitudes, phases, and polarizations along wave propagation paths, and 3) arbitrarily polarized reference/incident E-Fields. The current effort expands the earlier modeling technique by incorporating a shell program to automatically control the reference E-Field polarization and aperture scan angle.

Model results, generated on a MICROVAX processing system, using standard Fortran, are validated against a previously published modeling effort [4] and contractor furnished measured data on a production radar-radome system. Predicted BSE was within 1.0 mRad of published and measured data for all cases in which the model was applied to the respective system. The validated cases are extended by predicting BSE sensitivity effects under numerous polarization states, i.e., various linear/circular combinations of aperture element and reference E-Field polarizations. Analysis and modeling results clearly indicate that 1) given circularly polarized elements, radome-induced BSE is heavily dependant on both the aperture scan angle and reference E-Field polarization, 2) given linearly polarized elements, radome-induced BSE is primarily dependant on aperture scan angle and less sensitive to changes in reference E-Field polarization, and 3) for sensitive/dependant BSE cases, the BSE exhibits "asymmetrical" characteristics for polarization states where one might intuitively expect symmetrical error.
ANALYSIS APPROACH

This effort builds on previous research efforts [2,4,5,6] which characterized monopulse BSE for tangent ogive radomes. Generally, past efforts focused on the scan angle dependence of system BSE for a limited number of polarization cases and identified scan regions inherently possessing greater BSE degradation as shown in Fig 1. This effort extends these results by performing an analysis driven by polarization sensitivity effects. A modeling technique developed and validated by [2] served as the basis for the current work; the following development closely parallels the previous effort and is introduced with permission.

![Figure 1: Ogive Radome Showing BSE Regions](image)

Incident E-Fields are established using a GO ray-trace receive technique for rays in a bundle, each of which experiences amplitude, phase, and polarization distortion upon propagating through the radome. At each ray-radome intersection point a local "plane of incidence" is established and complex TE and TM transmission coefficients calculated.

Aperture element voltages are calculated from incident E-Fields which have propagated via GO through the radome structure. Element voltages are combined to generate a monopulse error signal which is compared with known scan angle information to establish radome-induced BSE.

For a reference E-Field $\vec{E}_0$, incident on the outside of the radome, $E_0(m)$ incident on an aperture element is clearly dependant on the complex reference field strength $E_0$, initial reference polarization $\hat{p}_0$, and wave propagation direction with respect to the radome surface orientation.

Eq (2) defines parallel and perpendicular unit vectors for establishing the local "plane of incidence" used for E-Field decomposition. These definitions were developed by Munk [7]. Superscripts i and t in Eq (1) differentiate between the incidence and transmission sides of the radome.

$$\hat{a}_i = \frac{\hat{n} \times \hat{k}}{|\hat{n} \times \hat{k}|}; \hat{a}_t = \hat{a}_i \times \hat{k}$$

The total voltage response $V_m$ of a typical aperture element is given by Eq (4) where $E_{CP}(m)$ and $E_{XP}(m)$ are calculated per Eq (3). The $A_m$ and $\phi_m$ terms in Eq (4) represent amplitude and phase weights used in controlling pattern shape and main beam pointing direction. Assuming mutual coupling effects are identical for all elements within the array, the CP element pattern $E_{CP}^r(\theta, \phi)$, XP element pattern $E_{XP}^r(\theta, \phi)$, and element polarization directions $\hat{p}_0$ are identical. Independent CP and XP element patterns allow for varying polarization responses to be analyzed depending on the specific element type being used.

$$V_m = A_m e^{j\phi_m} \left[ f_{CP}(\theta, \phi) E_{CP}(m) + f_{XP}(\theta, \phi) E_{XP}(m) \right]$$

A "simple" method is employed to analyze tracking performance. The radar aperture is divided into symmetrical quadrants. Complex element voltages, calculated per Eq (4), are summed within each aperture quadrant to produce quadrant sum voltages. These are then combined to form monopulse sum and difference voltages, $V_{SUM}$ and $V_{FIELD}$, respectively. The monopulse error signal $E_{m}(\beta, \gamma, \nu)$ is formed from the complex monopulse voltage ratio $V_{DEL}/V_{SUM}$ using an "exact" monopulse processor implemented as in Eq (5). $E_{m}(\beta, \gamma, \nu)$ is defined over an angular range of $\gamma$ for a $\hat{p}$ polarized incident wave at a frequency of $\nu$. The sensitivity $K$ is determined by the slope of the normalized difference pattern with units of $(v/v)/Rad$ [8].

$$E_{m}(\beta, \gamma, \nu) = \text{Re} \left[ \frac{V_{DEL}/V_{SUM}}{K} \right]$$

The monopulse error signal $E_{m}(\beta, \gamma, \nu)$ is used to establish and characterize "system" BSE sensitivity under varying $\hat{p}$ polarization conditions. In this context, "system" BSE is defined as the angle indicated by Eq (5) when the aperture has no pointing error, i.e., the aperture scan direction equals the true source location. This is equivalent to fixing the aperture scan direction.
while repositioning the source until Eq (5) equals zero. The angular difference between the scan direction and source location is the system BSE. For a given aperture scan direction, system BSE may be expressed as in Eq (6) where \( \hat{n}_{s} \) is a unit vector in the aperture scan direction and unit vector \( \hat{n}_{mp} \) represents the direction of the source location such that \( E_{mp}(\phi, \gamma, \nu) = 0 \).

\[
\theta_{BSE} = \cos^{-1}(\hat{n}_{s} \cdot \hat{n}_{mp})
\]  

**RESULTS**

Initial validation of analysis and modeling results is accomplished using a production radome, radar, and monopulse processing system. The production system is a mechanically scanned, 1368-element aperture, approximately 28-wavelengths in diameter with linearly polarized slotted waveguide elements. A modified cosine/cosine\(^2\) amplitude taper is applied across the aperture yielding a half-power beamwidth (HPBW) of approximately 2.48\(^\circ\) and a first side-lobe level (FSSL) of approximately -30 dB. The production radome is a solid tapered wall design empirically "tuned" to provide minimum BSE. It is modeled using a reference ogive surface with a length of 90.26\(\lambda\), a base diameter of 36.136\(\lambda\), and constructed of material with a nominal dielectric constant of \( E_r = 4.8 \) and a loss-tangent of 0.014. For analysis purposes, the reference E-Field and aperture element polarization vectors are separated by an angle defined as the polarization tilt angle. The polarization tilt angle is measured relative to the aperture element polarization with a plus (+) sign indicating counterclockwise rotation and a minus (-) indicating clockwise rotation as viewed facing the aperture. Hence, for a tilt angle of 0\(^\circ\) the reference E-Field and element polarization vectors are equal. The polarization tilt angle is varied between \( \pm 60\)\(^\circ\) while the aperture scan angle is varied between 0\(^\circ\) and 40\(^\circ\). The polarization tilt limits of \( \pm 60\)\(^\circ\) are to ensure that the linearly polarized aperture receives enough energy for reliable processing. The resultant BSE for the production system is shown in Fig 2. This figure shows the BSE of Left/Right monopulse processing with the aperture scanned in azimuth only.

![Figure 2: In-Plane BSE of Production System, Azimuth Scan](image)

As defined here, in-plane BSE is generated by performing monopulse processing in the same plane as the aperture scan plane, i.e., azimuth scanning and elevation monopulse BSE calculations, and cross-plane BSE is generated by performing monopulse processing in the plane orthogonal to the aperture scan plane, i.e., azimuth scanning and elevation monopulse BSE calculations.

Fig 3 is a plot of data extracted from Fig 2 for the case where the polarization tilt angle is zero. Measured data in the figure represents BSE data taken at the radome design frequency and represents the average error of three units randomly selected at the production facility. Comparison of measured BSE data with modeled results reveals a BSE prediction error of approximately 0.028\(^\circ\) (0.5 mRads) which compares favorably with previously validated results [3].

![Figure 3: Measured Data vs. Current Work](image)

From Fig 2, it appears that radome-induced BSE is independent of the incident E-Field polarization tilt angle, at least for linearly polarized apertures. If this were true, it would indicate that a table look-up calibration technique could effectively eliminate system tracking error using only aperture scan angle information, i.e., BSE could be calibrated out as a function of scan angle for all possible received polarization states. However, Fig 4 clearly demonstrates the dependence of BSE on incident E-Field polarization tilt angle, even for linearly polarized apertures.

![Figure 4: In-Plane BSE of Production System, Diagonal Scan](image)

In Fig 4, the aperture is scanned diagonally, i.e., in both azimuth and elevation. The polarization dependance is due to the asymmetry of the radome depolarization effect. In the azimuth scan case of Fig 2, the depolarization had a form of symmetry.
above and below the azimuth scan plane; since an ogive is a figure of revolution, the top and bottom portions of the radome are reflected about the azimuth plane. However, there is no symmetry about a diagonal scan plane, so polarization dependance is evident.

The dependance of radome-induced BSE on incident E-Field polarization was previously identified for tangent ogive radomes [4,6]. These published results form a basis for validating the current modeling technique which extends previous results by identifying and substantiating the existence of an "asymmetric" BSE dependance on incident polarization. For comparison with published results, data is generated using a constant thickness \( t = 0.31665 \) tangent ogive radome. The radome is a single layer design with a length of \( 30.0h \), a base diameter of \( 10.0h \), and constructed of material with a dielectric constant of \( E_\varepsilon = 3.2 \) and a loss-tangent of 0.008. The system is a mechanically scanned, 208-element aperture, approximately 8-wavelengths in diameter with right-hand circularly (RHC) polarized elements. The aperture is gimbaled 2.0\( \text{h} \) from the radome base and weighted with a uniform amplitude taper.

Predicted BSE results are generated for non-reflective in-plane and cross-plane BSE scanning cases. Figs 5 thru 8 show model results for the two cases considered. Figs 5 and 6 represent the in-plane scanning/processing case and Figs 7 and 8 represent the cross-plane case. For both cases the aperture is scanned in the azimuth plane from 0° to 40° while the linearly polarized incident E-Field tilt angle is varied between ±90°. Current 2-D data (X,+,X) in Figs 6 and 8 represents specific polarization cases extracted from Figs 5 and 7, respectively, for comparison with previously published results. In all cases, current BSE model results compare very well and clearly exhibit the polarization dependence identified previously [4]. Not evident in the 2-D comparisons, and hence not identified by previous work, is the "asymmetric" BSE characteristics which appear in the 3-D plots of Figs 5 and 7. Given an arbitrary reference polarization state, i.e., select a linearly polarized incident E-Field with an arbitrary tilt angle as the reference polarization, any equal change (plus and minus) in the polarization tilt angle about the reference angle results in an "asymmetric" BSE response. For example compare the ±45° tilt angle cases in Figs 5 and 7. Clearly, radome-induced BSE is dependant on both the incident wave polarization tilt angle and the aperture scan angle.

To ensure the asymmetrical and dual-dependance behavior of the radome-induced BSE is not an isolated phenomena for this particular radome-radar system, model results are generated using the production radome-radar system with RHC elements replacing the original linearly polarized elements. Figs 9 and 10 are production BSE results using RHC elements for azimuth and diagonal (45.0° azimuth-elevation plane) aperture scans. Diagonal scan BSE data is generated by scanning the aperture in the diagonal plane while calculating azimuth BSE. In both cases, the BSE exhibits the same asymmetry and polarization dependence characteristics previously identified. Additionally, comparison of the two figures indicates a scan plane dependence as well.

The dependance of BSE on both aperture scan angle and incident polarization could greatly complicate the simplest table look-up scheme for BSE calibration or even have a major impact on the overall monopulse system design. Although aperture scan angle information is generally available, from either electrical or mechanical positioning components, monopulse systems do not typically "measure" or estimate incident wave polarization.

Since a circularly polarized transmitted radar wave may be returned with a predominant linear component (dependant on target geometry), systems with circularly polarized elements may be incapable of correctly calibrating out or correcting radome-induced BSE. Even systems with linearly polarized apertures may receive energy in a polarization state different than transmitted (different than expected). In such a case, a look-up table may provide an incorrect BSE calibration factor.

![Figure 5: In-Plane BSE of Published Radome Case](image)

![Figure 6: In-Plane BSE, Published vs. Current Results](image)

![Figure 7: Cross-Plane BSE of Published Radome Case](image)
CONCLUSION

A polarization dependant GO propagation technique is extended to analyze and model electrically large radar-radome monopulse processing systems. Extended model results are validated against empirical, published experimental, and measured BSE data for a production radar-radome system. Radome-induced BSE is characterized under varying polarization conditions, i.e., reference E-Field vs. element polarization and scan angle, and found to exhibit a considerable amount of dependence/sensitivity for specific cases considered. Generally, BSE exhibits less dependence on incident wave polarization when aperture elements are linearly polarized and a higher degree of sensitivity when aperture elements are circularly polarized.

REFERENCES


