A TWO-DIMENSIONAL RAY-TRACING METHOD FOR THE CALCULATION OF RADOME BORESIGHT ERROR AND ANTENNA PATTERN DISTORTION

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Naval Air Systems Command
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ABSTRACT

A two-dimensional ray tracing analysis for the calculation of radome boresight error and antenna pattern distortion is presented here. Emphasis has been placed on the development of a method having considerable flexibility, so as to enable application of the method to a wide range of antenna-radome problems, and on relative ease of calculation, so as to minimize calculation time. Several example problems are calculated to demonstrate the usefulness of the approach. Comparisons between calculations and measurements have been included whenever measured data were available. Instructions for use of this completely computerized method are included along with several tables describing variables and the complete computer program with necessary subroutines. Programs are written in Fortran IV language suitable for use on the OSU version of the IBM system 360/75 (some minor changes may be required for use on other 360/75 installations).
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A TWO-DIMENSIONAL RAY-TRACING METHOD FOR THE CALCULATION OF RADOME BORESIGHT ERROR AND ANTENNA PATTERN DISTORTION

I. INTRODUCTION

Streamlined radomes for aircraft and missile guidance systems must be carefully designed for high transmission efficiency and minimum boresight error. Since the usual antenna-radome system is large in terms of wavelengths, exact methods for the calculation of radome errors, such as the integral equation methods of Van Doeren and Hahn, prove to be difficult to apply. Frequently these methods can only be applied to a small portion of the radome such as the vertex region. Therefore approximate methods continue to be useful in radome analysis.

This report presents a two-dimensional approximate method for calculating radome boresight error and antenna pattern distortion. A ray analysis is used to determine the effects of the radome on the antenna. These effects are used to modify the source aperture distribution which is numerically integrated to determine the far-zone field pattern of the antenna-radome system. The Ohio State University-IBM System 360/75 high speed digital computer is used for all calculations. The calculated results agree reasonably well with experimental data and require little computer time. Several calculations of typical radome design problems are discussed.

II. THE BASIC METHOD

A. General Considerations

The analysis is based upon a two-dimensional model of the antenna-radome system as shown in Fig. 1. The radome is represented by its cross-section and the source antenna is represented by a one-dimensional aperture having a known amplitude and phase distribution. Rays are traced from the aperture to the radome wall to determine angles of incidence to be used in calculating radome effects. The radome is approximated by a plane multilayer oriented at the calculated angle of incidence at each ray intersection. The plane wave, plane-sheet transmission coefficient and insertion phase delay are calculated for each ray. These values are used to modify the original source distribution function such that a reconstructed aperture distribution is obtained which includes the radome effects. This distribution function is then numerically integrated by high-speed digital computer to determine the approximate far-field pattern of the antenna-radome system which is compared...
Fig. 1. Two-dimensional model for antenna-radome system.
to the pattern obtained without the radome to determine pattern distortion and boresight error.

B. Ray Tracing

In the usual antenna-radome system the antenna aperture plane is displaced by some distance $d_a$ from the gimbling axes of the antenna. When the antenna is scanned, description of the aperture plane becomes difficult in a fixed coordinate system. For this reason two coordinate systems are used to describe the antenna-radome geometry, as shown in Fig. 2. The radome is described in a fixed $(x, y)$ frame which has its axes centered on the antenna gimbal axis. The antenna aperture is described in $(x', y')$ frame which rotates about the antenna gimbal axis with the angle of rotation corresponding to some look angle $\phi_L$. Points in the $(x', y')$ system are related to points in the $(x, y)$ system by the following transformation:

\[
\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \phi_L & -\sin \phi_L \\ \sin \phi_L & \cos \phi_L \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}
\]

The radome is assumed to be constructed of $n$ geometry sections which can be described by the following general second-order equation:

\[
F(x, y) = a_n x^2 + b_n y^2 + c_n xy + d_n x + e_n y + f_n = 0
\]

where $(x, y)$ are the coordinates of Fig. 2 and $a_n \ldots f_n$ are a set of geometrical constants which define the $n$-th radome section. A set of $m$ equally-spaced rays from the antenna aperture to the radome inner wall are selected to represent the problem. A ray drawn from a point $(x_a, y_a)$ on the aperture plane to the radome wall is described by the point-slope form as:

\[
y - y_a = m_R(x - x_a)
\]

where $m_R$ is the slope of a ray in the $(x, y)$ frame. The antenna points to be used are determined in the $(x', y')$ frame by

\[
x'_a = d_a
\]
where

\[ y'_a = \frac{A}{2NR} (2m - 2 - NR) \]

A is the total aperture length  
NR is the number of rays to be used  
m is the index of a particular ray  
d_a is the perpendicular distance from the origin to the aperture plane as in Fig. 2.
The set of m points determined by Eqs. (4) and (5) are transformed by
Eq. (1) to the set of \((x_a, y_a)\) points to be used in Eq. (3). Substituting
Eq. (3) into Eq. (2) we get the following quadratic in \(x\):

\[
x_m^2 + \left(\frac{-2bmR^2 x_a + 2bRy_a - cmRx_a + cy_a + d + eR}{a + bmR^2 + cmR}\right) x_m
+ \left(\frac{-2bRy_a x_a + bmR^2 x_a^2 + by_a^2 - emRx_a + ey_a + f}{a + bmR^2 + cmR}\right) = 0.
\]  

The solution of Eq. (6) gives the \(x\)-coordinate of the point of intersection
of the \(m\)-th ray and the radome. Since Eq. (6) is of the form:

\[
x_m^2 + 2Bx_m + C = 0
\]

the solution of \(x_m\) (6) can be written as

\[
x_m = -B \pm \sqrt{B^2 - C}
\]

where

2\(B\) is the coefficient of the linear term in Eq. (6)
\(C\) is the constant term in Eq. (6).

From the geometry of the system it is seen that the positive square
root is selected in Eq. (8) to give the proper point of intersection. This
value of \(x_m\) is substituted into Eq. (3) to obtain the \(y\)-coordinate of the
intersection point:

\[
y_m = mR(x_m - x_a) + y_a.
\]

The derivative of Eq. (2) evaluated at \((x_m, y_m)\) gives the slope of
the tangent to the radome surface at the \(m\)-th intersection point:

\[
m_T = \frac{-2ax_m + Cy_m + d}{(2by_m + Cx_m + e)}.
\]
Provided that neither the tangent line to the radome nor the ray is parallel to the y-axis and that the two lines are not perpendicular, the angle of intersection of the two lines is:

\[
\theta^m = \tan^{-1} \frac{m_R - m_T}{1 + m_R m_T}
\]

which is the complement of the angle of incidence of the m-th ray and the radome inner wall.

\[
\phi^m = \frac{\pi}{2} - \theta^m
\]

is the angle of incidence. As will be discussed later the average angle of incidence for two adjacent rays will be used in further calculations:

\[
\phi_A = (\phi_i^m + \phi_i^{m+1})/2
\]

The two exceptions to Eq. (11) mentioned above are treated specifically in the computer program. The constants a through f in Eq. (1) depend upon the specific geometry of the radome. Logic statements in the program assure that the ray intersection is calculated in the proper geometrical section. The angle of incidence calculated in Eq. (13) is stored in an m x n array indicating that the m-th ray is used with the n-th set of geometrical and electrical constants. The a_n...f_n constants and the associated n geometry boundaries are usually calculated in the program, however, for specialized cases they may be read in directly.

C. Pattern Calculation

The basic calculation is that of a section of the far zone field pattern of the antenna radiating in the presence of the radome. The angular range over which the pattern is calculated varies from one degree about the antenna look angle for boresight error calculation and from 10 to 90 degrees about the look angle for pattern distortion calculation. Within the one degree interval used for boresight calculation only a few discrete points are calculated.

The far-zone field pattern for the one-dimensional source representation shown in Fig. 1 is given by:
\[ E(\phi) = \int_{-L}^{L} F(y) e^{j\phi(y)} e^{jky \sin \phi} dy \]

where:

- \( F(y) \) is the amplitude distribution function
- \( \phi(y) \) is the phase distribution function
- \( \phi \) is the pattern angle
- \( L \) is the length of the aperture.

In general \( F(y) \) and \( \phi(y) \) are arbitrary functions such that the evaluation of the integral requires numerical methods. These functions are determined by the given source distribution functions and modified later to account for the presence of the radome. Rays are traced from the aperture plane to the radome inner wall where they are modified by the plane wave, plane-sheet transmission coefficient \(|T|^2\) and insertion phase delay (IPD), to a new aperture plane immediately outside the radome. Here a "reconstructed" aperture is defined which determines the far-field of the antenna-radome system according to Eq. (14). A few comments on ray tracing follow.

The usual ray analysis uses a set of \( n \) equally-spaced rays. As this \( n \) is increased the predicted result varies up to some value of \( n \) where further addition of rays no longer changes the answer. This answer is not necessarily the correct answer but merely the best answer that the ray tracing solution can predict. This \( n \) required for a convergent answer using equally spaced rays frequently becomes quite large, typically 500 rays for a 10\( \lambda \) aperture and a streamlined radome. Evaluation of Eq. (14) using a large \( n \) consumes an excessive amount of computer time which is undesirable. An alternative to this approach is to use a set of fewer unevenly-spaced weighted rays to analyze the problem such as the set shown in Fig. 1. Since the radome effects, \(|T|^2\) and IPD, are strongly dependent on incidence angle, close spacing of the rays is required only if the radome curvature is changing rapidly. More widely spaced rays can be used in regions where the curvature variation is slight. The most efficient ray analysis uses the fewest number of rays required to obtain the convergent answer. The numerical treatment which will be applied to the reconstructed aperture is equivalent to performing such a weighted ray tracing. This treatment is described below.

The source antenna has associated with it a large number of equally-spaced rays, say 500. A subaperture of the source is defined as that section of the source aperture between two successive rays and has associated with it a ray emanating from its center which intersects the
radome inner wall at angle $\theta_A$ of Eq. (13). The local amplitude and phase associated with this subaperture is calculated from the known source distribution function. In the case of a circular aperture, as shown in Fig. 3, the equivalent one-dimensional source must be tapered by the factor

\[(15) \quad A_0(y) = \cos \left(\sin^{-1} \frac{y}{R}\right)\]

This factor takes into account the effective power radiated from each segment represented by the chord length at the coordinate $y$, as in Fig. 3. If the circular aperture itself has an amplitude taper, $F(r)$, the equivalent one-dimensional aperture taper required is:

\[(16) \quad A(y) = F(y) A_0(y)\]

where $A_0(y)$ is found from Eq. (15).

Fig. 3. Amplitude taper of a one-dimensional aperture for equivalence to a two-dimensional circular aperture.
This subaperture, according to conventional ray optics, illuminates only the small subsection of the radome wall lying between its two defining rays which is approximated as a plane sheet oriented at $\theta_A$. Plane wave, plane-sheet $|T|^2$ and IPD are calculated using the method of Richmond$^4$ for the rays associated with each subaperture. The local subaperture field distribution is modified by the local $|T|^2$ and IPD. The reconstructed aperture is thus completed specifying the integrand function $F(y)$ and $\phi(y)$ of Eq. (14).

The numerical treatment of the aperture integral involves breaking the integral down into several sections, or subapertures, as determined by the rate of change of the integrand, integrating over these subapertures, and summing the integrals. Equation (17) specifies the calculation.

\[
E(\phi) = \sum_{n=1}^{N} \int_{L_n} F_n(y) e^{i\phi_n(y)} e^{jk\sin\phi(y)} dy
\]

where:

- $L_n$ - length of the n-th subaperture
- $\phi_n$ = phase of the n-th subaperture
- $F_n$ = amplitude of the n-th subaperture
- $\phi$ = pattern angle

The process of determining the aperture subdivision is as follows. Fixed amplitude and phase deviations are specified, usually 0.05 to 0.10 and 2 to 3 degrees respectively. The length, amplitude, and phase of the first subaperture are determined by scanning from the center of the reconstructed aperture, point by point towards the positive endpoint of the aperture, until either of the fixed deviations occurs. At this point the first subaperture boundary is defined and the average value of amplitude and phase are computed for the included points. The first sub-aperture is then assigned the three constants $F_1$, $\phi_1$, and $L_1$ of Eq. (17). The scan continues across the positive half of the aperture until all points are included, returns to the aperture center and similarly scans the negative portion of the reconstructed aperture. Thus the n values of $F_n(y)$, $\phi_n(y)$ and $L_n$ are determined. Equation (17) is then evaluated as the summation of N integrals having uniform illuminations. This result is written as:

9
where the term $\phi_n$ contains an additional term which accounts for the $n$-th subaperture being displaced from the coordinate axis. Euler's equation is used to evaluate Eq. (18) on the computer. The range on $\phi$ which is calculated is pre-assigned and depends upon the desired end result, i.e., pattern distortion or boresight error. The method of scanning the aperture from the center out to each end is used to preserve the symmetry of the system.

D. Boresight Error

The boresight error of an antenna-radome system can be defined as the difference between the actual target direction and the antenna pointing direction. In a well designed system this difference is a few tenths of a degree and is due primarily to phase and amplitude distortions of the antenna pattern caused by the radome. The boresight error is evaluated in this analysis from phase monopulse patterns which are generated by making one-half of the source aperture opposite in sign from the other half. This pattern is characterized by a deep null on the beam axis. The object being tracked or guided by the particular radar system has the characteristic direction of the null which is referred to as the boresight direction. The shift in the location of this null due to the addition of a radome to an antenna system is the radome boresight error. If the antenna is scanning in a particular direction and the boresight error is in the same direction it is defined to be a positive error.

In calculating the boresight error several considerations simplify the task. The null-shift is generally a fraction of a degree, thus making the calculation of only a small portion of the pattern necessary. Also, the pattern over a small interval enclosing the null is monotonically increasing on both sides of the null and approximately symmetrical. The null location is determined by computing one pattern point on each side of the null so as to enclose the null in a bracket. By use of the symmetry and monotone properties of the pattern the relative values of the two points calculated indicate which point is closest to the null. From this information a third point is calculated which halves the size of the bracket containing the null. Examination of the field magnitudes at each end of the new bracket now predicts the calculation of a fourth point which again halves the bracket containing the null. This process can be continued
indefinitely to obtain the null location to any desired accuracy. Starting with a two degree interval the null location will be known to within $\frac{1}{2^n}$ degrees for $n$ such calculations. In this analysis an $n$ of 11 is used which gives an accuracy of 0.0005 degrees in the null location. Figure 4 illustrates a typical calculation.

![Diagram](image)

**Fig. 4.** Far-zone field points calculated to determine the null location for a monopulse difference pattern of an antenna-radome system. The order of the points calculated is indicated by the number.
III. DISCUSSION OF COMPUTER PROGRAM

The computer program for the discussed calculations is composed of a main deck and several subroutines as illustrated in Fig. 5. The programs are written in Fortran IV language suitable for calculation on the two Ohio State University computers, the IBM 7094 and the IBM System 360/75. A brief description of the function of each routine follows.

**Fig. 5.** Organization of computer program.
1. **Main Program:** Read in all pertinent data; call necessary subroutines; calculate antenna patterns with and without radome; determines relative power transmission and radome boresight error as a function of antenna look angle.

2. **Geometry:** determines the set of geometry coefficients for each of the n radome geometry sections.

3. **Ray Trace:** determines the boundaries between the n radome geometry sections; determines the n x m matrix of incidence angles corresponding to the n geometry sections and the m rays.

4. **Multilayer Transmission:** determines the transmission coefficient and insertion phase delay for the n x m matrix of incidence angles.

5. **Aperture Taper:** determines the amplitude and phase associated with each ray. Also calculates any aperture blocking or metal nosecap approximations.

6. **Graph:** calculates and plots the normalized far-zone power pattern in dBs with and without radome.

7. **Sidelobe Level:** calculates the level of the maximum sidelobe as a percent of main beam intensity and as dBs down from main beam intensity. Also calculates the location of the first sidelobe for the no-radome case and the power level at this location with the radome installed.

8. **Half-Power Beamwidth:** calculated the half-power beamwidth of the antenna-radome system with and without radome.

Switching from the main program to the desired subroutines is accomplished by means of two input cards named "title" and "source" which contain key words describing the type of calculation desired. For example, if "no" occurs in source (3), indicating that the no-radome case is to be calculated, the multilayer transmission subroutine is not called. Comment cards have been placed at the beginning of the main program which explain all of the options used. Also, most program variables are explained in this extensive set of comment statements.

Figure 6 is a functional flow diagram of the calculation. The significant definitions of terms used in this diagram are listed in Table I.
Fig. 6. Functional flow diagram of computer calculation.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>Number of cases to be run.</td>
</tr>
<tr>
<td>NGS</td>
<td>Number of geometry sections.</td>
</tr>
<tr>
<td>N</td>
<td>Number of layers in each section.</td>
</tr>
<tr>
<td>SHAPE</td>
<td>Geometrical shape of each section.</td>
</tr>
<tr>
<td>(XOO, YOO)</td>
<td>Coordinates of center of an ogive section.</td>
</tr>
<tr>
<td>ROO</td>
<td>Radius of an ogive section.</td>
</tr>
<tr>
<td>PHLIN</td>
<td>Included half-angle of a cone section.</td>
</tr>
<tr>
<td>(XLIN, YLIN)</td>
<td>Any point on a conical section.</td>
</tr>
<tr>
<td>AA, ...FF</td>
<td>Geometry constants of Eq. (1).</td>
</tr>
<tr>
<td>LI</td>
<td>Total number of lock angles used.</td>
</tr>
<tr>
<td>POLIZ</td>
<td>Polarization</td>
</tr>
<tr>
<td>A</td>
<td>Length of source aperture.</td>
</tr>
<tr>
<td>NUM</td>
<td>Number of points calculated in partial pattern.</td>
</tr>
<tr>
<td>DCE</td>
<td>Relative dielectric constant of a layer.</td>
</tr>
<tr>
<td>D</td>
<td>Thickness of a layer in inches.</td>
</tr>
<tr>
<td>TD</td>
<td>Loss tangent of a layer.</td>
</tr>
<tr>
<td>FREQ</td>
<td>Frequency in gigahertz</td>
</tr>
<tr>
<td>PHD</td>
<td>Phase allowance used in numerical integration.</td>
</tr>
<tr>
<td>TRD</td>
<td>Transmission coefficient allowance.</td>
</tr>
<tr>
<td>SPAN</td>
<td>Angular range of pattern calculation.</td>
</tr>
<tr>
<td>PL</td>
<td>Look angle in degrees</td>
</tr>
<tr>
<td>RPL</td>
<td>Look angle in radians</td>
</tr>
<tr>
<td>TAPER</td>
<td>Definition of aperture taper used.</td>
</tr>
<tr>
<td>LT</td>
<td>Present value of LL</td>
</tr>
<tr>
<td>ANEA</td>
<td>Number of equal length subapertures</td>
</tr>
<tr>
<td>MI</td>
<td>ANEA</td>
</tr>
<tr>
<td>NRE</td>
<td>Number of equal spaced rays</td>
</tr>
<tr>
<td>NR</td>
<td>NRE - 1</td>
</tr>
<tr>
<td>AF</td>
<td>Fractional length of a subaperture of source</td>
</tr>
<tr>
<td>CF</td>
<td>Phase-center correction for a subaperture</td>
</tr>
<tr>
<td>TL, CL, SL</td>
<td>Tangent, cosine, sine of look angle.</td>
</tr>
<tr>
<td>CL2, SL2</td>
<td>Cosine, sine of twice look angle.</td>
</tr>
<tr>
<td>SL</td>
<td>Sine-squared of look angle</td>
</tr>
<tr>
<td>MM</td>
<td>Number of subaperture immediately below Y-axis (half-aperture subdivision point)</td>
</tr>
<tr>
<td>XGB, YGB</td>
<td>Coordinates of geometry bounds between geometry sections</td>
</tr>
<tr>
<td>YO</td>
<td>Y-coordinate of center of a subaperture.</td>
</tr>
<tr>
<td>LG</td>
<td>Number for a specific geometry section.</td>
</tr>
<tr>
<td>TI</td>
<td>Angle of incidence</td>
</tr>
<tr>
<td>NKRRRI</td>
<td>Ray trace subroutine</td>
</tr>
<tr>
<td>NKJRM</td>
<td>Multilayer transmission subroutine</td>
</tr>
<tr>
<td>AAT</td>
<td>Aperture amplitude taper</td>
</tr>
</tbody>
</table>
### TABLE I (Cont.)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHST</td>
<td>Aperture phase taper</td>
</tr>
<tr>
<td>FIPD</td>
<td>Insertion phase delay</td>
</tr>
<tr>
<td>TC</td>
<td>Transmission coefficient</td>
</tr>
<tr>
<td>TR</td>
<td>Transmission factor for a subaperture</td>
</tr>
<tr>
<td>PH</td>
<td>Phase factor for a subaperture</td>
</tr>
<tr>
<td>RPWR</td>
<td>Relative power normalized to no radome case</td>
</tr>
<tr>
<td>XMAX</td>
<td>Pattern maximum</td>
</tr>
<tr>
<td>BMAX</td>
<td>Angle at which XMAX occurs</td>
</tr>
<tr>
<td>BN'ULL</td>
<td>Angle at which pattern null occurs</td>
</tr>
<tr>
<td>BSEM</td>
<td>Boresight error in milliradians</td>
</tr>
<tr>
<td>SLL</td>
<td>Sidelobe level in percent</td>
</tr>
<tr>
<td>SLDB</td>
<td>Sidelobe level in dB</td>
</tr>
<tr>
<td>HPBW</td>
<td>Half-power beamwidth in degrees</td>
</tr>
</tbody>
</table>

To indicate the execution time for various program calculations the following table is presented. 500 rays are used with a 4 section radome in all cases. IBM System 360/75.

#### TABLE II

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Execution Time for 500 Rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ray Trace</td>
<td>0.350 seconds</td>
</tr>
<tr>
<td>Multilayer</td>
<td>0.625 &quot;</td>
</tr>
<tr>
<td>Taper</td>
<td>0.083 &quot;</td>
</tr>
<tr>
<td>Average Aperture Distribution</td>
<td>0.025 &quot;</td>
</tr>
<tr>
<td>Null</td>
<td>0.050 &quot;</td>
</tr>
<tr>
<td>100 Point Partial Pattern</td>
<td>2.400 &quot;</td>
</tr>
<tr>
<td>Plot 100 Pt Pattern</td>
<td>0.250 &quot;</td>
</tr>
<tr>
<td>Combined Sidelobe and</td>
<td>0.017 &quot;</td>
</tr>
<tr>
<td>Half-Power Beamwidth</td>
<td></td>
</tr>
</tbody>
</table>

It is seen above that calculations which constitute one look angle can often be executed in less than one minute.
IV. ANALYSIS AND DESIGN OF ANTENNA-RADOME SYSTEMS

In this section several problems in antenna-radome system design will be investigated in order to demonstrate the use of the method as well as to point out its applicability to a wide range of problems. It should be emphasized at this time that all calculations are based on the two-dimensional model of the antenna-radome system and that the accuracy of the calculations is unknown. Verification of results is possible either by comparison with measurements or by comparison with results obtained using a more rigorous theory. As was stated earlier rigorous theories presently available are not easily applied if they can be applied at all. Therefore, whenever possible, results will be compared to measured data.

Two specific modern radomes configurations will be used in most of the calculations to follow. The first radome is characterized as a half-wave-wall design having an ogival body with a hemispheric nosecap. The aft portion of the radome is conically faired to the associated missile body. Construction is entirely of pyroceram ($\varepsilon_r = 5.5$). The radome wall thickness is approximately one-half wavelength. The fineness ratio, which is defined as the ratio of the axial length to the base diameter of a radome, is 2.0. The second radome is derived from the first by removing the hemispheric nosecap and extending the ogive body to form a closed radome. All parameters remain the same with the exception of the Fineness Ratio which becomes 2.25. The choice of these two shapes will allow an evaluation of the effects of blunting the nose of a radome, which is frequently necessary because of aerodynamic heating at the radome tip. Some other radome configurations are analyzed which will be specifically described when considered. Some special design situations require modification of the basic method; these will be pointed out when necessary.

A. Convergence Of The Ray-Optics Solution

As was pointed out in Section II-C a ray-tracing calculation has the property of converging to a fixed answer as the number of rays used is increased. This section presents calculations on two radome geometries to illustrate this convergence and to examine the number of rays required to obtain the convergent solution. Figure 7 shows the calculated boresight error versus the number of equally spaced rays used in the calculation for the pyroceram radome having an ogival body and a hemispheric nosecap. Two representative look angles are used to
Fig. 7. Calculated boresight error vs. number of equally spaced rays at two representative look angle. Center design frequency and perpendicular polarization for the pyroceram ogive radome with hemispheric nosecap.

illustrate the convergence; complete tabulated data for this calculation at ten look angles are included as Appendix A. Figure 8 shows the same calculation for the radome with the nosecap removed and the ogive extended to complete the radome. Figure 9 shows the percent difference from the final answer for the 7.5° look angle case. It is seen that to obtain the convergent solution (0% error) a large number of equally-spaced rays is required. The presence of the nosecap is seen to have little effect on the convergence of the solution if more than 10 rays are used.
Fig. 8. Calculated boresight error vs. number of equally spaced rays at two representative look angles. Center design frequency and perpendicular polarization for the pyroceram ogive radome without hemispheric nosecap.

B. Numerical Integration Of The
Reconstructed Aperture

This section demonstrates the convergence obtained using the numerical integration technique of weighted subapertures explained in Section II-C. 501 equally-spaced rays are used to represent the ten wavelength aperture used with the radomes of Figs. 7 through 9 in all of the following calculations. Boresight error (BSE), relative on-axis power (RPWR), and the number of weighted subapertures obtained (N) are calculated for various combinations of phase allowance (PHD) and amplitude allowance (TRD) in approximating the field over each subaperture by uniform amplitude and phase. Table III shows some representative calculated results with BSE and PHD in degrees. Appendix B gives the complete data for this calculation at ten look angles. The values obtained for 0 amplitude and 0° phase allowances are the same results obtained in Section A of this Chapter, i.e., the convergent answer from a large number of equally spaced rays. The number of aperture points indicated in the table are the number of subsections of the aperture which result for a given phase and amplitude allowance combination and indicate the relative time consumption for a computer pattern calculation. The table shows that the convergent answer is obtained using almost any of the given allowances - for the complete ogive radome the answer is obtained using as few as 7 subsections of the original 500 point aperture.
Fig. 9. Percent difference from convergent ray-tracing solution vs. number of rays. Perpendicular polarization at center design frequency. Look angle 7.5°.

approximation. With the large phase and amplitude allowances, 30° and 0.2 respectively: the error is still less than 2%. In calculations to follow an amplitude allowance of 0.1 and a phase allowance of 3.0 degrees are generally used. 501 equally spaced rays are used throughout since this number assures that the convergent solution can be obtained. The combined time consumption for tracing 501 rays and computing the associated values of $|T|^2$ and IPD is only on the order of 1 second. As was pointed out earlier the significant computer time usage occurs in calculating pattern points. This is because each pattern point requires summing contributions from each aperture point used. For example using 500 equally spaced rays, 10 look angles, and calculating 100 points in the far-field pattern the total number of calculations is 500,000. If only 10 aperture points are used the number of calculations is reduced to 10,000 which is quite significant.
<table>
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<tr>
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<th>Boresight Error</th>
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<td></td>
<td></td>
<td>Ogive</td>
<td>Ogive-Hemi</td>
<td>Ogive</td>
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</table>
C. Electrical Design Of A Radome Wall

The high speed attained using the two-dimensional analysis results in relatively low cost calculations. This allows the method to be used to advantage as a design tool. The approach is to select an approximate design in terms of the complex dielectric constants, wall thicknesses, number of layers, and geometrical shape. A specific parameter, for example wall thickness, is varied in small steps above and below the design specification. Calculations of desired electrical parameters, such as boresight error, transmission, sidelobe level, etc. are made at each incremental variation. Data are then compared to determine an optimum design. One such example follows.

Figure 10 shows the calculated boresight error for the pyroceram radome as a function of its wall thickness. The current design thickness is specified as 0 percent. From the curves it can be seen that for any look angle the boresight error approaches a low value in the range of -3 to -5 percent. Further, in this range the actual value of error for a given look angle remains relatively constant. This indicates that the radome would operate well in this region and show practically no change in error due to small frequency drifts, dimensional tolerances, or thermal gradients.

If we examine the curves near 0 percent or higher we find that the radome will be sensitive to the above three mentioned considerations and operate with significantly higher boresight error as well. Thus it appears that a 4 percent reduction in wall thickness would reduce the maximum boresight error by 50 percent. The on-axis transmission efficiency of the radome is calculated simultaneously with the boresight error in order that the effects of a design change on transmission can be observed. Figure 11 shows that decreasing the wall thickness by 4 percent causes a 14 percent net loss in transmitter power. This is probably not excessive in view of the improvement in boresight performance.

D. Radome Boresight Error Versus System Bandwidth

If the calculated curves of Fig. 10 are correct, precise agreement between calculated and measured data in the region of design thickness (0%) is unexpected. A small dimensional error could easily cause a 15-20 percent change in boresight error. Figure 12 shows a comparison between calculated and measured data for the pyroceram radome. Agreement is only fair in this case. The frequencies in Fig. 12 correspond to the upper and lower frequencies of a 1.5 percent bandwidth design.
Fig. 10. Calculated boresight error for pyroceram ogive radome with hemispheric nosecap as a function of its wall thickness. Perpendicular polarization at design frequency.

E. Source Taper Effects

Many radar designs utilize carefully controlled amplitude tapers in order to achieve an antenna pattern having very low sidelobes. Phased array techniques available today emphasize this method. A study to determine the pattern distortion in terms of change in sidelobe level and half-power beamwidth due to the addition of a radome to such an antenna system was carried out. In addition, the effects of the use of an amplitude taper on the system boresight error characteristics were calculated. Two antenna-radome systems were analyzed, the pyroceram ogive radome with the hemispheric nosecap (blunted nose case) and the complete ogive...
Fig. 11. On-axis transmission efficiency for pyroceram ogive radome with hemispheric nosecone as a function of its wall thickness. Perpendicular polarization at design frequency.

radome (pointed nose case). An identical antenna having a variable amplitude taper was analyzed for the two radomes. Particular emphasis was placed on the "cosine-squared on a pedestal" distribution since it provides a convenient method for varying the antenna pattern over a broad range of sidelobe levels. Also, this distribution is commonly used to achieve low-sidelobe pencil beam antennas.

Figure 13 shows the sidelobe level obtained using the two antenna-radome systems. The blunted nose radome is seen to degrade the antenna performance severely while the pointed nose radome produces inconsequential pattern distortion. All calculations were made at look angle 0° in order to emphasize the difference between the two systems. These calculations are corroborated to some extent by measurements performed.
Fig. 12. Calculated and measured boresight error for pyroceram ogive radome with hemispheric nosecap. $F_{\text{HIGH}}$ and $F_{\text{LOW}}$ denote the two extremes of a 1.5% bandwidth design. Perpendicular polarization.

on a similar antenna-radome system by Styron and Hoots of the Brunswick Corporation. They measured pattern distortion due to a blunted nose conical radome in terms of sidelobe degradation for three aperture tapers. They found that a basic 30 dB sidelobe antenna was reduced to an approximately 21 dB system and that the radome controlled the sidelobe level rather than the aperture taper. No similar set of measurements are available for the pointed nose radome, however, Styron and Hoots stated that the pattern degradation was most severe at offsets where the center antenna ray impinged near the radome nose and that for offsets further from the nose the degradation was minimal. This tends to verify the calculations for the pointed nose case.
Fig. 13. Calculated sidelobe level for the pyroceram ogive radome with and without hemispheric nosecap. Look angle 0°, perpendicular polarization, design frequency. Aperture amplitude taper is cosine-squared on a variable pedestal.
Figure 14 shows that the half-power beamwidth is relatively unaffected by the presence of the blunt nose radome. Similar results were obtained for the pointed nose case.

Figures 15 and 16 show the effects of several amplitude tapers on the boresight error performance of the two antenna-radome systems. The blunted-nose radome is seen to have considerably poorer boresight performance when an amplitude taper is used. This may be attributed to the much smaller radius of curvature in the vertex region which causes considerable phase distortion in the aperture distribution. Also, since this ray-tracing analysis uses a collimated beam projecting from the source through the radome, it is likely that the resulting higher concentrations of energy near the vertex region tend to over-emphasize the effects of the vertex region. Thus the effects of the blunted nose on the

![Graph showing the effect of an aperture amplitude taper on antenna-radome system bandwidth. Blunt nose pyroceram ogive radome, design frequency, perpendicular polarization.](image-url)
Fig. 15. Effects of several aperture amplitude tapers on system boresight error. Pointed nose pyroceramic ogive radome, perpendicular polarization at design frequency.

radome are somewhat exaggerated. From the error curves it is seen that in both cases the more nearly uniform aperture distributions produce the lowest boresight error. The best boresight performance is obtained with the uniform distribution, however, the cosine-squared on a pedestal, or something similar, can be used for sidelobe control without seriously affecting the boresight performance. Measurements by Styron and Hoots support the above calculations for the blunted nose radome case.

F. Aperture Blocking

In the two dimensional ray-tracing approximation a metallic portion of a radome, such as a protective rain-erosion cap, is treated as an aperture block. This requires specific changes in the computer program for two reasons. First, the perfectly collimated beam assumed in the ray tracing approach predicts that the effects of an obstacle in front of an antenna are independent of the distance between the obstacle and the antenna. The second problem is that the portion of the source aperture
Fig. 16. Effects of several aperture amplitude tapers on system boresight error. Pointed nose pyroceram ogive radome, perpendicular polarization at design frequency.
blocked in the two-dimensional model is much larger than the actual area blockage in the three-dimensional problem. A study was made to determine a suitable two-dimensional representation of the three-dimensional block. Details of the specific treatment for aperture blocks are given below.

Figure 17 shows an aperture block of radius $h$ located at a distance $l$ from an antenna aperture of radius $R$. The source aperture is projected to the plane of the block using a divergence angle $\theta_1$ equal to the half-power beamwidth to determine a projected aperture radius $R'$:

$$R' = R + l \sin \theta_1$$

The ratio of the block area to the projected source area is calculated as:

![Diagram](image)

**Fig. 17. Geometry - aperture blocking calculation.**
Equation (20) gives that fraction of the source area to be blocked out for any value of \( l \). In the one-dimensional aperture approximation for a planar source the block is inserted at \( l = 0 \) even though the block is located at \( l \); hence \( h \) must be reduced to account for the distance \( l \). The effective blocked area at the source is:

\[
A_{\text{BLOCKED}} = A_{\text{SOURCE}} \cdot \text{RATIO}
\]

which gives:

\[
h' = \left( \frac{A_{\text{BLOCKED}}}{\pi} \right)^{\frac{1}{2}}
\]

as the reduced length of the block. This is the approximate method used to account for the antenna-obstacle separation.

A second approximation is required because the one-dimensional block does not represent the two-dimensional block in the other dimension. Figure 18 shows that the blockage in the two-dimensional case represented by the one-dimensional block is a strip across the entire aperture. The approximation used here is to reduce the block length such that the resulting strip area is equal to the actual area of the block. In this way, even though the shapes of the aperture blocks differ, the source area blocked out is the same. With reference to Fig. 19, the strip area is:

\[
A_{\text{STRIP}} = R^2(\pi - \theta + \sin \theta)
\]

where \( \theta \) in radians is given by:

\[
\theta = 2 \cos^{-1}\left(\frac{y}{R}\right)
\]

Using Eq. (21) we set \( A_{\text{STRIP}} = A_{\text{BLOCKED}} \):
Fig. 18. Effective aperture blockage in two dimensions by a one-dimensional aperture block.

\[
\pi R^2 \times \text{RATIO} = R^2(\pi - \theta - \sin \theta)
\]

Removing the \( R^2 \) terms and rewriting Eq. (25) in homogeneous form:

\[
\theta - \sin \theta \quad \pi (1 - \text{RATIO}) = 0
\]

This equation can be solved to any degree of accuracy using Newton's method.

\[
a_2 = a_1 - \frac{f(a_1)}{f'(a_1)}
\]
Fig. 19. Geometry used in calculating the area of a circular strip.

where \( a_1 \) is an approximate solution of Eq. (26) which is \( f \) in Eq. (27). The value \( a_2 \) is a better approximate solution than \( a_1 \). By iterating Eq. (27) we can obtain any desired accuracy in the approximation. Since most blocks are small a value of 170° is used for \( a_1 \) in the program. In the problem being considered Eq. (27) takes the form:

\[
\begin{align*}
\theta_2 &= \theta_1 - \frac{\sin \theta_1 - \pi(1 - \text{RATIO})}{1 - \cos \theta_1} \\
\end{align*}
\]

The resulting block width in the one-dimensional aperture approximation using this approximation is:

\[
(29) \quad h'' = 2R \cos(\theta/2)
\]
where $\theta$ is the angle associated with the strip as shown in Fig. 19.

In order to determine the accuracy obtained using the above two-dimensional aperture blocking approximations some sample calculations were made and compared to the calculated and measured aperture blocking results of Collier. In his report Collier used a $16.4\lambda$ parabolic dish having a $2.2\lambda$ diameter feed located $2.2\lambda$ in front of the aperture plane. He considered obstacles ranging in size from $3.4\lambda$ to $9.7\lambda$ which could be positioned from $20\lambda$ to $100\lambda$ from the aperture plane. The frequency was $32.7$ GHz. The medium sized obstacle of $4.7\lambda$ was chosen for comparison here. Collier used a severe radial taper, as shown in Fig. 20, to represent the antenna aperture distribution. The central amplitude of zero was used to account for the aperture blocking due to the feed. The measured pattern reported showed an approximately $5^\circ$ beamwidth and $16.5$ dB sidelobes. This taper was represented here by a piecewise linear approximation with the exception that the curve was extended to 10 at the origin and the feed treated as a separate aperture block. The calculated pattern using

![Fig. 20. Aperture amplitude taper used in Collier aperture blocking calculation.](image)

34
the two-dimensional approximations showed a beamwidth of 5.29° and a sidelobe level of 16.32 dB which is in excellent agreement with Collier's measurements. Figure 21 shows the calculated sidelobe level for the antenna in the presence of the obstacle as a function of aperture-obstacle separation. The modified two-dimensional model generally shows very good agreement with measurements and with the three-dimensional calculations.

C. Electrical Performance Of A Radome In A Hyper-Environment

Due to the high speed of modern aircraft and missiles, radomes are often subjected to severe environments. Nonuniform temperature distributions exist about the radome wall which result in variations in the temperature dependent quantities of dielectric constant, loss tangent, and wall thickness. The variations in these quantities alter the

![Graph showing comparison of calculated sidelobe level by two-dimensional approximate method with three-dimensional calculations and measurements.](image)

Fig. 21. Comparison of calculated sidelobe level by two-dimensional approximate method with three-dimensional calculations and measurements.
boresight error performance of the antenna-radome system. Figure 22 shows a representative temperature profile which a radome may encounter. The boresight error characteristics of the pyroceram radome having a hemispheric nosecap were calculated for this temperature profile as an example. To approximate the effects of the temperature profile, the radome is subdivided into several sections, each of which has a fixed set of dielectric constant, loss tangent, and wall thickness parameters. The subdivision is determined by observing the rate of change of these parameters with temperature and the rate of change of temperature along the radome wall. References 7 and 8 were used for this purpose. Figure 23 shows the calculated boresight error in the presence of the temperature profile of Fig. 22. Figure 24 shows a similar set of curves with the original wall thickness reduced by 1.5%. These results indicate that the boresight error performance of the radome may actually improve in a severe thermal environment. The effect of the temperature profile in this case is seen to be similar to the design technique of constructing a tapered radome wall to improve radome performance.

As shown in Fig. 22 there is a temperature gradient from the outside to the inside of the radome wall. In the above example the temperature was assumed to vary linearly with distance through the wall. In case there is a nonlinear variation in temperature or parameter constants as a function of temperature through the wall, a further approximation consisting of subdividing each section into several layers having variable parameters can be used. Thus the final subdivision of the radome in this case would be one of several geometry sections having differing numbers of layers.

H. Comparison Of Boresight Measurements And Calculations

Boresight calculations using the ray tracing method described in this report are compared in this section with measured data supplied by The U.S. Naval Air Development Center at Johnsville, Pa. and with calculations and measurements taken from the literature. Exact radome geometry was not always known in the following cases, hence some comparisons were made on the best estimate basis.

Case 1

The previously described half-wave wall conically-faired ogive radome with a hemispheric nosecap is examined here. A constant wall thickness of pyroceram (ε = 5.5) was used throughout. Calculations and
Fig. 22. Temperature profile used to simulate the case of a radome operating in a hyper-environment.
Fig. 23. Calculated boresight error for blunt-nosed pyroceram ogive radome in the presence of the temperature profile of Fig. 22. Perpendicular polarization at design frequency.
Fig. 24. Calculated boresight error. Same case as Fig. 23 with radome wall thickness reduced by 1.5%.
measurements at the high, low, and center frequencies of a 1.5% bandwidth design were made for both perpendicular and parallel polarizations. Two sets of measurements were furnished by the USNADC, both of which are included in the comparisons to give an indication of experimental deviations. This deviation is generally a result of a lack of symmetry in the radome. Figures 25 and 26 show the comparisons between calculations and measurements for perpendicular and parallel polarization at the low frequency end of the band. Agreement between calculation and measurement is reasonably good for the perpendicular polarization case, however, the agreement is poor for parallel polarization. Figures 27 and 28 give the same comparisons for the design frequency. Perpendicular polarization shows very good agreement in this case while agreement remains poor for parallel polarization. Figures 29 and 30 show the comparison for the high end of the frequency band. Agreement is also very good for the case of perpendicular polarization and poor for parallel polarization.

Fig. 25. Calculated and measured boresight error for a blunted-nose pyroceram ogive radome at the lower limit of a 1.5% bandwidth design. Perpendicular polarization.
Fig. 26. Calculated and measured boresight error for a blunted-nose pyroceram ogive radome at the lower limit of a 1.5% bandwidth design. Parallel polarization.

Case 2

This comparison uses the same radome geometry as in Case 1 except that the construction is of polyimide (e = 4.2). Measurements and calculations at the design frequency for perpendicular and parallel polarizations are shown in Fig. 31. Agreement is good for both polarizations in this example. Measurements were furnished by USNADC.
Fig. 27. Calculated and measured boresight error for a blunted-nose pyroceram ogive radome at the design frequency. Perpendicular polarization.

Case 3

This comparison uses a radome having basically the same construction as in Case 1, i.e., conical fairing, ogive body, and hemispheric nose cap. The main body of the radome was constructed of polyimide ($\varepsilon = 4.2$). A rain erosion cap of alumina ($\varepsilon = 8.9$) was sprayed on the tip end of the radome extending back six inches. Exact dimensional data was unavailable for this case, therefore, estimates were made as to the probable design. Calculations of boresight error (BSE) and transmission efficiency ($|T|^2$) were made at the probable design thickness and at $\pm 2.5\%$ and $\pm 5\%$ increments about this design thickness. In the region of the alumina nose cap the main body of the radome was assumed to be of thinner wall to adjust for the increased dielectric constant of the cap material. The source of measured data was a report by The Brunswick Corporation. Reference 11 also stated that the radome had been "corrected" - which amounts to adding patches of dielectric material to the radome inner wall to locally alter the phase shift value through the wall. Thus the geometry is relatively uncertain. High and low frequency
calculations were made at perpendicular polarization since these corresponded to the reported measurements. Figures 32 and 33 show the high and low frequency boresight error calculations for the estimated geometrical construction compared to the measurements reported in Ref. 11. Measurements were made at several roll angles resulting in the spread of value shown by the shaded portions in Figs. 32 and 33. Agreement was not expected to be good in this case, however, considering the assumptions required, agreement is satisfactory. The general shape of the curves, i.e., the initial negative error at small look angles and the shift to positive error at larger look angles is predicted. The amplitude of the negative swing is considerably larger than the measurement, however, the positive error amplitude is in good agreement with the measurements. This could be explained by the "correction" performed.

Fig. 28. Calculated and measured boresight error for a blunted-nose pyroceram ogive radome at the design frequency. Parallel polarization.
on the radome as mentioned above. Using the main body (aft of the nose cap) wall dimensions corresponding to Figs. 32 and 33 as a base the radome error was then calculated at $\pm 2.5\%$ and $\pm 5\%$ of this value with the nose dimensions held constant. In all cases the rain erosion cap was taken to be 0.030 inches thick. Figures 34 and 35 show these calculations compared to the measurements. Excellent agreement between calculations and measurements is obtained for the $+2.5\%$ case inciting that this wall thickness is probably closer to the actual value than the original assumed value. Another view of this same data is shown in Fig. 37 which indicates that $+2.5\%$ is about optimum for a boresight error design point. The computer program simultaneously calculates transmission efficiency with boresight error. Figure 37 shows the
Fig. 30. Calculated and measured boresight error for a
blunted-nose pyroceram radome at the upper
limit of a 1.5% bandwidth design. Parallel
polarization.

\[ |T|^2 \] curves which correspond to Figs. 33 through 36. Since radomes
of this type are frequently designed for maximum transmission, the
indication is that the design wall thickness was +2.5% or more above
the assumed value.

Case 4

Several radome body geometries previously analyzed by General
Dynamics are examined. Calculations of boresight error are made
and compared to similar calculations by G.P. Tricoles of General
Dynamics Corporation, San Diego, California. Since Tricoles uses
a different ray-tracing calculation these comparisons are presented
merely to show similarities and disagreements between the calculated
results. Table IV indicates the geometrical differences among the
Fig. 31. Calculated and measured boresight error for a blunt-nose polyimide radome at the design frequency.

various radome configurations. Table V follows the radome curves to indicate the general agreement between the two calculations. The comparisons are given for the several configurations at the high and low ends of a 1.5% bandwidth for perpendicular and parallel polarizations in Figs. 38 through 51.
Fig. 32. Comparison between measurements and calculations for the "estimated" geometrical construction of a polyimide radome having an alumina nosecap. Perpendicular polarization. High frequency of 1.5% bandwidth design. Main radome body thickness assumed to be 0.340 inches.

Fig. 33. Comparison between measurements and calculations for the "estimated geometrical construction of radome of Fig. 32. Perpendicular polarization, low frequency of a 1.5% bandwidth.
Fig. 34. Comparison between measurements and calculations at ±2.5% and ±5% of the probable design thickness of the main body or the radome of Fig. 32. Perpendicular polarization, high frequency.
Fig. 35. Comparison between measurements and calculations at ±2.5% and ±5% of the probable design thickness of the main radome body for the radome of Fig. 32. Perpendicular polarization at the low frequency.
Fig. 36. Calculated transmission efficiency vs wall thickness vs look angle for the radome of Fig. 32. Perpendicular polarization at the high frequency.
Fig. 37. Calculated transmission efficiency vs wall thickness vs look angle for the radome of Fig. 32. Perpendicular polarization at the high frequency.
TABLE IV
Description of Seven Example Radomes, All Dimensions are in Inches. Sketch Pertains to Secant Ogives Only.

![Graph of ogives and their dimensions](image)

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Fig. 38. Comparison between Tricoles and Kilcoyne calculations. Radome 1 in Table IV. Parallel polarization. $F_L$ and $F_H$ denote the low and high frequencies of a 1.5% bandwidth.

Fig. 39. Comparison between Tricoles and Kilcoyne calculations. Radome 1 in Table IV. Perpendicular polarization.
Fig. 40. Comparison between Tricoles and Kilcoyne calculations. Radome 2 in Table IV. Parallel polarization.

Fig. 41. Comparison between Tricoles and Kilcoyne calculations. Radome 2 in Table IV. Perpendicular polarization.
Fig. 42. Comparison between Tricoles and Kilcoyne calculations. Radome 3 in Table IV. Parallel polarization.

Fig. 43. Comparison between Tricoles and Kilcoyne calculations. Radome 3 in Table IV. Perpendicular polarization.
Fig. 44. Comparison between Tricoles and Kilcoyne calculations. Radome 4 in Table IV. Parallel polarization.

Fig. 45. Comparison between Tricoles and Kilcoyne calculations. Radome 4 in Table IV. Perpendicular polarization.
Fig. 46. Comparison between Tricoles and Kilooyne calculations, Radome 5 in Table IV. Parallel polarization.

Fig. 47. Comparison between Tricoles and Kilooyne calculation, Radome 5 in Table IV. Perpendicular polarization.
Fig. 48. Comparison between Tricoles and Kilcoyne calculations. Radome 6 in Table IV. Parallel polarization.

Fig. 49. Comparison between Tricoles and Kilcoyne calculations. Radome 6 in Table IV. Perpendicular polarization.
Fig. 50. Comparison between Tricole and Kilocoyne calculations. Radome 7 in Table IV. Parallel polarization.

Fig. 51. Comparison between Tricole and Kilocoyne calculations. Radome 7 in Table IV. Perpendicular polarization.
TABLE V
Relative Agreement Between Tri-foles and Kilcoyne Calculations
FH = 1.015 FL

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I. Effects Due to the Blunting of a Radome Nose Section

The high speed of a modern aircraft or missile frequently results in the generation of temperatures at the leading edge (tip) that are above the maximum safe operating temperatures of even the best ceramic radome materials. When it is necessary to locate a radome at the tip section, special design precautions are required which generally take the form of either blunting the radome tip, which increases the tip area, or placing a protective metal cap at the tip of a pointed system. This section is included to summarize the electrical effects due to the blunting of the radome tip which have been indicated in previous sections and to illustrate the far-zone power pattern plot which the computer program generates. Calculations of boresight error, transmission efficiency, and antenna pattern distortion are presented for an identical antenna system operating with a pointed radome and with a blunted version of the same radome. All calculations are for perpendicular polarization at the center design frequency. The two radomes used in this example are the pyroceram ogive radomes described earlier with and without the hemispheric nose cap.

Figure 52 shows the effects of blunting the radome tip on the boresight error characteristics of the antenna-radome system. Figure 53 shows the relative on-axis transmitted power calculated from the sum pattern of the monopulse antenna for the two systems. The "no-radome"
Fig. 52. Calculated effects on radome boresight error due to the blunting of the tip of a pyroceram ogive radome. Perpendicular polarization at the design frequency.

The pointed-nose case is represented by the 100% relative power level at all look angles. From these figures it can be seen that the ray tracing theory predicts the pointed-nose case to give considerably better boresight error performance as well as having about 5% greater on-axis power transmission.

Figures 54, 55, and 56 show the normalized far-zone power patterns for the antenna without radome, with pointed radome, and with the blunted radome respectively for look angle 0°.
Fig. 53. Calculated transmission efficiency for the case of the radome of Fig. 52.
Fig. 54. Computer generated far-zone power pattern for the antenna without radome.
Fig. 55. Computer generated far-zone power pattern for the antenna in the presence of a pointed-nose ogive radome. Perpendicular polarization at the design frequency.
Fig. 56. Computer generated far-zone power pattern for the blunied-nose version of the radome of Fig. 55.
V. CONCLUSIONS

A completely computerized two-dimensional ray tracing analyses of radome boresight error and antenna pattern distortion has been developed. Application of this method to several complicated antenna-radome problems has been demonstrated which shows the usefulness of the method both for the design and the analysis of antenna-radome systems. Several example cases were calculated and compared with experimental data and with other calculations. Agreement between measurements and calculations was in general reasonably good. The method was modified to include the analysis of aperture blocking effects in order to form a basis for the calculation of radome systems involving metallic nosecaps. Calculations and measurements of this case will be included in a future report.

The computer program written for the calculation of this two-dimensional method is relatively long and involved; however, it has been written in such a way as to make its use by others relatively simple and convenient.

The method can be applied to a wide range of antenna-radome problems. Calculation of results is extremely fast, thus making the method an economical approach to radome design and modification.

ACKNOWLEDGEMENT

Measured data and some calculations used in comparisons in this report were furnished by The U.S. Naval Air Development Center, Johnsville, Warminster, Pennsylvania. The author gratefully acknowledges Mr. Walter C. Beamer of USNADC.
APPENDIX A

This appendix contains calculated boresight error (BSE) and relative power transmission (RPWR) for several equally-spaced ray selections at ten look angles to further demonstrate the convergence of the ray tracing solution which was explained in Chapter IV-A. Tables VI and VII show the BSE and RPWR as a function of the number of equally-spaced rays (NRE) used for the pyroceram ogive radome with and without the hemispheric nosecap. Perpendicular polarization was used throughout. BSE is in milliradians and RPWR has a value of 1.0 for the no-radome case. Look angle ($\phi_L$) is in degrees.
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<th>RPWR</th>
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### TABLE VII
Pyroceram Ogive Without Nosecap

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APPENDIX B

This appendix contains calculated boresight error and on-axis power transmission for several choices of phase allowance (PHD) and amplitude allowance (TRD) parameters in the numerical integration technique explained in Chapter IV-B. The radomes used are the same as those of Appendix A. Look angle ($\phi_L$) is in degrees, boresight error (BSE) is in milliradians, PHD is in degrees, TRD and relative on-axis power (RPWR) are normalized fractions. The number of subapertures (N) used refers to the number of subsections of the 500 point reconstructed aperture remaining after averaging the aperture distribution functions. Tables VIII, IX, X, and XI show the calculated BSE, RPWR, and N for 12 choices of PHD and TRD for the blunted (with hemispheric nosecone) and pointed (without nosecone) radomes respectively.
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</table>
A. Required Input Data

The following table lists all the required inputs for a calculation of radome boresight error and/or antenna pattern properties. All data are read in from punched cards. The order of the input of the data depends upon the calculation and therefore can be varied.
<table>
<thead>
<tr>
<th>Variables</th>
<th>Description of Variable</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>MC</td>
<td>Number of cases to be calculated</td>
<td>Integer Number</td>
</tr>
<tr>
<td>LL(I)</td>
<td>Number of look angles for which calculations are made for the I-th case on MC</td>
<td>Integer Number</td>
</tr>
<tr>
<td>PL(I)</td>
<td>The I-th look angle on LL</td>
<td>Decimal Degrees</td>
</tr>
<tr>
<td>NRE(I)</td>
<td>The number of equally spaced rays used for the I-th case on MC</td>
<td>Integer Number</td>
</tr>
<tr>
<td>POLIZ</td>
<td>Polarization: Either perpendicular or parallel</td>
<td>Alphabetic</td>
</tr>
<tr>
<td>TITLE</td>
<td>Description of Calculation</td>
<td>Alphanumeric</td>
</tr>
<tr>
<td>SOURCE</td>
<td>Specifies source type, taper, presence of obstacles, presence of radome, source taper, etc. See comment cards at beginning of program for complete description</td>
<td>Alphanumeric</td>
</tr>
<tr>
<td>FREQ</td>
<td>Frequency in megacycles</td>
<td>Decimal</td>
</tr>
<tr>
<td>NUM</td>
<td>One less than the number of points calculated in a partial pattern calculation</td>
<td>Integer Number</td>
</tr>
<tr>
<td>SPAN</td>
<td>One-half the angular range over which pattern points are calculated</td>
<td>Decimal Degrees</td>
</tr>
<tr>
<td>NOS</td>
<td>Number of geometry sections used to define the radome shape</td>
<td>Integer Number</td>
</tr>
<tr>
<td>N(I)</td>
<td>The number of layers in the I-th geometry section of NOS</td>
<td>Integer Number</td>
</tr>
<tr>
<td>SHAPE(I)</td>
<td>The shape of the I-th section on NOS</td>
<td>Alphabetic</td>
</tr>
<tr>
<td>DCE(I, IL)</td>
<td>The dielectric constant of the I-th layer of the IL-th geometry section</td>
<td>Decimal Number</td>
</tr>
</tbody>
</table>

76
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description of Variable</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(I, IL)</td>
<td>The thickness of the I-th layer of the IL-th geometry section</td>
<td>Decimal Inches</td>
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<tr>
<td>TD(I, IL)</td>
<td>The loss tangent of the I-th layer of the IL-th geometry section</td>
<td>Decimal Number</td>
</tr>
<tr>
<td>XOO, YOO</td>
<td>The coordinates of the center of an ogive radome section</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>ROO</td>
<td>The radius of an ogive section</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>XLIN, YLIN</td>
<td>Coordinates of a point on a conical section of a radome</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>PHLIN</td>
<td>Included angle of a conical section of a radome</td>
<td>Decimal Degrees</td>
</tr>
<tr>
<td>DFATSP</td>
<td>The distance from the coordinate axes to the source aperture plane</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>A</td>
<td>The length of the aperture plane</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>TAPER</td>
<td>Description of aperture amplitude taper</td>
<td>Alphanumeric</td>
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<tr>
<td>PHD</td>
<td>Phase allowance used in averaging the reconstructed aperture</td>
<td>Decimal Degrees</td>
</tr>
<tr>
<td>TRD</td>
<td>Transmission allowance used in averaging the reconstructed aperture</td>
<td>Decimal Number</td>
</tr>
<tr>
<td>NBLOK</td>
<td>The number of a geometry section which is an aperture block (metal). If none NBLOK = 0</td>
<td>Integer Number</td>
</tr>
<tr>
<td>XGB(I)</td>
<td>The x-coordinate of a boundary between two geometry sections, I and I+1</td>
<td>Decimal Inches</td>
</tr>
<tr>
<td>STAP(I)</td>
<td>The amplitude of a step used in a step + function amplitude taper. I on MC</td>
<td>Decimal Number</td>
</tr>
</tbody>
</table>
B. Description Of A Typical Calculation

The SOURCE card plays a key role in determining the calculation procedure. SOURCE contains twelve alphanumeric words which control various phases of the calculation. Twelve comparison words are read into the program as data statements. By comparing the contents of the SOURCE card to the data statements the desired subroutines are called or the desired calculations are made. Each word of SOURCE contains 6 alphanumeric characters or blanks (which are designated by ") Each word is explained below.

Source (1) indicates the calculation of the monopulse difference pattern by FMONOP. The sum pattern is calculated otherwise.

Source (2) is not used.

Source (3) indicates the calculation of the no-radome case by bNOBB.

Source (4) indicates the use of an aperture pedestal + function taper by the word STEPB.

Source (5) indicates the absence of an aperture amplitude taper by FNNOAT.

Source (6) indicates the absence of an aperture phase taper by FNPHST.

Source (7) causes the program to calculate sidelobe level and half-power beamwidth when the word OPTION occurs there.

Source (8) indicates the use of a circular aperture by CIRCLE.

Source (9) indicates the presence of an aperture block by bBLOCK.

Source (10) calls for a graph of the far-zone pattern by PLOTB.

Source (11) indicates that special x-geometry boundaries are to be read in by the word SXGBB.

Source (12) causes a write-out of ray-tracing and multilayer calculations by WRITER.
Similarly TITLE(l) indicates the calculation of boresight error by the word FNULL. Otherwise a partial pattern calculation is carried out. All other alphanumeric input cards are similarly used, e.g., the words OGIVE and CONE on the shape card cause the program to call either the ogive or cone subroutine respectively, to calculate the geometric constants associated with a radome section. One alphanumeric word enables the taper subroutine to utilize any one of a set of pre-programmed aperture tapers. The TAPER card specifies this word.

Thus for a typical calculation the number of different cases to be run and the various differences between cases are determined. Data which does not change from case to case is read in between the following two specific cards:

If (L.GT.1) Go to 937

Read ......

937 Continue

This prevents unnecessary duplication of computer reading time.

Two or more completely different sets of calculations, such as the boresight error curves for differing radomes, may be carried out on one run by utilizing the cards

DO 949 IY = 1, 4

Complete program

949 Continue

as shown. These cards are in the program permanently so that runs may be combined without re-compiling the program (which consumes about 1/2 minute). The number 4 is completely arbitrary. These cards cause an abnormal termination of the computer and consequent error message when less than 4 runs are made, however this is no problem because the calculations are finished when the termination occurs.

C. Sample Data Lists

Two example calculations, one of boresight error and one of antenna pattern parameters, are discussed to illustrate the use of the program.
1. Boresight error

This example uses an ogive radome having a hemispheric nosecap. Since the calculation requires separate equations for the geometry of the ogive walls on the upper and lower sections, the cap is also divided into two sections to maintain symmetry in the geometrical description of the radome. This results in a four-section radome as shown in the sketch below.

![Sketch of a four-section radome](image)

Wall construction in all four sections is a constant A-sandwich. Five cases are to be calculated at four look angles. Referring to Table XIII case MC = 1 is the "no-radome" case which is calculated for reference. Since the pattern without radome is independent of look angle, PL = 0 is used. Cases MC = 2, 3 correspond to perpendicular, parallel polarization calculations for the same radome. Cases 4, 5 correspond to perpendicular, parallel calculations for a similar radome but with a different core dielectric constant. All data of Table XIII are explained on the right hand margin of the table. Reference to Table XII will define the variables.

2. Antenna pattern parameters

This example uses an ogive radome having a hemispheric nosecap. The aft portion of the radome is conical for fairing purposes. Thus there are 6 geometry sections, 3 on each side of the coordinate axes. Eight cases are calculated corresponding to four different aperture distributions with and without radome. The far-zone pattern is calculated and plotted for the angular range of ±45° (span) about the beam axis. Sidelobe level and half-power beamwidth with and without radome are the
quantities being calculated as a function of source distribution. As can be seen from Table XIV the quantity of data read in after the initial run (\(MC = 1\)) is minimal. This is typical.
<table>
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<tr>
<th>TABLE XIII</th>
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|            | SXGB     | 4 |
|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |

|            | PERPENDICULAR |
|            | 0.0003 | 4 |
|            | 0.040  | 4 |
|            | 0.192  | 4 |
|            | 0.0057 | 4 |
|            | 8.9    | 4 |
|            | 2.8    | 4 |

|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |

|            | PERPENDICULAR |
|            | 0.0003 | 4 |
|            | 0.040  | 4 |
|            | 0.192  | 4 |
|            | 0.0057 | 4 |
|            | 8.9    | 4 |
|            | 2.8    | 4 |

<p>|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |
|            | XOO,YOO,ROO | 4 |</p>
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**PARALLEL POLARIZATION**

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**PARALLEL POLARIZATION**

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**PARALLEL POLARIZATION**

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D. Computer Programs
MAIN

ALL CALCULATIONS NOW ASSUME THE RADIAN IS SYMMETRIC ABOUT THE AXIS
AA, BR, CC, HI, I I I ARE THE DEFINING CONSTANTS FOR A GIVEN MODE.
AF IS THE LENGTH OF 4TH SUBAPERTURE.
CF IS PHASE CORRECTION DUE TO THE 4TH SUBAPERTURE LOCATION AWAY
FROM THE ORIGIN.
P IS THE PATTERN ANGLE PHI. MEASURED IN THE X-Y PLANE.
PL IS THE THICKNESS ANGLE IN DEGREES.
AR IS THE FAR FIELD AMPLITUDE.
O IS THE OUTPUT PARAMETER FOR THE GRAPH SUBROUTINE.
RPL IS THE LENS ANGLE IN DEGREES.
RIP IS THE INSERTION DISTANCE PHASE DELAY FOR A RAY.
PH IS THE TOTAL PHASE TERM FOR A GIVEN SUBAPERTURE.
TI IS THE ANGLE OF INCIDENCE FOR A RAY.

AAT APERTURE AMPLITUDE TAPER.
TITLE INDICATES WHETHER TO CALCULATE THE NULL OR 2 PARTIAL PATTERN.
B IS THE ANGLE USED IN GRAPH TO PLOT THE PHI AXIS.
MH INDICATES THE DIVISION BETWEEN THE TWO HALVES OF THE APERTURE.
MM IS THE NUMBER OF THAT SUBAPERTURE IMMEDIATELY BELOW THE X-AXIS.
YC IS THE Y-COORD OF THE CENTER OF A SUBAPERTURE AT LOOK ANGLE 0.
PHST IS THE PHASE TAPER.
DCE IS THE REAL PART OF THE RELATIVE PERMITIVITY.
DCE 1, L IS THE DIELECTRIC CONSTANT FOR THE 1TH LAYER OF THE 4TH
GEOMETRY SECTION.
TDL IS THE LOSS FACTOR FOR 1TH LAYER, 1TH GEOMETRY SECTION.
D 1, L IS THE THICKNESS IN LINES FOR THE 1TH LAYER, 1TH GEOMETRY.
TC IS THE AMPLITUDE TRANSMISSION COEFFICIENT FOR A RAY.
TR IS THE TOTAL TRANSMISSION FACTOR FOR A SUBAPERTURE.
POLZ INDICATES PEP OR PAR POLARIZATION FOR MULTILAYER CALC.
XGB IS THE X-COORDINATE OF A RADOME GEOMETRY DISCONTINUITY.
YGP IS THE Y-COORDINATE OF A RADOME GEOMETRY DISCONTINUITY.
NRE IS THE NUMBER OF EQUALLY SPACED RAYS USED
NKE IS CHOSEN uneven TO GET A RAY THROUGH THE ORIGIN.
T IS THE ANGLE OF INCIDENCE FROM THE CENTER OF A SUBAPERTURE TO
THE RADIUS INNER XRAY.
LL INDICATES THE TOTAL NUMBER OF DIFFERENT LOOK ANGLES EXAMINED.
X00, Y00, Z00 INDICATE THE CENTER, RADIUS FOR AN GIVEN SECTION IN
THE X, Y, Z PLANE.
YO IS THE MAXIMUM MAGNITUDE OF Y-COORDINATE FOR A SUBAPERTURE AT
LOOK ANGLE 0.0 DEGREES.
MC IS THE TOTAL NUMBER OF CASES TO BE RUN.
A TOTAL SOURCE APERTURE LENGTH.
NDS IS THE NUMBER OF RADOME SECTIONS HAVING DIFFERENT GEOMETRY.
FREQ IS THE FREQUENCY IN MEGACYCLES.
ANFA IS THE NUMBER OF EQUAL-LENGTH SUBAPERTURES.
NUM IS REL LESS THAN THE NUMBER OF FIELD POINTS TO BE CALCULATED
IN A PARTIAL PATTERN TYPE CALCULATION.
FJ IS THE COMPLEX NUMBER J.
SPAN IS THE ANGULAR RANGE OF CALCULATION ABOUT THE X-RAY AXIS.

Fig. 57. Main program - Page 1.

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PSEP IS THE CORRECT ERROR IN MILLIRADIANS.
IS IS THE SLOPE OF THE RAY FROM 1 TO THE RADOME CURVE AT P X, Y.
TL IS THE SLOPE OF THE RAY AT THE SAME POINT P X, Y.
SLL IS Sidelobe level in DB.
M1 IS THE NUMBER OF SUBAPERTURES.
ISCALE IS A SPREADING FACTOR FOR GRAPH WHEN FEW POINTS ARE USED.
RPWR IS THE POWER AT BEAM MAXIMUM RELATIVE TO THE NO RADOME CASE.
LX IS THE PRESENT VALUE OF THE LOOK ANGLE INDEX I IN MAIN.
THE TLIM VARIABLE PREVENTS COMPUTER ROUND OFF ERROR.
FRDP IS THE POWER NORMALIZING TERM.
TAPER INDICATES (IN A ONE WORD HOLLERITH FIELD) THE SOURCE TAPER.
DRST IS 1/2 THE LENGTH OF A SYMMETRICALLY PLACED APERTURE BLOCK.
SOURCE(1) INDICATES THE CALCULATION OF A MONOPULSE DIFFERENCE.
SOURCE(2) (BY MOVE THE SUM PATTERN IS CALCULATED OTHERWISE).
SOURCE(3) INDICATES CALCULATION OF THE NO RADOME CASE BY 'NO'.
SOURCE(4) INDICATES THE USE OF AN APERTURE PEDELSTAL FUNCTION TAPER.
BY THE WORD 'STEP'.
SOURCE(5) INDICATES THE ABSENCE OF AN AMPLITUDE TAPER BY 'ENGAAT'.
SOURCE(6) INDICATES THE ABSENCE OF AN PHASE TAPER BY 'ENPHST'.
SOURCE 7 CALLS GRAPH, SLL, HPBW WHEN THE WORD OPTION OCCURS THERE.
SOURCE(8) INDICATES THE USE OF A CIRCULAR APERTURE BY 'CIRCLE'.
SOURCE(9) INDICATES THE PRESENCE OF AN APERTURE BLOCK BY 'BLOCK'.
SOURCE(10) CALLS FOR A GRAPH OF THE FAR-FIELD BY 'PLOT'.
SOURCE(11) INDICATES THAT SPECIFIC X-GEOMETRY BOUNDARIES ARE TO BE 
READ IN BY 'XGHR'. OTHERWISE PROGRAM CALCULATES THE XGR'S.
SOURCE(12) CAUSES A WRITE-OUT OF RAY-TRACE AND MULTILAYER CALCULATIONS.
THE DO 949 LOOP ALLOWS THE ENTIRE PROGRAM TO BE RECYCLED.
RAF, RCF, XTR, PPH ARE TEMPORARY LOCATIONS FOR RECONSTRUCTED APERTURE
COEFFICIENTS AF, CF, TR, PPL.
DFAST = DISTANCE FROM AXIS TO SOURCE PLANE.
THE Sidelobe level subroutine calculates the power level at the 1ST
LOCATION OF THE RADOME CASE EVERY TIME IN ADDITION TO THE 
MAXIMUM Sidelobe level. WHEN NO Sidelobe IS DETECTED THIS IS TAKEN
AS Sidelobe level.
DFAST = DISTANCE FROM AXIS TO SOURCE PLANE.

DOUBLE PRECISION AA, RR, CC, DD, EE, FF, XGB, YSH, PI, BB2, CCC, DISC, DYDX, X,
Y, TS, TI, CL, CL2, SL, SL2, SL2, CL, SL2, TI, RPL, DISCU, XOC, YOC, XIC
1, XA, YA, DFTSP, XLIN, YLIN, PHLIN
COMMON T(501, 12), SOURCE(I2), PI, RAPES, DEGRAD, ML, NOS, TX, MC, A, YC(501)
1, YA(501), YA(501), DFTSP, XLIN, YLIN, PHLIN,
1 PHTS(501), ZAT(501), TAPER, NFLOK1, NFLOK2, YO(501), YCX
COMMON /RHP/ Y, STAP(25)
COMMON /RRP/ RPL(25), XGR(12), TL, SL, SL2, CL2, SL2, XOC, YOC, ROL, CS
1 AA(12), RR(12), CC(12), DD(12), EE(12), FF(12)

Fig. 57. Main program - Page 2.
Fig. 57. Main program - Page 3.

88
RADeg = 180./p1
I = 0, 1
DO 949 IY = 1, 2
MG2 = 1
READ(5,2) MC
READ(5,11) PHO,TAN
PHO = PHO * DEG2RAD
READ(5,2) (LL(I), I = 1, MC)
DO 300 L = 1, MC
M = 1
MM = 0
RP:I = 1.
LT = LL(L)
MCX = L
IF (L.GT.1) GO TO 937
READ(5,2) 5BLK1, 5BLK2
READ(5,12) DFATS
READ(5,1) A
FNRP = A
READ(5,2) NUM
NUM2 = NUM + 1
TNUM = NUM
TNUM2 = THU-9/2.
READ(5,17) SPAN
RSPAN = SPA*F.DEG2RAD
READ(5,150) TAPER
READ(5,2) (NRE(I), I = 1, MC)
READ(5,150) (TITLE(I), I = 1, 12)
READ(5,2) NOS
NOS = 1 + NOS
READ(5,10) (N(I), I = 1, NOS)
READ(5,150) (SHAPE(I), I = 1, NOS)
DO 121 I = 1, NOS
IX = I
IF (SHAPE(IX).EQ.0.GIVE) GO TO 155
IF (SHAPE(IX).EQ.0.GIVE) GO TO 157
READ(5,9) AA(IX), BB(IX), CC(IX), DD(IX), EE(IX), FF(IX)
GO TO 121
155 READ(5,12) XON, YON, X00
CALL GIVE
GO TO 121
157 READ(5,12) XLIN, YLIN, PHLIN
CALL CONIC
121 CONTINUE
READ(5,150) (POLZ(I), I = 1, 3)
READ(5,1) (PL(I), I = 1, LT)
IF (POLZ(1).EQ.0.PARALL) GO TO 909
DO 120 L = 1, NOS

Fig. 57. Main program - Page 4.
Fig. 57. Main program - Page 5.
MAIN DATE = 69197

C1 = 0.
DO 416 J = 1, J;
C2 = CF2 + CF(JP)
AF2 = AF2 + AF(JP)
TR2 = TR2 + TR(JP)
416 PH2 = PH2 + PH(JP)
J1 = J1 + 1
T3 = J0 - J1
RAF(J1) = AF2
RCF(J1) = CF2 / T3
RPH(J1) = PH2 / T3
RTR(J1) = TR2 / T3
J0 = J
IF(J, NE.1) GO TO 412
GO TO 418
411 J2 = 1
404 J0 = J0 + 1
TR1 = TR(J0)
PH1 = PH(J0)
401 J = J + 1
IF(J, EQ. M1) GO TO 402
DTR = TR(J) - TR1
DPH = PH(J) - PH1
IF(AAS(D1) - T?0) 407, 407, 402
407 IF(AA$S(D?H)-?PHD) 401, 402, 402
402 PH2 = 0.
TR2 = 0.
AF2 = 0.
CF2 = 0.
DO 403 JP = J0, J
CF2 = CF2 + CF(JP)
AF2 = AF2 + AF(JP)
TR2 = TR2 + TR(JP)
403 PH2 = PH2 + PH(JP)
J1 = J1 + 1
T3 = J0 - J1
RAF(J1) = AF2
RCF(J1) = CF2 / T3
RPH(J1) = PH2 / T3
RTR(J1) = TR2 / T3
J0 = J
IF(M1 - J) 405, 405, 404
418 M1 = J1
M2 = M1 - J5
M5(J) = M2
J4 = J4 + 1
WRITE(6, 421) J1, M1, J4, ML, J5

Fig. 57. Main program - Page 7.
C    RAF,RC1,RTP,PM ARE TEMPORARY LOCATIONS FOR RECONSTRUCTED APERTURE.
C    COEFFICIENTS AF,CF,TR,PH.
WRITE(6,406) J
406 FORMAT(2X,55HNUMBER OF SUPAPERATURES USED IN RECONSTRUCTED APERTURE  
  1 15)
DO 419 J=1,ML
  AF(J)=RAF(J4-J)
  CF(J)=RCF(J4-) 
  TR(J)=RTR(J4-J)
419 P=0
419 PH=PH(J4-J)
DO 420 J=1,ML
  AF(J+ML)=RAF(J)
  CF(J+ML)=RCF(J)
  TR(J+ML)=RTR(J)
420 PH(J+ML)=PH(J)
DO 417 J=1,ML
417 PHO(J)=PH(J)*RADFS
WRITE(6,407)
407 FORMAT(2X,35HFORMATTED SCALER COEFFICIENTS/4X,2HAF,8X,2HCF,:  
  1X,2HR,R,3X,3HPH//)
WRITE(6,409) (AF(J),CF(J),TR(J),PHO(J),J=1,ML)
409 FORMAT(3H16.0,F10.4)
  TIME=TIME+TIME
WRITE(6,1009) TIME
WRITE(6,5) TIME
1009 FORMAT(1X,36HTIME TO CALC. RECONSTRUCTED APERTURE,F10.3,8H SECONDS  
  1)
  IF(1.GT.1) GO TO 943
943 CONTINUE
  IF(SOURCE(1).NE.FM4) GO TO 25
  DO 27 NN=1,ML
     AF(NN)=AF(NN)
27 CONTINUE
  27 WRITE(6,151) MC,Y,ML,LT
WRITE(6,3) HN(1)
  IF(TITLE(1).EQ.FM1000) GO TO 60
  GO TO 34
60 K=0
CALL SCLUK1
  KR=0
  P(1)=RSPAN
  P(2)=-RSPAN
500 K=K+1
  E(K)=(0.,0.)
DO 900 M=1,ML
  S=W*A*SIN(P(K))*AF(M)*5
  IF(S.LT.0.1 AND S.GT.-0.10) GO TO 800

Fig. 57. Main program - Page 8.
Fig. 57. Main program - Page 9.
Fig. 57. Main program - Page 10.
IF (SCURC(:1) .NE. OPTION) GO TO 112
IF (SCURC(:10) .NE. PLOT) GO TO 113
CALL SLOK1
ISCALE=60/NUM
CALL GRAPHAE,XMAX,0.,NUM2,B,(ISCALE)
TIME=PCLUK1(1.)
TIME=TIME/60.
WRITE(6,1006) TIME
WRITE(6,5) TIME
1006 FORMAT(1X,13HTIME IN GRAPH,F10.3,8H SECONDS)
113 CALL SLOK1
CALL HPBII(AE, XMAX,NUM2, R)
TIME=RCLUK1(1.)
TIME=TIME/60.
WRITE(6,1007) TIME
WRITE(6,5) TIME
1007 FORMAT(1X,12HTIME IN HPBII,F10.3,8H SECONDS)
116 CALL SLOK1
961 MM=1+MMMK
CALL SLL(4,F,XMAX,NUM2,AB,BSLMAX,AL,B,$950,$964,$51)
GO TO 951
964 MM=0
950 IF (SOURCE(:3),EQ.,FNORAD) GO TO 962
WRITE(6,151)
1551 FORMAT;///THE POWER LEVEL AT THE POSITION OF THE 1ST SLICE LUME
1 WITH NO RADOME IS CALCULATED BELOW ///
1
P(1)=BSLMAX
K=1
KR=11
P(2)=P(1)
GO TO 952
951 K=0
KR=0
P(1)= BSLMAX-DEGRAD
P(2)= BSLMAX+DEGRAD
1500 K=K+1
952 E(K)=(0.,0.)
DO 1900 M=1,MI
S=W*A*SIN(P(K)*AF(M)*.5
IF(S.LT.0.10.ANd.S.GT.-0.10) GO TO 1300
SS=SINC SS/S
GO TO 1810
1800 SS=1.
1810 O=W*A*CF(M)*S1N(P(K))P(H(K))
CO=COS(N)
SO=1N(N)
E1= TR(M)*A*AF(M)*SO
E2= E1*CO

Fig. 57. Main program - Page 11.
Fig. 57. Main program - Page 12.
Fig. 58. Ogive geometry subprogram.
COMP=C
DA1=69199

SUBROUTINE CONIC
DOUBLE PRECISION AA, BB, CC, DD, EE, FF, XX, YY, PI, PI2, PI3, CC1, DISC, OX, X, Y, T, S, T, CI, C2, S2, C2L, S2L, T1, AP, DISC, UO, YO, RO
1 XA, YA, BFATSP, XLIN, YLIN, PHLIN
COMON T(I501), 1, SOURCE(I72), PI, RADEG, DEGRAD, M1, NOS, IX, NC, A, YC(I501)
1, XA(I501), YA(I501), BFATSP, XLIN, YLIN, PHLIN,
1 PHSL(I501), AA(I501), TAPER, NL0K1, NL0K2, Y0(I501), NGX
COMMON /KS17/ X2L(I2), XGD12, I, L, S, L2, C2L, S2L, XOO, YOO, ROO, Cl,
1 AA(I2), B1(I2), CC(I2), B2(I2), FF(I2), FF(I2)
1, ANEA, AF(I501), CF(I501), WH(I25), LI, PL(I25), 
RPHLIN=PHLIN*PI GRAD
1=1X
AA(I)=0.
RO(I)=0.
CC(I)=0.
DD(I)=TAN(RPHLIN)
FF(I)=1.
FF(I)=YLIN*X(I)-YLIN
RETURN
END

Fig. 59. Cone geometry subprogram.
Figure 60. Ray trace subprogram - Page 1.
200 CONTINUE
WRITE(6,7) (XGB(I), I=1,NN0S)
DO 180 L=1,NN0S
IF(BB(L).EQ.0.) GO TO 182
TLIM=DATBSSF(FL(I))
IF(DABS(AA(L)),GT,TLIM) TLIM= AA(L)
IF(DABS(BB(L)),GT,TLIM) TLIM= BB(L)
IF(DABS(CC(L)),GT,TLIM) TLIM= CC(L)
IF(DABS(DD(L)),GT,TLIM) TLIM= DD(L)
IF(DABS(EE(L)),GT,TLIM) TLIM= EE(L)
TLIM=TLIM*0.000001
DISCU=((CC(L)*XGB(L)+EE(L))/(2.*BB(L)))**2-(AA(L)*XGB(L)**2+DD(L))**2))
1*XGB(L)+FF(L))/BB(L)
IF(DABS(DISCU),LT,TLIM) DISCU=0.
IF(L.EQ.NN0SS) GO TO 68
67 YGR(L)=-(CC(L)*XGB(L)+EE(L))/(2.*BB(L)))*DSQRT(DISCU)
GO TO 183
68 YGB(L)=-(CC(L)*XGB(L)+EE(L))/(2.*BB(L))*DSQRT(DISCU)
GO TO 183
182 YGB(L)=-(AA(L)*XGB(L)*XGB(L)+DD(L)*XGB(L)+FF(L))/(CC(L)*XGB(L)+EE(L))
183 IF(DABS(YGB(L)),LT,1.E-3) YGB(L)=0.
IF(L.EQ.NN0SS) GO TO 180
NI=NI+1-L
YGB(NI)=-YGB(L)
180 CONTINUE
WRITE(6,52) (YGB(I), I=1,NN0S)
181 WRITE(6,13) PL(LLLX)
WRITE(6,6)
DC 20 I=1,1R
T2=I
20 Y0(I)=A/(2.*A)*E*(2.*T2-2.*A)
IF(SOURCE(I),EQ,FORAD) GO TO 48
DO 210 I=1,1R
XA(I)= CL*DFATSP-Y0(I)*SL
210 YA(I)= SL*DFATSP+Y0(I)*CL
DO 190 M=1,1R
DO 170 L=1,NN0S
LG(M)=L
IF(BB(L),EQ,0.) GO TO 30
XAC=XA(M)
YAC=YA(M)
AAA=AA(L)+BB(L)*TL+CC(L)*TL
BBB=-2.*BB(L)*TL*XAC+2.*BB(L)*TL*YAC-CC(L)*TL*XAC-CC(L)*YAC+DD(L)*L+EE(L)*TL
CCC=-2.*PR(I)*TL*XAC+BB(L)*TL*YAC+BB(L)*YAC-CC(L)*L
1 TL*XAC+EE(L)+YAC+FF(L)

Fig. 60. Ray trace subprogram - Page 2.

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Fig. 60. Ray trace subprogram - Page 3.
SURROUNGE \textit{NKJRM}

\begin{verbatim}
DOUBLE PRECISION AA, BB, CC, DD, EE, FF, XGB, YGB, PI, DBH, CCC, DISC, DXD, X,
                   Y, TS, TL, CL, CL2, SL, SL2, C2L, S2L, TL, RPL, DISCU, XOO, YOO, ROD
                     1, XA, YA, DFATSP, XLIN, YLIN, PHLIN, DOBST

DOUBLE PRECISION TR

COMMON T(501,12), SOURCE(12), PI, RADEG, DEGAD, M1, NOS, IX, MC, A, YC(501)
 1, XA(501), YA(501), DFATSP, XLIN, YLIN, PHLIN, DOBST,
 1 PSHT(501), ATV(501), TAPER, NBL0K1, NBL02, Y0(501), MCX

COMMON /JPR/ N(12), D(12,12), DCE(12,12), TD(12,12), FIPD(501), TC(501)
 1, FREQ, POLIZ

DIMENSION R(12), G(12), SR(12), NNL(12), DDD(12)

1 FORMAT(F10.2,9X,F11.6,1X,F10.6,2110)
2 FORMAT (5F15.6)
3 FORMAT (115,4F15.9)
4 FORMAT (F15.7,4F10.6,F15.7)
5 FORMAT(1H1)
6 FORMAT(7X,1HT,IOX,4HFIPD,9X,11HTRANS cnEFF,9X,IHK,9X,1HL).
999 FORMAT(' WALL THICKNESS = 'FK10.6/

DATA PARALL/4H PAR /
DATA RMIN/00000001/
DATA WRITER/4HWRIT/
DATA FNRAD/4H NO /
IF(SOURCE(3).EQ.FNRAD) GO TO 557
DO 6 L=1,NOS
NN(L)=N(L)+1
NNL=NN(L)
6 DCE(NNL,L)=1.
WRITE(6,8)
DO 5 L=1,NOS
NL=N(L)
DDD(L)=0.
DO 5 I=1,NL
IF(I.EQ.1) WRITE(6,999) D(I,L)
5 DDD(L)=DDD(L)+D(I,L)
DO 60 K=1,M1
DO 60 L=1,NOS
IF(T(K,L).LT.0.) GO TO 60
IF(L.EQ.NBL0K1 OR L.EQ.NBL02) GO TO 100
GO TO 101
100 FIPD(K)=0.
TC(K)=0.
GO TO 60
101 TH=T(K,L)*DEGAD
DD=2.*COS(TH)*DDD(L)*PI
S=SIN(TH)*SIN(TH)
SR(1)=SQRT(DCE(1,L)-S)
IF(POLIZ .EQ. PARALL) GO TO 210
RR=(SR(1)-COS(TH))/(SR(1)+COS(TH))

Fig. 61. Multilayer transmission subprogram - Page 1.

103
\end{verbatim}
GO TO 211
210 \( PR = (SR(1) - DCE(1,L) \times \cos(TH)) / (SR(1) + DCE(1,L) \times \cos(TH)) \)
211 CONTINUE

\( NL = NL(L) \)
DO 10 I=1,NL
11 I=I+1
\( SR(I) = \sqrt{DCE(I,L) - S} \)
G(I) = 2.*PI*D(I,L)*SR(I)
IF(POLIZ .EQ. PARALL)GO TO 110
R(I) = (SR(I) - SR(I)) / (SR(I) + SR(I))
GO TO 10

110 R(I) = (DCE(I,L) * SR(I) - DCE(I,L) * SR(I)) / (DCE(I,L) * SR(I) * SR(I))
CONTINUE
10 CONTINUE

AQ = 1.-RR
DO 15 I=1,NL
15 AQ = AQ * (1.-R(I))

AQ = AQ / AQ
W = 1.180314E+4 / FR
GG = G(I) / W
CG = COS(GG)
SG = SIN(GG)
AD = PI*DCE(1,L)*TD(1,L)*D(I,L) / (W*SR(I))
X1 = CG * (1.-AD)
Y1 = -SG * (1.+AD)
X2 = -RR*CG * (1.+AD)
Y2 = -RR*SG * (1.+AD)
X3 = RR*CG * (1.-AD)
Y3 = RR*SG * (1.-AD)
X4 = CG * (1.+AD)
Y4 = SG * (1.+AD)
NNL = NN(L)
DO 35 I=2,NNL
20 UI=1.
U2=-R(NL)
U3=-R(NL)
U4=1.
V1=0.
V2=0.
V3=0.
V4=0.
GO TO 30
25 II=I-1
AD = PI*DCE(1,L)*TD(1,L)*D(I,L) / (W*SR(I))
GG = G(I) / W
CG = COS(GG)
SG = SIN(GG)

Fig. 61. Multilayer transmission subprogram - Page 2.
U1 = CG*(1. - AD)
V1 = - SG*(1. - AD)
U2 = RI*CG*(1. + AD)
V2 = RI*SG*(1. + AD)
U3 = RI*CG*(1. - AD)
V3 = RI*SG*(1. - AD)
U4 = CG*(1. + AD)
V4 = SG*(1. + AD)

30 P1 = X1*U1 - Y1*V1 + X2*U3 - Y2*V3
Q1 = Y1*U1 + X1*V1 + Y2*U3 + X2*V3
P2 = X1*U2 - Y1*V2 + X2*U4 - Y2*V4
Q2 = Y1*U2 + X1*V2 + X2*U4 + Y2*V4
P3 = Y3*U1 - Y3*V1 + X4*U3 - Y4*V3
Q3 = Y3*U1 + X3*V1 + X4*U3 + Y4*V3
P4 = X3*U2 - Y3*V2 + X4*U4 - Y4*V4
Q4 = Y3*U2 + X3*V2 + X4*U4 + Y4*U4

X1 = P1
X2 = P2
X3 = P3
X4 = P4
Y1 = Q1
Y2 = Q2
Y3 = Q3

35 Y4 = Q4
RCR = (-X3*X4-Y3*Y4) / (X4*X4+Y4*Y4)
RCI = (-Y3*X4+X3*Y4) / (X4*X4+Y4*Y4)
RC2 = RCR*RCR+RCI*RCI
RC = SQRT(RC2)
TR = (X1+X2*RCR-Y2*RCI)*AQ
TI = (Y1+Y2*RCR+X2*RCI)*AQ
TC2 = TR*TR+TI*TI
TC = SQRT(TC2)

IF (TR.EQ.0. .AND. TI.EQ.0.) TI=TI*MIN
XX = DATAN2(TI,TR)

48 FIPD(K) = RADI*G2((XX+DD/W)
IF (FIPD(K) .LT. 0.) FIPD(K) = FIPD(K)+360.
IF (SOURCE(12).EQ.WRITER) WRITE(6,1) T(K,L),FIPD(K),TC(K),K,L

60 CONTINUE
50 CONTINUE
557 RETURN
END

Fig. 61. Multilayer transmission subprogram - Page 3
SUBROUTINE APAPER

DOUBLE PRECISION YA,PR,CC,DD,EE,FF,XG,YG,P1,P3,GC,DG,XYDX,
1Y,TS,TL,CL,SL,SL',C2L,S2L,TL,RP1,DISCU,XUC,YUC,ROU

1,XA,YA,DFAT,SX,XLIN,YLIN,PHILN

COMMON /T/P/ Y,STAP,25

COMMON T(501,12),SOURCE(12),PI,RADEF,DEGRAD,P1,NOS,1X,MC,1,YC(501)

1,XA(501),YA(501),DFAT,SX,XLIN,YLIN,PHILN,

1 PHST(501),ALT(501),TAPER,NBLU1,NBLK2,YO(501),MCX

11 FORMAT (6F15.6)
152 FORMAT(3X,3SHUNIFORM APERTURE DISTRIBUTION USED.//)
153 FORMAT(2X,2F10.4)
154 FORMAT(5X,10OBSTACLE HEIGHT F10.6///)
155 FORMAT(6X,21OBSTACLE HEIGHT MODIFIED F10.6///)

DATA FLIN/4HFLIN/

DATA CUS6/4HCUS6/

DATA CIRCLF/6HCIRCLE/

DATA COSI/6HCOSI/

DATA RAD4/6HRAD4/

DATA RAD5/6HRAD5/

DATA PLI/6HPLI/

DATA COS2/6HCOS2/

DATA FMOAT/6HFMOAT/

DATA FNPHST/6HFNPST/

DATA 4BLOCK/6CBLOK /

OBST=0.

RAD=.5*A

RADSQ=RAD*DAD

RADI=1./RAD

PADSQ=RADI*RADI

IF(SOURCE(9).LE.BLOCK) GO TO 13.

READ(5,11) OBST

WRITE(6,154) OBST

IF(SOURCE(9).LE.CIRCLF) GO TO 13.

RADY=RAD/Y

OBSTSQ=OBST*OBST

READ(5,11) OBSTD

THET= Y/(2.*A)

RATIO=OBST*OBST/(RADY*OBST*D*THET)**2

AO= RATIO*PI*RADSQ

THET1= AO.

THET1= THE11*DEGRAD

DO 15 N=1,10

THETZ=THET1-(THET1-SIN(THET1)-PI*(1.-RATIO))/(1.-COS(THET1))

IF(ABS(THETZ-THET1).LT.1.E-4) GO TO 17

THET1D= RAPED*THET1

WRITE(6,19) THET1D

19 FORMAT('THET1A = 'F12.6)

15 THET1=THET2

Fig. 62. Aperture taper subprogram - Page 1.
17 OBST = RAD * COS(THET1/2.
WRITE(6, 155) OBST
ASTRIP = (PI - THET1 + SIN(THET1)) * RADSQ
WRITE(6, 18) AO, ASTRIP
18 FORMAT('OBSTACLE AREA = 'F12.6, 'STRIP AREA = 'F12.6)
13 DO 87 IL = 1, M1
     YC(IL) = (YO(IL) + YO(IL+1)) / 2.
     YCT = YC(IL)
     ABSYCT = ABS(YCT)
     IF(SOURCE(5).EQ.FNOAAT) GO TO 83
     CAM = 1.
     IF(SOURCE(8).EQ.CIRCLE) CAM = SQRT(RADSQ - YCT * YCT)
     IF(TAPER.EQ.COS) GO TO 1
     IF(TAPER.EQ.Cos2) GO TO 2
     IF(TAPER.EQ.PL) GO TO 3
     IF(TAPER.EQ.Rad1) GO TO 4
     IF(TAPER.EQ.Cos6) GO TO 5
     IF(TAPER.EQ.Fl) GO TO 7
1 AAT(IL) = SQRT(ACOS(YC(IL)) * YC(IL))
     GO TO 84
2 AAT(IL) = DCOS(PI * YC(IL)/A)
     GO TO 84
3 IF(ABS(YC(IL)).LT.0.936603) AAT(IL) = 1. * CAM
     IF(ABS(YC(IL)).GE.0.936603 .AND. ABS(YC(IL)).LT.1.183924) AAT(IL) = (0.9
1789 - (ABS(YC(IL)) - 0.986603) * 0.0421 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.1.183924 .AND. ABS(YC(IL)).LT.1.381244) AAT(IL) = (0.9
1368 - (ABS(YC(IL)) - 1.183924) * 0.0631 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.1.381244 .AND. ABS(YC(IL)).LT.1.578565) AAT(IL) = (0.9
1737 - (ABS(YC(IL)) - 1.381244) * 0.3364 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.1.578565 .AND. ABS(YC(IL)).LT.1.775885) AAT(IL) = (0.9
1368 - (ABS(YC(IL)) - 1.578565) * 0.3684 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.1.775885 .AND. ABS(YC(IL)).LT.1.973206) AAT(IL) = (0.9
1684 - (ABS(YC(IL)) - 1.775885) * 0.0316 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.1.973206 .AND. ABS(YC(IL)).LT.2.170526) AAT(IL) = (0.9
1368 - (ABS(YC(IL)) - 1.973206) * 0.0210 / 0.197321) * CAM
     IF(ABS(YC(IL)).GE.2.170526 .AND. ABS(YC(IL)).LT.2.362488) AAT(IL) = (0.9
1158 - (ABS(YC(IL)) - 2.170526) * 0.0316 / 0.591962) * CAM
     IF(ABS(YC(IL)).GE.2.362488) AAT(IL) = 0.0842 * CAM
     GO TO 84
4 AAT(IL) = (1. - YCT * YCT * RADSQ) * CAM
     GO TO 84
5 AAT(IL) = (((1. - YCT * YCT * RADSQ)) * 2) * CAM
     GO TO 84
6 AAT(IL) = DCOS(PI * YC(IL)/A)**2 + STAP(MCX)
     GO TO 84
7 AAT(IL) = 1 - ABS(YC(IL)) / RAD
     GO TO 84

Fig. 62. Aperture taper subprogram - Page 2.
83 AAT(IL)=1.
84 IF(AATSYCIL,LT,111,9) AAT(IL)=0.
  IF(SOURCIE(6),EQ,11,9) GO TO 85
  PHST(IL)=1*SORT(110.25+YC(IL)*YC(IL))
  GO TO 82
85 PHST(IL)=0.
87 CONTINUE
  IF(SOURCE(0),EQ,1,9) AAT,AND,SOURCIE(6),EQ,1,9) WRITE(6,192)
  WRITE(6,193) (AAT(IL),PHST(IL),IL=1,N1,10)
  RETURN
END
Fig. 63. Graph subprogram.
SLi (DAT = (7) 1/1)

SUPPLMINT, SLI(A), XMAX, NUMGRAD, SLAY, SLB, P, R, O, M

FORMATS, SCALE, ACTNUMGRAD, SLAY, VAF, P, POS

P1 = 3.1415926535897912
DEGRAD = PI / PI
RANG = 180. / PI

11 FORMAT (4X, 8F10.5)
DATA PPM/0/
  (N, P, N) TO 12
  8X = 0
  N = 0
  I = N + 1
  IF (AE(N) = 1.5, 1).AND. AE(N+1) .LT. AE(N) ) GO TO 2
  GO TO 1

  2 M = M + 1
  A(N) = (AE(N) / XMAX) * 100.
  SLB(N) = B(N)
  WRITE (6, 11) A(N), SLB(N)
  CONTINUE

  1 IF (MGLE.1. AND. M .GE. 3) GO TO 13
  GO TO 14

  13 M = M / 2
  SLB(N) = SLB(N)
  WRITE (6, 25) N, SLB(N)
  CONTINUE

  25 FORMAT (4X, 'M1 = ', F15.1, ' M = ', F15.1)

  14 SLMAX = 0.
  DO 3 N = 1, M
  IF (A(N) .LT. SLMAX .AND. A(N) .LT. 75.) GO TO 6
  GO TO 3

  8 SLMAX = A(N)
  PSLMAX = SLB(N) * DEGRAD
  WRITE (6, 11) PSLMAX
  CONTINUE

  3 IF (SLMAX .LT. 0.0000001) GO TO 6
  SLDB = 20. * LOG10 (100. / SLMAX)
  GO TO 7

  6 WRITE (6, 9)
  9 FORMAT (10X, 29H Sidelobe detected!)
  RSL = SLPI + RAD
  RSLMAX = BSL
  RETURN

  7 WRITE (6, 5) SLMAX, SLDB
  5 FORMAT (10X, 29H Maximum sidelobe level, $.10, 4.2X, '.8F4.0,",'X, 14.1H 1, $.10, 4.6H OK )
  MM = 1
  RETURN

  12 MM = 0
  RSL = SLPI + DEGRAD
  RSLMAX = BSL
  RETURN

10 RETURN

11 END

Fig. 64. Sidelobe level subprogram.
SUBROUTINE HPBW(AX, XMAX, NUMBER, B)
DIMENSION AX(NUMBER), B(NUMBER)
DO 1 N=2, NUMBER
  IF(AX(N).GE.0.7071*XMAX.AND.AX(N-1).LT.0.7071*XMAX) GO TO 10
  IF(AX(N).LT.0.7071*XMAX.AND.AX(N-1).GE.0.7071*XMAX) GO TO 20
  GO TO 1
10 A1=AX(N)
   A2=AX(N-1)
   PA1=B(N)
   PA2=B(N-1)
   GO TO 2
20 A3=AX(N)
   A4=AX(N-1)
   PA3=B(N)
   PA4=B(N-1)
   CONTINUE
30 AMG1=PA2-(PA2-PA1)*(0.7071*XMAX-A2)/(A1-A2)
   AMG2=PA3+(PA4-PA3)*(0.7071*XMAX-A3)/(A4-A3)
   BW=AMG1-AMG2
   WRITE(6,40) BW
40 FORMAT(/'//10X,25H HALF-POWER BEAMWIDTH','F10.4,3X,RHDEGREES.'//)
RETURN
END

Fig. 65. Half-power beamwidth subprogram.

111
//B1370 JOB PHENIX, X
// FGJ920,KILCOYNE, N. R. X
// 6000, CLASS=C
//STEP1 EXEC PROC=FORTANG, PARM,CMP='ACD, MAP, ID', TIME, CMP=(1,40)
/*CMP EXEC PARM=FFORT

//SYSLIN DD UNIT=SYSDA,SPACE=(CYL,11,1)),DISP=(MOD, PASS),
/*X OCH=(RECFM=F8, LRECL=120, RLKSIZE=600)
//CM=SYSIN DD e
//STEP2 EXEC PROC=UNFORT, PARM, LKFD=43REF, TIME, LKFD=(1,20),
// TIME, GD=(3, 59), PGMMN, C0=150k
**XLKD EXEC PARM=ICN
//SYSL18 DD DNAME=SYSI,FORTLIN, DISP=SHR
//SYSL10 DD DNAME=EGO(MAIN), UNIT=SYSDA, SPACE=(CYL, 11, 1)),
// OC=(RECFM=U, LRECL=3072, DISP=(NEED, PASS)
//SYSUT1 DD DSOUL=A, FCB=(RECFM=FBA, LRECL=121, RLKSIZE=605)
//SYSUT1 DD UNIT=SYSDA, SPACE=(CYL, (2, 1))
//LKD SYSLIN DD DNAME=*,STEP1,CPP, SYSLIN, DISP=(SHR, DELETE)
//XG EXEC PARM=* LKFD=SYSLVCD
//XRTOSF001 DD DNAME=SYSIN
//C0,FRTOSF001 DD SYSOUT=A, SPACE=(CYL, (1,1), PLSE)
//X/RTOSF001 DD SYSOUT=A, OCH=(LRECL=121, RECFM=FBA, RLKSIZE=605)
//C0, SYSUMM DD SYSOUT=A, SPACE=(CYL, (3,1))
//S0, SYSIN DD e

Fig. 66. Required Job Control Language (JCL) for OSU PHENIX Computation
Procedure on IBM SYSTEM 360/75.
REFERENCES


A two-dimensional ray tracing analysis for the calculation of radome boresight error and antenna pattern distortion is presented here. Emphasis has been placed on the development of a method having considerable flexibility, so as to enable application of the method to a wide range of antenna-radome problems, and on relative ease of calculations, so as to minimize calculation time. Several example problems are calculated to demonstrate the usefulness of the approach. Comparisons between calculations and measurements have been included whenever measured data were available. Instructions for use of this completely computerized method are included along with several tables describing variables and the complete computer program with necessary subroutines. Programs are written in Fortran IV language suitable for use on the OSU version of the IBM system 360/75 (some minor changes may be required for use on other 360/75 installations).
UNCLASSIFIED
Security Classification

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INSTRUCTIONS

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