ENGINEERING EXPERIMENT STATION
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ANTENNA PATTERN ANALYSIS
FOR
TARGET VEHICLES

Final Report
EES/GIT Project A-1780
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**Keywords:** Target Vehicles, Scoring Antennas, BQM-34A, Antennas, DIGIDOPs, BOMARC, Pattern Analysis, Scale Model

This report contains a description of the boundary value computational method used in predicting the radiation pattern coverage for three target vehicles: TDU-X tow target, BQM-34A drone, and the BOMARC missile. Included are the predicted patterns of the scoring antennas for the three targets and all the antenna systems for the TDU-X tow target.

Scale model radiation patterns were measured and used to verify the computed patterns. It was concluded that the boundary value computational method was an effective method for determining the location of antennas on the targets.
Block 20.

and for obtaining an estimate of the percent coverage that will be obtained.
This report was prepared by personnel of the Engineering Experiment Station (EES) of the Georgia Institute of Technology, Atlanta, Georgia, 30332, under Contract F08635-76-C-0075 for the Air Force Armament Laboratory, Eglin Air Force Base, Florida, 32542. This task was under the general supervision of Mr. H. D. Harris, Chief, DLMQ, and Mr. F. Crumly, Group Leader, DLMQ. Mr. Glenn Hatcher, DLMQ, served as the Technical Program Monitor.

Report authors are Messrs. Harold L. Bassett, Charles E. Summers, and James W. Cofer, Jr., who are members of the Systems and Techniques Laboratory, Radar Applications Division of EES. This work was designated as EES Project A-1780 with Messrs. Bassett and Cofer serving as Co-Project Directors. The effective dates of the technical effort were from 15 September 1975 through 15 March 1976.

This technical report has been reviewed and is approved for publication.

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1. BACKGROUND

Under Contract F08635-76-C-0075 with the Armament Laboratory at
Eglin Air Force Base, Florida, EES personnel undertook a program to
analyze the radiation properties of several antenna systems located
on three (TDU-X, BQM-34A, and BOMARC) target-type vehicles. Both compu-
tational and experimental investigations were conducted. Three basic
mathematical approaches were considered: (1) boundary value (2) geome-
trical theory of diffraction, and (3) moment methods.

It was desired to determine if the boundary value computational
method was sufficient for use in locating the antennas on the targets
to achieve required antenna pattern coverage characteristics. This
technique is simple and inexpensive as compared to the more complex
gEometrical theory of diffraction technique (G.T.D.) and the moment
methods. Scale model measurements were made on each target in order
to validate the computer data.

The TDU-X tow target is a large center of gravity towed vehicle
that has the payload capacity to carry IRCM/ECM devices for airborne
testing. The target has subsystems to support the IRCM/ECM devices.
These subsystems are infrared/radar signatures, scoring, command receiver,
telemetry and beacons. Those subsystems that radiate or receive a signal
have unique antenna pattern requirements.

The major work presented is that of the antenna systems on the
TDU-X tow target. Computer techniques were utilized to model the TDU-X
tow target and to calculate antenna radiation pattern coverage for the
antenna systems. A scale model of the target was fabricated and the
computed patterns were verified by actual measurements.

The BQM-34A drone is the utility target for three services. The
augmentation and scoring equipment vary according to the user require-
ments. A recent requirement is to have radar augmentation and scoring
cO-located on the wing tip. This was one of the driving requirements
for this particular contractual effort.

The BOMARC is an interceptor missile that has been converted to
a target. The BOMARC is a large target vehicle that has a typical altitude
speed range of 72,000 feet at 2.72 Mach. The primary zone of attack is
the frontal zone; thus, the scoring antennas must be located in the forward half of the vehicle.

Only the DIGIDOPS scoring antenna radiation pattern coverage was calculated for the BQM-34A drone and the BOMARC interceptor. These patterns were also verified by scale model measurements.

Of significance is the fact that computer modeling techniques have become sufficiently sophisticated to be used in determining the location of antennas on a target for particular area coverages. Comparisons between the computed data and the scale model measured data bear this out.

2. SUMMARY OF TASKS

The effort was divided into three general tasks, one for each target vehicle. Antenna locations were analyzed by computer and by scale models for the three targets to determine optimum antenna mounting locations for the required pattern coverage.

a. TDU-X Tow Target

Antenna radiation pattern analyses were performed on five antenna systems:

1. DIGIDOPS scoring antennas
2. Command receiver antenna
3. Telemetry antenna
4. X-L Band augmentation antennas
5. and G-Band beacon antenna.

The DIGIDOPS scoring systems operate at 1775 MHz, and although it was desired to have complete spherical coverage for this antenna system, it was required that the antennas should be located to provide complete coverage for the rear hemisphere and for this coverage to extend toward the forward sector as far as possible.

The command receiver operates at 425 MHz, and lower hemisphere pattern coverage was desired. The command receiver antenna is a flush mounted tuned cavity.

The telemetry transmitter operates in the L-Band frequency region and the desired pattern coverage was omni-directional with suggested mounting on the lower part of the center fuselage.
The L-Band system of the X-L Band radar augmentation will be used in tracking the target by ground based radar, and a lower hemisphere omni-directional antenna pattern coverage was required. The X-Band portion of this system provides radar augmentation for airborne tracking radar, and it was required that this antenna system provide coverage toward the stern.

The G-Band beacon is also used to ground track the target, and it was required that the antenna pattern provide lower hemisphere coverage. This system operates at 5650 MHz and at 5720 MHz.

b. BOMARC Missile

Antenna radiation pattern analyses were performed on the DIGIDOPS scoring antenna operating at 1775 MHz. The primary zone of interest was the front hemisphere with total hemispherical coverage desired.

c. BQM-34 Drone Augmentation Pod

The DIGIDOPS scoring and the X-Band augmentation systems will share the same pod. Radiation pattern analyses were performed for antennas mounted on the wing-tip pod. Each pod-mounted scoring antenna was to provide hemispherical radiation pattern coverage toward the side of the drone on which the antenna was mounted.
SECTION II

TECHNICAL APPROACH

This section of the report contains a description of the computer modeling technique and the scale model measurements completed by the Engineering Experiment Station at Georgia Tech on this program for the antenna systems of interest.

1. INITIAL ANTENNA LOCATIONS

Because of the radiation pattern coverage requirements of the TDU-X telemetry, command, radar augmentation and G-Band beacon, these particular antenna systems were located on the target as indicated in Figure 1. Computer analyses and scale model radiation patterns were completed for these particular antenna systems and these data are presented in a later section of this report.

After considerable discussion it was decided to mount one of the scoring antennas on the bottom of the TDU-X fuselage and the other on the fuselage top but slightly offset from the bottom antenna along the fuselage axis. Varying offset distances were then modeled before the final locations were fixed. This is discussed in the following section on computer modeling of two target antenna patterns.

Based on past performance and location of the scoring antennas, these were located on the outboard sides of the BQM-34A wing pods for the computer analysis and scale model measurements. For the BOMARC missile, the scoring antennas were mounted on the right and left side of the fuselage forward of the wings.

The antenna systems were modeled for the locations as described above and the majority of the computed data were verified by scale model measurements.

2. COMPUTER MODELING TECHNIQUES

a. TDU-X DIGIDOPS Scoring Antenna System

(1) Mathematical Model

The computer model adopted was that resulting from a solution to the wave equation (subject to the appropriate boundary conditions) for radiation from rectangular slots on an infinite cylinder. This approach
Figure 1. Antenna Locations on TDU-X Tow Target
did not take into account the fact that the cylinders were not infinite (end effects) and the problem of scattering from the wings (wing blockage was considered). The DIGIDOPS antenna consists of two slots, one axial and one circumferential, mounted together in a "T" configuration. The antenna may be considered to be the superposition of two separate antennas (no mutual coupling).

Many authors have discussed the modeling of axial and circumferential slots on cylindrical surfaces. The basic approach used here is that of Silver and Saunders [1],* which is an approximate form of the result obtained by solving the boundary value problem. The far zone fields of the slots can be written for the axial slot as (see Figure 2 for geometric parameters)

\[
E_\phi = \frac{e^{-jkr}}{n} \int_{z_1}^{z_2} G_A(z)e^{jkr} \cos \theta \, dz \left[ \sum_{n=0}^{\infty} \frac{j^n e^{-jnf}}{H_{(2)'}^n(ka \sin \theta)} \frac{1}{2\pi} \int_{-\beta/2}^{\beta/2} F_A(\phi)e^{jn\phi} \, d\phi \right],
\]

where the electric field across the slot is characterized by,

\[
G_A(z) = \cos\left(\frac{nz}{a}\right),
\]

\[
F_A(\phi) = 1.
\]

Integrating the equations where necessary the \( \phi \)-component of the axial slot becomes,

\[
E_\phi = \frac{e^{-jkr}}{r} \cos\left(\frac{n}{2} \cos \theta \right) \frac{1}{\sin \theta} \sum_{n=0}^{\infty} \frac{e^{jn} \cos n\phi}{H_{(2)'}^n(ka \sin \theta)} \frac{\sin\left(\frac{\phi}{2}\right)}{\left(\frac{\phi}{2}\right)^2},
\]

\[e_n = 1, \ n = 0,
\]

\[e_n = 2, \ n \neq 0, \ x = ka \sin \theta.
\]

*References are indicated by [] and are included as Section V.
Figure 2. Geometry for Axial Slot on a Cylinder
Patterns were generated for one axial slot located at \( \theta = 90^\circ, \phi = 90^\circ \) on a 7-inch radius cylinder. The pattern for this slot is shown in Figure 3. The slot dimensions used were 1.0-inch by 3.327-inch. This plot is a three dimensional one with the power pattern shown as a function of the variables \( \theta \) and \( \phi \). The height of the surface above the floor is an indication of the power intensity along a particular direction \( \theta, \phi \). Care should be exercised when interpreting such plots since this coordinate transformation implies equal weighting of the pole and equator regions of the farfield sphere; however, plots of this type are useful for locating regions of low coverage.

The circumferential slot, unlike the axial, has both a \( \theta \) and a \( \phi \) component. The equations describing the two components for a circumferential slot are [2],

\[
E_\theta = -\frac{e^{-jkr}}{\pi r} \int_{z_1}^{z_2} G_c(z)e^{jkr \cos \theta} \cos \theta dz \left[ \sum_{n=-\infty}^{\infty} \frac{j^n e^{-j\phi}}{\sin \theta H_n(2)(ka \sin \theta)} \frac{1}{2\pi} \int_{\beta_1}^{\beta_2} F_c(\beta)e^{jn\beta d\beta} \right],
\]

and

\[
F_\phi = \frac{e^{-jkr}}{\pi r} \int_{z_1}^{z_2} G_c(z)e^{jkr \cos \theta} \frac{\cot \theta}{ka \sin \theta} \left[ \sum_{n=-\infty}^{\infty} \frac{n_1 j^n e^{-j\phi}}{H_n(2)'(ka \sin \theta)} \frac{1}{2\pi} \int_{\beta_1}^{\beta_2} F_c(\beta)e^{jn\beta d\beta} \right],
\]

where the electric field across the slot is given by

\[
G_c(z) = 1,
\]

\[
F_c(\phi) = \cos \left( \frac{n\phi}{\beta} \right),
\]

and the geometric parameters are defined in Figure 4.
Figure 3. Calculated Radiation Pattern ($E^2$) for a Single Axial Slot on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included
Figure 4. Geometry for Circumferential Slot on a Cylinder
Performing the integration as before, the following useful equations are obtained.

\[ E_{\theta} = -\frac{je^{-jkr}}{\pi r} \left( a \sin \left[ \frac{k(\alpha)}{2} \cos \theta \right] \right) \frac{\sum_{n=0}^{\infty} \frac{e^{jn\phi}}{\sin \theta h_n(2)(ka \sin \theta)}}{\left( \frac{1}{\beta} \cos \left( \frac{n\theta}{2} \right) \right)} \]  

(7)

\[ E_{\phi} = -\frac{2je^{-jkr}}{\pi r} \left( a \sin \left[ k(\alpha) \cos \theta \right] \right) \frac{\cot \theta}{ka \sin \theta} \frac{\sum_{n=0}^{\infty} \frac{n!^{n \sin n\phi}}{h_n(2)'(ka \sin \theta)}}{\left( \frac{1}{\beta} \cos \left( \frac{n\beta}{2} \right) \right)} \]  

(8)

These equations were programmed on a digital computer to generate the pattern of a circumferential slot (see Figures 5, 6). For small values of \( \theta \), the above equations for \( E \) are invalid; therefore, for \( \theta = 0^\circ \), the pattern was assumed to have the same value as for \( \theta = 2^\circ \). The same dimensions were used for the circumferential slots as for the axial.

The complete DIGIDOPS antenna pattern was produced by a superposition of the axial and circumferential patterns. The basic equation used to add the two patterns was

\[ E_t(\theta, \phi) = E_a(\theta, \phi)e^{-j\psi_1} + E_c(\theta, \phi)e^{-j\psi_2} \]  

(9)

where \( a \) and \( c \) denote axial and circumferential patterns, respectively, and \( \psi_1 \) and \( \psi_2 \) are the absolute phases of the two slot patterns at the farfield point (i.e., total phase equal to initial phase plus path length dependence).
Figure 5. Calculated Radiation Pattern ($E_0^2$) for one Circumferential Slot (Positioned on Top) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included.
Figure 6. Calculated Radiation Pattern ($E^2$) for One Circumferential Slot (Positioned on Top) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included.
The current configuration (for the models seen at Tyndall Air Force Base) for the two DIGIDOPS antennas is shown in Figures 7 and 8. The spacing along the z-axis between the center of the two antennas is 8 inches. Patterns were calculated for the case of two axial antennas, one on top of the cylinder ($\phi = 90^\circ$) and one on the bottom ($\phi = -90^\circ$) with the spacing along the z-axis as 7.0 inches. This pattern is demonstrated three dimensionally in Figure 9. The $E_{\phi}^2$ pattern for one crossed pair of slots on the cylinder was calculated and shown in Figure 10. The total power pattern for the complete system with two DIGIDOPS antennas is given in Figure 11.

The spacing between the DIGIDOPS antennas was varied in steps of $\lambda/4$ from 0 to $\lambda/2$ along the z-axis. The patterns for the antennas spaced zero are given in Figures 12, 13, and 14. The patterns for the antennas spaced $\lambda/4$ are given in Figures 15, 16, and 17. The patterns for the antennas spaced $\lambda/2$ are given in Figures 18, 19, and 20. The first of the set of three patterns in each group is the $E_{\phi}^2$ component. The second is the $E_{\theta}^2$ component, while the third is the total power ($E_{\theta}^2 + E_{\phi}^2$). The plots show that there was no significant change in the coverage for the three spacings.

(2) Wing Effects

Blockage for the TDU-X DIGIDOPS antennas was taken into account by deriving an angular mask behind which the antenna patterns were set to zero. This model assumes no forward or back scattering from the wings and is sufficient to show the effect of the wings in coverage.

A blockage matrix was drawn up so that the blockage as a function of $\theta$ and $\phi$ could be entered into the computer analysis. This matrix was specified in 2-degree increments in $\theta$ and $\phi$.

The blockage matrix for an antenna located above the wings ($\phi = 90^\circ$) is given in Figure 21. The shaded areas indicate the angles at which the pattern is set to zero. An example of the effect of the blockage on a single axial slot located at $\phi = 90^\circ$ is given in Figure 22.

The blockage matrix for an antenna located below the wings ($\phi = -90^\circ$) is given in Figure 23. In this figure, as in the previous matrix diagram, the shaded areas indicate the angles at which the pattern is set to zero. An example of the effect of this blockage on a single axial slot at $\phi = -90^\circ$ is given in Figure 24.
Figure 7. DIGIDOPS Scoring Antenna Dual Cavity-Backed Slot Configuration

Figure 8. Displacement Between Top and Bottom TDU-X Scoring Antennas
Figure 9. Calculated Radiation Pattern ($E_\phi^2$) for Two Axial Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included.
Figure 10. Calculated Radiation Pattern ($E^2_r$) for One Pair of Crossed Slots (Positioned on Top) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included
Figure 11. Calculated Radiation Pattern \((E_0^2 + E_\phi^2)\) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included.
Figure 12. Calculated Radiation Pattern ($E_0^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. (Zero Spacing Between Top and Bottom Antennas)
Figure 13. Calculated Radiation Pattern ($E_\theta^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. (Zero Spacing Between Top and Bottom Antennas)
Figure 14. Calculated Radiation Pattern \((E_0^2 + E_2^2)\) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conductive Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. (Zero Spacing Between Top and Bottom Antennas)
Figure 15. Calculated Radiation Pattern ($E_0^2$) for Two Pairs of Crossed slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included ($\lambda/4$ Spacing Between Top and Bottom Antennas)
Figure 16. Calculated Radiation Pattern ($E^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. ($\lambda/4$ Spacing Between Top and Bottom Antennas)
Figure 17. Calculated Radiation Pattern ($E_\theta^2 + E_\phi^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. ($\lambda/4$ Spacing Between Top and Bottom Antennas)
Figure 18. Calculated Radiation Pattern \( (E_\theta^2) \) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. (\( \lambda/2 \) Spacing Between Top and Bottom Antennas)
Figure 19. Calculated Radiation Pattern ($E_\phi^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. ($\lambda/2$ Spacing Between Top and Bottom Antennas)
Figure 20. Calculated Radiation Pattern ($E_\theta^2 + E_\phi^2$) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by APATL) on a Conducting Right Circular Cylinder having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Not Included. ($\lambda$/2 Spacing Between Top and Bottom Antennas)
Figure 21. Blockage Matrix For Antenna Located on Top of TDU-X
Figure 22. Calculated Radiation Pattern ($E^2_	heta$) for a Single Axial Slot on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Included.
Figure 23. Blockage Matrix For Antenna Located on Bottom of TDU-X
Figure 24. Calculated Radiation Pattern ($E^2$) for One Axial Slot (positioned on bottom) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Included
The effect of the total wing blockage for the actual configuration of DIGIDOPS antennas is given in Figure 25. Where there is blockage, there is a tendency for the other antenna to fill it. This is a pattern showing total power \( (E_\theta^2 + E_\phi^2) \). If the effect of scattering were to be included the blockage would be filled in even more.

3) Pattern Gain

The gains for these antenna patterns were calculated using the basic equation

\[
G = 10 \log_{10} \left[ \frac{4\pi E_{\max}^2}{\Delta \theta \Delta \phi \sum_i \sin \theta_i \left[ \sum_j E^2(\theta_i, \phi_j) \right]} \right],
\]

(10)

Note that this calculation actually yields directivity since element efficiency is not included. True gain is found by subtracting element losses from directivity values.

The gains calculated for a single axial slot at \( \phi = 90^\circ \) was 5.35 dB. The gain calculated for the total power \( (E_\theta^2 + E_\phi^2) \) of a pair of DIGIDOPS antennas mounted in the present configuration was 4.1 dB. The gain for the single slot with blockage was 5.9 dB and for the DIGIDOPS with blockage was 4.5 dB.

4) Power Coverage Functions

Power coverage functions are very similar to probability distribution functions in that they depict the relative area of the farfield sphere over which the power is below a certain level versus the level. This is accomplished by numerically stepping through the data at one power level at a time and adding up the spherical surface areas over which the power is below the subject level. Such a plot shows at a glance the amount of the pattern that is below any given power level. The plot is a good method for comparing coverage for different antenna configurations. A composite plot of the coverage functions was made for the four different DIGIDOPS positions examined earlier to compare the coverage. There were three different cases plotted, Figures 26, 27, and 28, which show the coverage for \( E_\theta^2, E_\phi^2 \), and the total power.
Figure 25. Calculated Radiation Pattern \( (E_x^2 + E_y^2) \) for Two Pairs of Crossed Slots (Positioned on Top and Bottom as Indicated by AFATL) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target. Wing and Pod Blockage Was Included.
Figure 26. Power Distribution Function \( \left( E^2 \right) \) for Two Pairs of Crossed Slots (One Pair Each on Top and Bottom) on the TDU-X Target. Slot Positions are Indicated. No Wing and Pod Blockage Included.

Slot Spacing specified by AFATL
Slot Spacing = 0
Slot Spacing = \( \lambda/4 \)
Slot Spacing = \( \lambda/2 \)
Figure 27. Power Distribution Function ($L^2_0$) for Two Pairs of Crossed Slots (One Pair Each on Top and Bottom) on the TDU-X Target. Slot Positions are Indicated. No Wing and Pod Blockage Included.
Figure 23. Power Distribution Function (Total Power, $E_0^2 + E_2^2$) for Two Pairs of Crossed Slots (One Pair Each on Top and Bottom) on the TDU-X Target. Slot Positions are Indicated. No Wing and Pod Blockage Included.
(\(E_{\theta}^2 + E_{\phi}^2\)), respectively. The plots show that for this antenna configuration the coverage does not change significantly with variations in antenna location. The power coverage function for the total power \((E_{\theta}^2 + E_{\phi}^2)\) for the original position with blockage included is shown in Figure 29 for comparison.

(5) Summary of Computed Results

The analysis of the DIGIDOPS system on the TDU-X showed that typically good coverage was attained for the antennas used. The blockage included did not affect the coverage in the areas needed because of the tendency of the antennas to fill in the gaps. The location of the DIGIDOPS antennas on the TDU-X for the positions that were modeled was not found to affect the antenna pattern nor the coverage significantly.

The principal plane patterns of the final configuration of the TDU-X scoring antennas are presented in Figures 30 through 35. The antenna gain is approximately 0 dBi. These patterns can be compared with the scale model radiation patterns of Figures 41 through 46. This comparison will be discussed in the data summary section of the TDU-X later in this report.

b. TDU-X Command Receiver Antenna

The computer analysis for the command receiver antenna utilized a slot on a cylinder and the equation presented previously. This pattern is shown in Figure 36.

c. Telemetry Transmitter Antenna and L-Band Augmentation Antenna

The computer analysis for the TDU-X tow target Telemetry Transmitting stub and L-Band Augmentation Antenna was accomplished by modeling the antenna as a dipole on the surface of an infinite cylinder in a manner similar to the DIGIDOP's antenna. As with the DIGIDOP's analysis, this method does not consider the effect of the finite extent of the tow target but is sufficient for modeling purposes.

The mathematical model used is that discussed by Carter [3]. The basic equations used for the \(\theta\) and \(\phi\) components of the electric field are
Figure 29. Power Distribution Function (Total Power, $E_0^2 + E_1^2$) for Two Pairs of Crossed Slots (One Pair Each on Top and Bottom) on the TDU-X Target. Slot Positions are Indicated. Wing and Pod Blockage Included.
Figure 30. Principal Plane Plot, E9, TDU-X Scoring Antennas, Pitch Angle 90°, Variable Roll Angle
Figure 31. Principal Plane Plot, EØ, TDU-X Scoring Antennas, Pitch Angle 90°, Variable Roll Angle
Figure 32. Principal Plane Pattern, $E_\phi$, TDU-X Scoring Antennas, Roll Angle $90^\circ$, Variable Pitch Angle
Figure 33. Principal Plane Pattern, E8, TDU-X Scoring Antennas, Roll Angle 90°, Variable Pitch Angle
Figure 34. Principal Plane Pattern, Eφ, TDU-X Scoring Antennas, Pitch and Roll Angles 0°, Variable Yaw Angle
Figure 35. Principal Plane Pattern, E9, TDU-X Scoring Antennas, Roll and Pitch Angles 0°, Variable Yaw Angle
Figure 36. Calculated Radiation Pattern for a Slot Antenna Positioned on Bottom of a Conducting Right Cylinder Having the Same Diameter as the TDU-X Target
\[ E_\theta = \sum_{n=1}^{\infty} \frac{j^n D_n \cos n\phi}{n} \], \quad (11) \\
\[ E_\phi = \sum_{n=1}^{\infty} \frac{(-j)^2}{ka \sin \theta} J_n B_n \sin n\phi \], \quad (12) \\
where,
\[ D_n = J_n'(ka \sin \theta) - \left[ \frac{J_n(ka \sin \theta)}{H_n'(2)(ka \sin \theta)} \right] H_n(ka \sin \theta) \], \quad (13) \\
and
\[ B_n = J_n(ka \sin \theta) - \left[ \frac{J_n'(ka \sin \theta)}{H_n'(2)(ka \sin \theta)} \right] H_n(ka \sin \theta) \], \quad (14) \\
where a is the radius of the cylinder.

The stub antenna was located at \( \phi = -90 \) degrees and the \( \theta \) and \( \phi \) components were calculated separately, and the three dimensional patterns plotted (Figure 37, 38).

3. MEASURED DATA - SCALE MODEL AND FULL SCALE PATTERNS

Scale models of the TDU-X tow target and the BQM-34A wing pod were fabricated and used in obtaining measured antenna radiation pattern data. A scale model BOMARC was obtained from Eglin AFB and was used to model the DIGIDOPS scoring antenna system. Most of the measured data were obtained on the TDU-X scale model. It should be noted that this particular effort was done to verify the computed data.

a. TDU-X Tow Target

A one-fifth scale model of the TDU-X tow target was fabricated for use in the measurement program. A photograph of this model is presented in Figure 39. The antennas tested with the model were DIGIDOPS, Telemetry, and L-Band Augmentation.

1) Scoring Antennas

A photograph of one of the scale model DIGIDOPS scoring antennas is presented in Figure 40. This antenna was fabricated from sections of K-band waveguide. Teflon plugs were used to load the cavity-backed slots in a manner similar to the full scale antennas.
Figure 37. Calculated Radiation Pattern \((E_r)^2\) for One Monopole (positioned on bottom) on a Conducting Right Cylinder Having the Same Dimensions as the TDU-X Target
40-dB DYNAMIC RANGE

Figure 38. Calculated Radiation Pattern for One Monopole (positioned on bottom) on a Conducting Right Circular Cylinder Having the Same Diameter as the TDU-X Target
Figure 40. Scaled Antenna - DIGIDOES
Only the primary radiation patterns will be presented herein. A number of patterns were run with a single antenna and were used to verify computer input data. In addition, some radiation patterns were made without the target fins to determine the effect on the patterns. The principal plane plots for the two polarizations are plotted in Figures 41 through 46. A comparison of these data to that of Figures 30 through 35 reveals that the computer modeling, although not exact, is a sufficient means of determining the coverage characteristics of two target antenna systems.

Figure 41 shows a principal plane pattern of the TDU-X scoring antennas in the roll plane with the target at a 90-degree pitch angle. Since the antennas are mounted on the top and bottom of the vehicle, good pattern coverage is provided in these areas. As a comparison, the computed pattern is presented in Figure 30. Although the right and left side coverage is predicted to be lower than the measured coverage, the comparison is favorable.

The horizontal polarization roll plane pattern is presented in Figure 42 and the expected coverage was obtained. The vertical polarization pitch plane pattern is shown in Figure 43. The predicted pattern of Figure 32 indicates deep nulls on the nose and tail of the target, whereas the measured pattern indicates good tail coverage. This difference is caused by two factors: (1) the reflections from the fins and the pods enhance the tail coverage and (2) the measured antennas do not possess the ideal cross polarization characteristics of the antennas utilized in the pattern predictions. The horizontally polarized pitch plane pattern is presented in Figure 44. Good agreement exists between these pattern cuts.

The yaw plane cuts are shown in Figures 45 and 46 for the TDU-X scoring antennas. Note the blockage effects of the fins in Figures 34 and 35. Although the measured patterns indicate that the blockage is not as severe as predicted, they do serve as good indicators of the areas where coverage problems will arise.

The remaining individual $\theta$, $\phi$ pattern cuts are not included in this report. These data have been analyzed and summarized and are
Figure 41. Principal Plane Plot, TDU-X Scoring Antennas, Vertical Polarization, Two Antennas at Top and Bottom
Figure 42. Principal Plane Plot, TDU-X Scoring Antennas, Horizontal Polarization, Two Antennas Located at Top and Bottom
Figure 43. Principal Plane Plot, TDU-X Scoring Antennas, Vertical Polarization, Two Antennas at Top and Bottom
Figure 44. Principal Plane Plot, TDU-X Scoring Antennas, Horizontal Polarization, Two Antennas at Top and Bottom
Figure 45. Principal Plane Plot, TDU-X Scoring Antennas, Vertical Polarization, Two Antennas Located at Top and Bottom
Figure 46. Principal Plane Plot, TDU-X Scoring Antennas, Horizontal Polarization, Two Antennas Located at Top and Bottom.

ROLL ANGLE 0°
PITCH ANGLE 0°
YAW VARIABLE

0
90°
180°
270°
360°
0°
-90°
-180°
-270°
-360°

TAIL
LEFT
Nose
RIGHT
presented herein in two ways. First, the data have been plotted in contours as presented in Figures 47 and 48. These two plots are cylindrical equal spaced projections. The equal spaced projections distort the pattern contours, but the areas near the nose and tail (poles) have been expanded. Since tail coverage was of keen interest, it was felt that this presentation would be best. The plots of Figures 47 and 48 should not be used to determine percentage of total spherical area covered by certain gain contours. The contour plots are based on the measured pattern in the coordinate system of Figure 49.

These contour plots of measured data were graphed in another form as shown in Figures 50 and 51. The second method of presenting the overall data is the 3-D antenna pattern plots as previously presented (see Figure 25).

In all of the scoring antenna plots presented herein, the gain of the antenna (i.e., the gain at the maximum power level) is 0 dB.

(2) Telemetry Antenna - TDU-X

The principal plane scale model radiation patterns of the telemetry antenna are shown in Figures 52 through 55. Both horizontal and vertical polarization are included.

Lower hemispherical coverage was desired and was obtained except for the null directly beneath the antenna, which was expected.

(3) L-Band Augmentation Antenna - TDU-X

The principal plane plots of the forward L-Band antenna are presented in Figures 56 and 57. These patterns are almost identical to those of the telemetry antenna.

Isolation measurements between the telemetry antenna and the L-Band augmentation antenna were made over the L-Band frequency range. Typically, an isolation of 30 dB between these two antenna terminals is maintained over this frequency range.

b. BQM-34A Drone

The DIGIDOPS scoring antennas were mounted on the outer edge of the wing-tip pods as indicated in Figure 58. Scale model antenna
Figure 47. Radiation Pattern Contour Plot, TDU-X Scoring Antennas, Vertical Polarization
Figure 48. Radiation Pattern Contour Plot, TDU-X Scoring Antennas, Horizontal Polarization
Figure 49. Coordinate System to Interpret Radiation Pattern Contour Plots
Figure 50. Measured Radiation Pattern Data for TDU-X Scoring Antennas ($E_\theta$). Two Antennas Located at Top and Bottom.
Figure 51. Measured Radiation Pattern Data for TDU-X Scoring Antenna ($E_\phi$). Two Antennas Located at Top and Bottom
Figure 52. TDU-X Telemetry Antenna Radiation Pattern, Vertical Polarization, Roll and Pitch Angle 0°, Yaw Angle Variable
Figure 53. TDU-X Telemetry Antenna Radiation Pattern, Vertical Polarization, Pitch and Yaw Angles 0°, Roll Angle Variable
Figure 54. TDU-X Telemetry Antenna Radiation Pattern, Horizontal Polarization, Variable Yaw Angle
Figure 55. TDU-X Telemetry Antenna Radiation Pattern, Horizontal Polarization, Variable Roll Angle
Figure 56. TDU-X L-Band Augmentation Antenna Radiation Pattern, Vertical Polarization, Variable Yaw Angle
Figure 57. TDU-X L-Band Augmentation Antenna Radiation Pattern, Vertical Polarization, Variable Roll Angle
Figure 58. Photograph of Scale Model BQM-34A Pod with Scoring Antennas.
pattern measurements were taken on one T-slot antenna mounted on the pod without utilizing the main body as a part of the ground. Principal plane radiation pattern measurements for the scale model antenna (one antenna only) are shown in Figures 59 through 62. Good coverage was obtained from the antenna only on the side of the drone where the antenna was mounted. It is felt that the two antennas, each mounted on the outboard side of the wing-tip pods, will act independently of one another.

c. BOMARC Scoring Antennas

The scaled antennas were mounted onto a one-eighth scale mock BOMARC missile for the radiation pattern measurements. The antennas were mounted on the left and right sides of the fuselage and forward of the wings at the station recommended by AFATL. Radiation patterns were measured in the yaw plane with the roll angle at 0°, 45°, and 90°. Presented in Figures 63 and 64 are the horizontal polarization plots for the 0° and 90° roll angle cases. The pattern coverage is excellent except for small regions off the nose and the tail.

d. Full-Scale Measurements

Two X-Band antennas, the cylindrically shaped antenna and the conical spiral, were each mounted on a cylindrical ground plane for pattern measurements. The cylindrical antenna had good omni-directional coverage, as expected, whereas the conical spiral possessed a narrower beamwidth which made it directional. Two principal plane radiation patterns of the conical spiral are presented in Figures 65 through 68, which include both linear polarizations. This particular antenna provides the design antenna pattern coverage.
Figure 59. BQM-34A Scoring Antenna Radiation Pattern, Vertical Polarization, Variable Yaw Angle
Figure 60. BQM-34A Scoring Antenna Radiation Pattern, Vertical Polarization, Variable Roll Angle
Figure 61. BQM-34A Scoring Antenna Radiation Pattern, Horizontal Polarization, Variable Yaw Angle
Figure 62. BQM-34A Scoring Antenna Radiation Pattern, Horizontal Polarization, Variable Roll Angle
Figure 63. BOMARC Scoring Antenna Radiation Pattern, Horizontal Polarization, Variable Yaw Angle
Figure 64. BOMARC Scoring Antenna Radiation Pattern, Horizontal Polarization, Roll Angle 90°, Variable Yaw Angle
Figure 65. Conical Spiral Radiation Pattern on 14-inch Diameter Cylinder, Vertical Polarization, Variable Yaw Angle (10 GHz)
Figure 66. Conical Spiral Radiation Pattern on 14-inch Diameter Cylinder, Vertical Polarization, Variable Roll Angle (10 GHz)
Figure 67. Conical Spiral Radiation Pattern on 14-inch Diameter Cylinder, Horizontal Polarization, Variable Yaw Angle (10 GHz)
Figure 68. Conical Spiral Radiation Pattern on 14-inch Diameter Cylinder, Horizontal Polarization, Variable Roll Angle (10 GHz)
In general, it can be stated that the computer modeling technique utilized on this program is an economical approach to the calculation of antenna radiation patterns of target vehicles. The wide beamwidth characteristics of the antenna systems evaluated did have an effect on the depth and position of radiation pattern nulls in the cases where two antennas formed the system, such as the DIGIDOPS scoring antennas. But the envelope of the radiation patterns and the percent coverage of each system were predicted relatively accurately.

The location of the mounting position for the TDU-X scoring antennas was determined through the computer modeling technique as described herein. It was determined that the two antennas should be positioned on the top and bottom of the tow target and as far aft as possible. It was determined that the antennas could be displaced from one another along the fuselage axis without any serious degradation of the desired rear coverage. Once the antenna positions were determined, based on the computer prediction data and on the desire to locate the antennas in a position compatible with other TDU-X equipment, scale model radiation patterns were made that verified the coverage predicted by the computer program.

The other TDU-X tow target antennas that were evaluated did provide coverage in the areas that were predicted and expected. The computed patterns were verified by measured data on the scaled model.

The wing-tip pod-mounted scoring antennas on the BQM-34A provide pattern coverage toward each side of the vehicle with some spill-over (top and bottom), but the percent spherical coverage is much less than that of the TDU-X scoring antennas. This is caused by the near flat shape of the outboard side of the pods. Each of the two scoring antennas could be utilized individually or summed together without little change in the radiation pattern coverage.

In summary, an economical method of predicting target antenna radiation pattern coverage has been presented. For the cases where exact positions of nulls are required, the described scale model measurements also proved to be an inexpensive route to follow.
SECTION IV
RECOMMENDATIONS

It is recommended that for future target antennas the following considerations be made:

(a) Utilize the antenna pattern prediction technique for determining the location of the antennas and for an estimate of the percent coverage that will be obtained,

(b) Utilize the scale model measurements for the cases where an antenna system is formed from two or more antenna elements and where severe pattern blockages and/or reflections are predicted,

(c) Utilize the scale model measurements to provide reliable contour plots that might be required by range instrumentation personnel.

It is also recommended that consideration should be given to expanding the current antenna pattern prediction computer program to include geometrical theory of diffraction techniques. This particular computer program, although expensive to implement, would be used in situations where time was an important factor and the scale model measurement program could not be implemented.

A final recommendation concerns the design of antennas for targets. It is felt that a program should be pursued that would address the design of stripline-type, multi-antenna configurations. Microwave and antenna technology has advanced to the point where these type antenna systems are viable and economical. It is felt that by utilizing good design techniques, target antenna systems could be built to be very efficient, lightweight, and with very little structural out-cuts required. Typically, three to five antenna systems could be fabricated from a 10-to 15-inch wide strip that wraps around the fuselage of the target. In fact, a patch antenna design has recently been developed and tested in-house that looks very promising for use on target vehicles.

As a final recommendation, the DIGIDOPS scoring antennas need to be redesigned so that they are more flexible in their positioning on a target. For example, the slot antennas could be replaced by printed circuit antennas utilizing a flexible substrate. These antennas could then conform to the outer surface of most any target of interest.
At least two ideas have been discussed with the Technical Program Monitor at ADTC/DLMQ. One of these approaches would specifically address the targets that could utilize fin-mounted antennas. Because of the complexity of the scoring problem, it is felt that the antenna system should not be a contributor to any errors that might arise in the analysis of scoring data. This implies a constant VSWR over a fairly broad bandwidth and good radiation pattern coverage. These two requirements are compatible and can be realized in relatively inexpensive antenna designs.

Since each of the targets has a number of radiating systems which might cause interference between systems, it will be necessary to implement a measurement program to determine the electromagnetic interference perturbations. Although analytical techniques are available to predict these effects, past experience has shown that a measurement program is necessary because of the complexity of the problem. With the high number of transmitting and receiving systems now utilized by each target, an EMI test program based on MIL-STD-461, which tests for both emissions and susceptibilities, should be initiated.
SECTION V
REFERENCES

