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RADAR TRANSPONDER ANTENNA PATTERN ANALYSIS FOR THE SPACE SHUTTLE

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ABSTRACT

In order to improve tracking capability, radar transponder antennas will soon be mounted on the shuttle solid rocket boosters (SRB). These four antennas, each being identical cavity-backed helices operating at 5.765 GHz, will be mounted near the top of the SRB's, adjacent to the intertank portion of the external tank. The purpose of this study is to calculate the roll-plane pattern (the plane perpendicular to the SRB axes and containing the antennas) in the presence of this complex electromagnetic environment.

The large electrical size of this problem mandates an optical (asymptotic) approach. Development of a specific code for this application is beyond the scope of a summer fellowship; thus a general purpose code, the Numerical Electromagnetics Code - Basic Scattering Code, was chosen as the computational tool. This code is based on the modern Geometrical Theory of Diffraction, and allows computation of scattering of bodies composed of canonical problems such as plates and elliptic cylinders.

Apertures mounted on a curved surface (the SRB) cannot be accommodated by the code, so an antenna model consisting of wires excited by a method of moments current input was devised that approximated the actual performance of the antennas. The improvised antenna model matched well with measurements taken at the MSFC range. The SRB's, the external tank, and the shuttle nose were modeled as circular cylinders, and the code was able to produce what is thought to be a reasonable roll-plane pattern.

ACKNOWLEDGEMENTS

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INTRODUCTION

In order to improve tracking of the shuttle's solid rocket boosters (SRB) after normal separation from the external tank (or in the event of abnormal separation), four radar transponder antennas will be mounted on the SRB's. The antennas are cavity-backed helices operating at a frequency of 5.765 GHz, and a pair them will be mounted on opposite sides of each SRB cylinder.

The patterns of two of these antennas mounted on a metallic cylinder having the same diameter as an SRB but only 4.5 feet tall have been measured at the MSFC antenna range and they appear to yield acceptable coverage. An attempt to measure the three-dimensional pattern of the antennas in the presence of both SRB's, the external tank (ET), and the orbiter is not practical, since the frequency of operation needed for a usable shuttle scale model is in the neighborhood of 90 GHz.

The purpose of this effort is to gain more information on the pattern of these antennas in the presence of the entire shuttle cluster. Since experimental means are not practical, classical electromagnetic theory along with modern computational methods will be used. Given the time restraints of a ten-week fellowship, the pattern is calculated in only one plane (the plane containing the antennas and which is perpendicular to the SRB axes).

OBJECTIVES

The objective of this effort is to calculate the two-dimensional pattern of the four radar transponder antennas in the presence of both SRB's, the ET, and the orbiter. The plane of interest is the plane containing the four antennas, which happens to be perpendicular to the SRB cylinder axis (and will henceforth be referred to as the "roll-plane" pattern). Specific attention will be given to accurate modeling of the antennas performance and matching model results to actual measurements.

The following assumptions are make throughout the report:

1. Portions of the shuttle cluster that do not penetrate the roll-plane are not included in the computations. This implies that the effects, if any, of the rounded ends of the SRB's, ET, and orbiter are ignored.

2. Polarization measurements were not made, but it is assumed that the radiation is circularly polarized.

3. The antennas will be placed at points on the SRB's that are adjacent to the intertank portion of the ET. This intertank section contains strengthening corrugations which are on the order of a wavelength high. In this analysis, the ET is assumed to be a smooth cylinder.

PATTERN CALCULATION

The locations for the radar transponder antennas on the shuttle cluster are shown in Fig. 1. The antennas are assumed to be operating at a frequency of 5.765 GHz and that the radiation is circularly polarized. Due to the symmetry of the problem and the fact that objects not in the roll-plane are being ignored, it is irrevelant whether the cluster is looked upon from the front or rear (this is why the direction of flight is not identified on cluster drawings in Figs. 7-10).

Previous to this effort, an estimate of the shadowing due to the cluster was made using a line-of-sight shadowing code [1]-[2]. In addition, some preliminary work was done to model the antennas in the presence of two cylinders [3], and the effects of corrugations of the external tank were partially examined [4]. The roll-plane pattern of all antennas in the presence of the entire cluster was not obtained, however.

Due to the large electrical size of the problem, we are forced to use an optics approach. The integral equation and differential equation methods require far too much computer memory and time for a problem of this size [5]. Physical optics could be applied, but there is no general purpose physical optics code in the public domain, and writing one for this specific purpose is beyond the scope of a summer fellowship. Thus, the only technique within our grasp is geometrical optics and the associated Geometrical Theory of Diffraction (GTD).

The modern GTD is an extension of Keller's diffraction theory. It modifies the geometrical optics field (direct, reflected, and refracted fields) to yield a field distribution which is continuous across spatial boundaries at which geometrical optics alone would predict discontinuities. It is a high-frequency asymptotic technique, however, and becomes more accurate as the frequency of operation becomes higher. Given the radar antenna wavelength and the size of the shuttle cluster, GTD can be expected to give good results for this problem.

Invoking GTD requires development of "diffraction coefficients" associated with the given problem [6]. Diffraction coefficients have been found for several

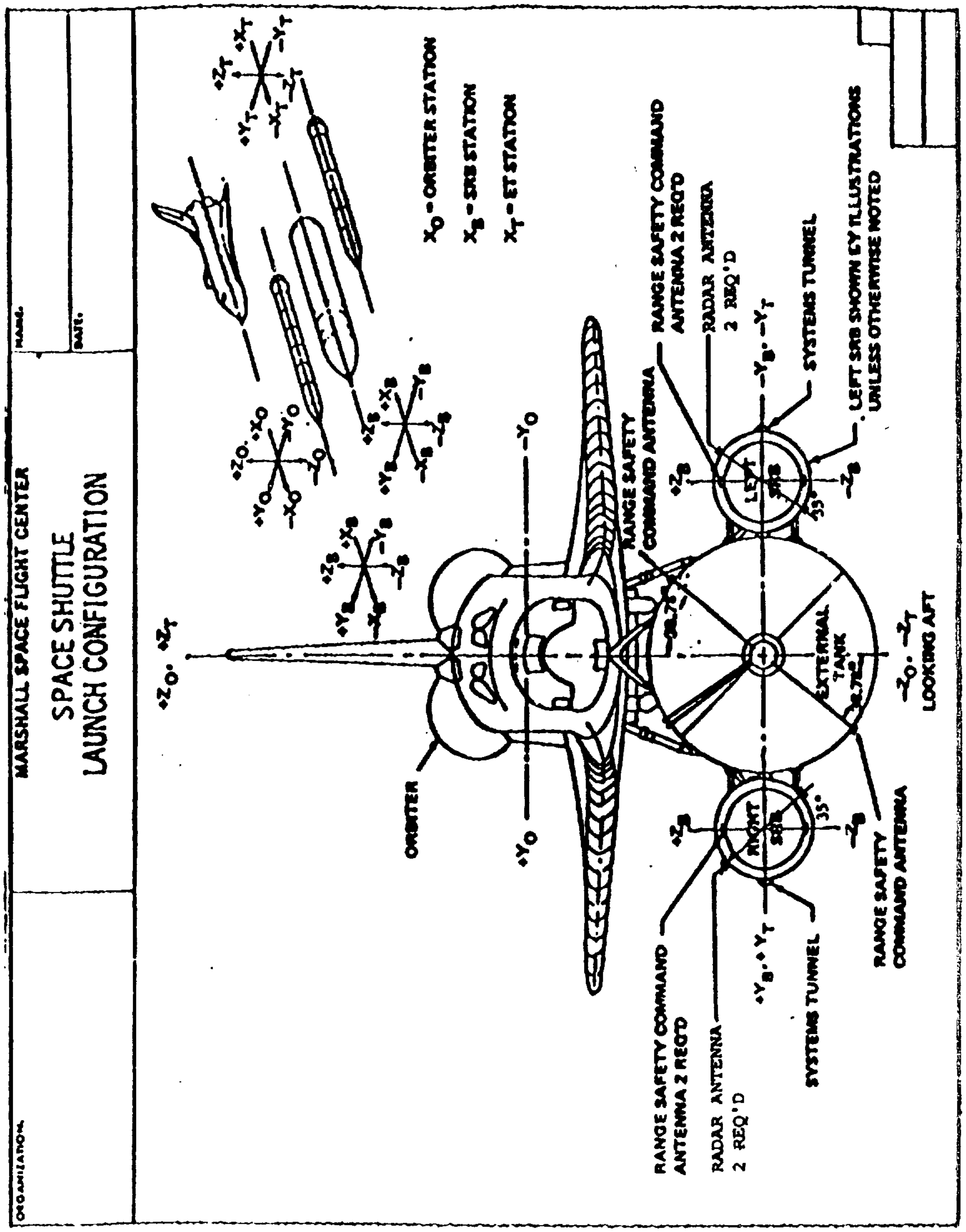


Figure 1. Antenna locations amid the cluster.

canonical problems, including plates, wedges, cones, and elliptic cylinders. Many practical antenna and scattering problems have been solved with GTD by approximating the antenna or scatterer by one or more canonical geometries. Since the scattered field is obtained by summing many rays that can exist from source to observation point, building a model of a structure from canonical problems is easy, since induced current interactions between different parts of the structure do not have to be explicitly computed.

This GTD ray tracing process lends itself well to the creation of a general purpose code; this was done by Prof. Ron Marhefka and his associates at the Ohio State University [7]. The code is named the Numerical Electromagnetics Code - Basic Scattering Code (NEC-BSC) and is implemented on the MSFC antenna range Compaq 386/20 personal computer.

The aspect of NEC-BSC that applies to this problem is its ability to calculate the far field pattern of an antenna array in the presence of complex structures, provided the structure can be modeled as a combination of canonical geometries. In reality, it is possible that many ray paths exist between the source and observation point; the code handles only the lower-order paths. For example, the code will compute direct, singly-reflected, singly-diffracted, doubly reflected, reflected-diffracted, and diffracted-reflected rays, but not doubly-diffracted ones.

These limitations in ray tracing can be significant, but the code does have limited warning capability which warns the user when a particular mode which is not calculated may be significant. This was not encountered during the course of this investigation. We will see that it does, however, introduce small discontinuities in the final pattern. This is not important; the theory of GTD tells us that the ignored modes would simply smooth out the discontinuity.

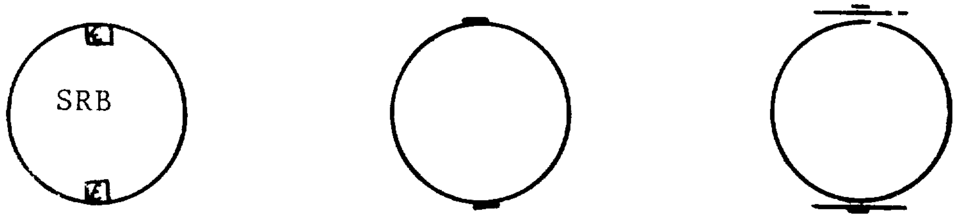
It should be stressed that NEC-BSC is, like many other general purpose electromagnetic codes, sensitive to the user's understanding of the underlying theory of the code and of electromagnetic theory in general. This was evident during this investigation when it was discovered that compiling NEC-BSC with an optimizing compiler causes errors in output when a linear source is placed parallel to the axis of a cylinder. A person without proper training using the code would not have noticed the problem and, most likely, would have generated erroneous results. Further comment on this can be found in the Results and Recommendations section.

Much of this effort was devoted to modeling the helix antennas, and is along the lines of that in [3]. Fig. 2a. represents the two antennas mounted on an SRB, with the aperture flush with the cylinder surface. NEC-BSC allows the user to specify an aperture as a source, but it cannot be mounted on a curved surface (Fig. 2b.). This is because the problem of a source mounted on a curved surface is a completely different type of diffraction problem (the "radiation" problem), and the code does not incorporate this diffraction theory.

Apertures are permitted to be mounted on flat plates, however. It seems logical, then, to mount an aperture on a small flat plate placed a small distance above the circular cylinder representing the SRB (the circular cylinder is another canonical problem which the code handles). Unfortunately, this will not work because doubly-diffracted fields are not computed, and thus the cylinder would not be illuminated by the antenna.

Since the actual helix antennas are circularly polarized, our model must be also. Circular polarization can also be obtained by crossed dipoles or crossed slots. It is known that a half-loop and its associated image can produce a field similar to that of a slot mounted on the cylinder surface [3]. Two of these half-loops are shown in Fig. 2d.; to create the other slot would require two more perpendicular to those drawn.

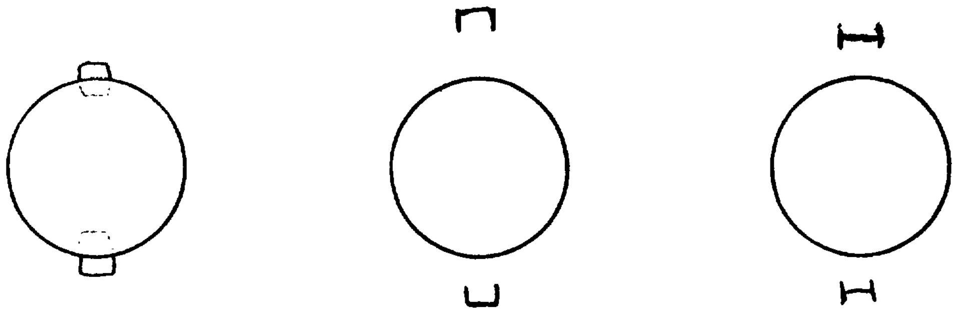
This cannot be trusted, however, because this would place the sources too close to the cylinder. This is because NEC-BSC is based on a high-frequency asymptotic theory and no two objects should ever be closer than one-quarter wavelength apart. This problem could be alleviated by raising the loops one-quarter wavelength off the cylinder surface, as shown in Fig. 2e.



a) helical antennas in SRB cylinder

b) apertures on curved surfaces not permitted

c) double diffraction not calculated



d) half-loops too close to cylinder surface

e) raised half-loops OK with MOM input

f) optimize

Figure 2. Antenna model development.

This is obviously not a physically viable situation. That is irrevelant though, since the code allows wire segments to be placed anywhere with any current magnitude and phase desired. In reality, the currents would interact and redistribute themselves to satisfy boundary conditions, but this input option is intended to allow the results from a method of moments analysis to be used as a source. In other words, any wire segment interaction would have already been included in the method of moments calculation (NEC-BSC cannot perform the current interaction calculation since it is not based on an integral equation approach). So, even though the currents used on the half-loop model are not derived from a method of moments procedure, we can still take advantage of this input option to create our antenna model.

The next step was to adjust the relative phasing, magnitude, and distance from the cylinder of the wire segments in an attempt to obtain a model that matched well with measured data taken at the antenna range. This was somewhat time-consuming, and was done on what was essentially a trial-and-error basis (Fig. 2f.).

To make the measurements at the antenna range, two of the cavity-backed helix antennas were mounted on a 4.5 foot high cylinder having the same diameter as the SRB. Thus, when developing the antenna model, a 4.5 foot high cylinder was assumed. When only one antenna was modeled, some discontinuities were evident on the side opposite the antenna. This is because of the fact that the code has some difficulty dealing with caustics (places where an infinite number of rays intersect). It so happens that the location of the caustic is at the maximum of the second antenna's pattern; fortunately this drowns out the discontinuity and yields an essentially continuous pattern. The final modeled pattern of two antennas mounted on a 4.5 foot high SRB section is given in Fig. 3. The radiation is very close to being circularly polarized.

The measured pattern for the same situation is given in Fig. 4, and both patterns are plotted for comparison purposes in Fig. 5. The calculated and measured patterns agree very well almost everywhere.

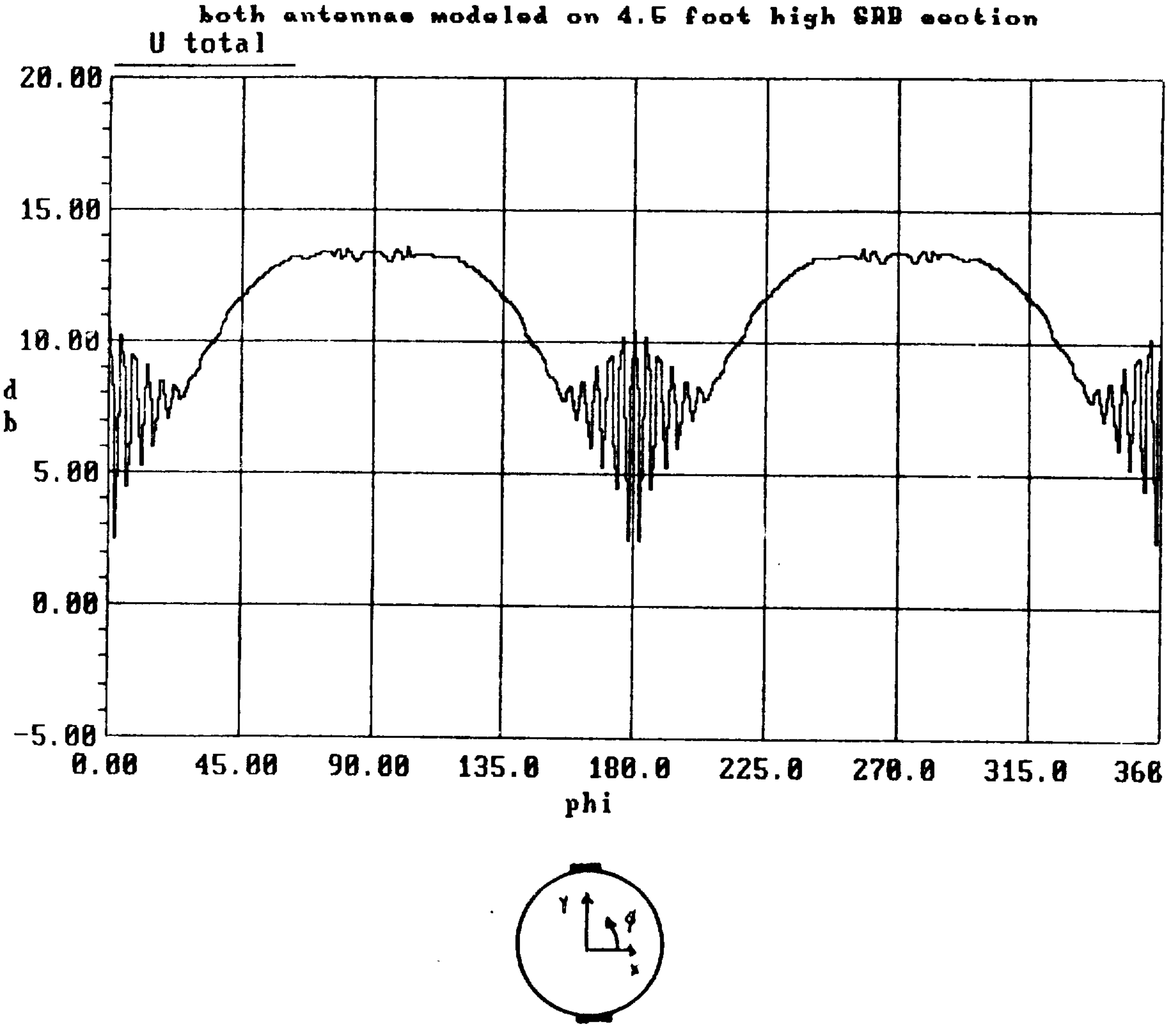


Figure 3. Pattern of two antenna models on one 4.5 foot high SRB section.

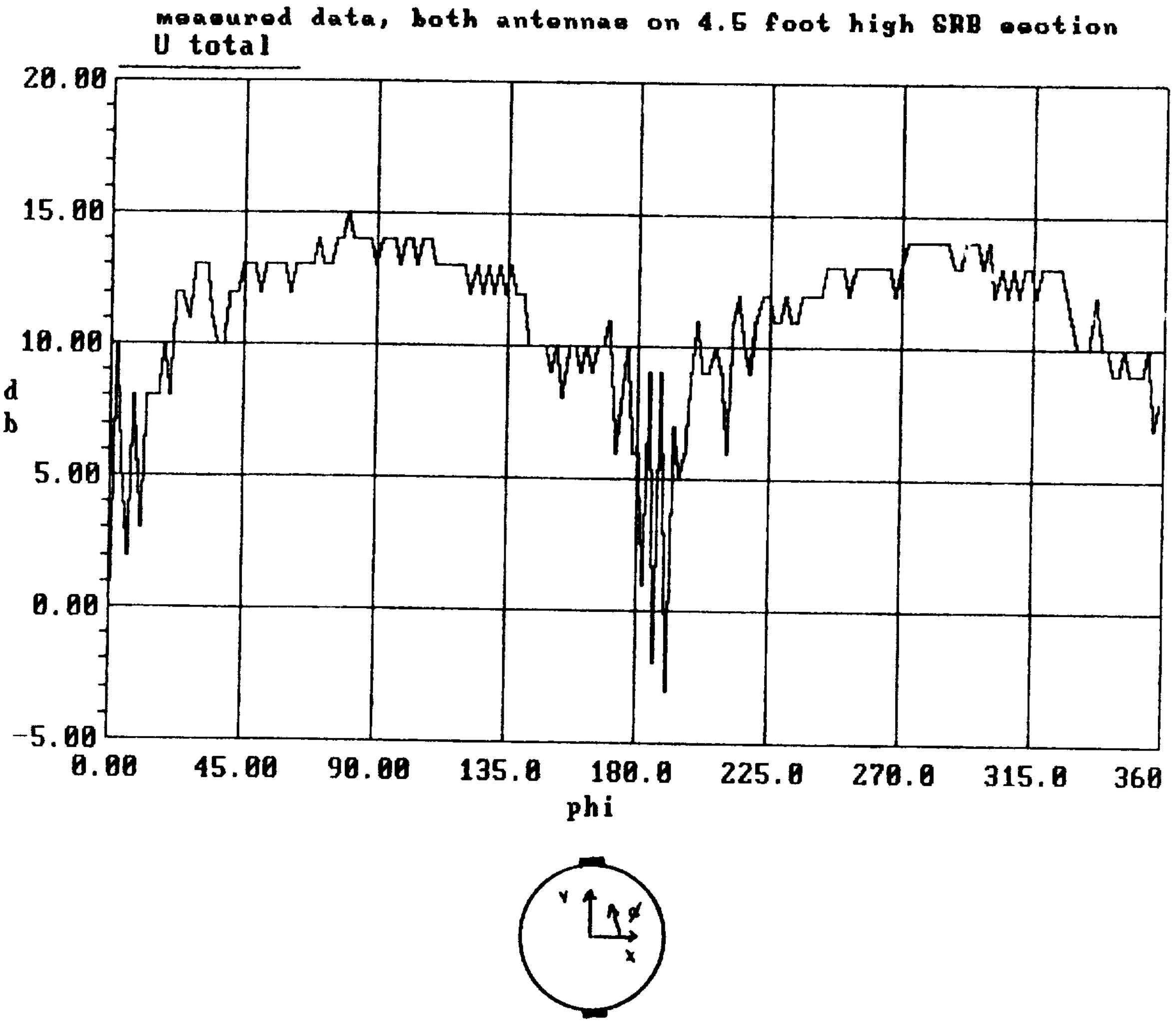


Figure 4. Measurement of roll-plane pattern of two antennas on 4.5 foot high SRB section.

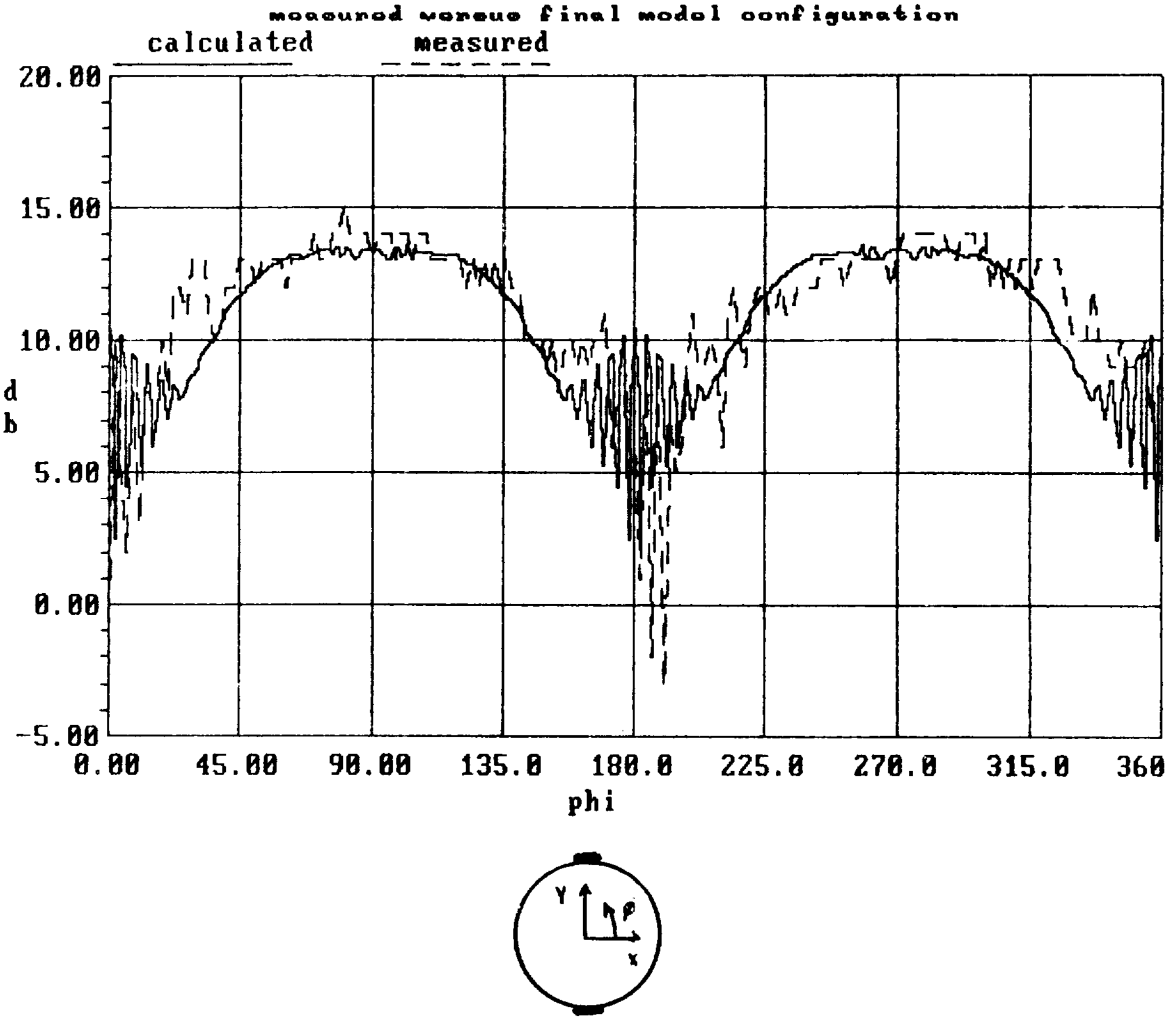


Figure 5. Comparison of measured pattern with calculated pattern.

Now that the two antenna/SRB model is developed, it is a straightforward matter complete the analysis. Fig. 6 gives the pattern of both SRB's, with the cylinders rotated by 35 degrees, to coincide with Fig. 1. The pattern is quite complicated, with very short distances between adjacent maxima and minima. This is to be expected, since the scattering centers are very far apart electrically. To gain more confidence in the pattern at this point in the development, the pattern of two dipoles tilted at 35 degrees from the x-axis operating at the same frequency was calculated and is plotted in Fig. 7. The periodicity between adjacent maxima and minima is similar to that of Fig. 6. Dipoles were chosen since they have a similar pattern to that of the two antenna/SRB model. The more complicated nature of the pattern of Fig. 6 can be attributed to multiple cylinder interactions.

Fig. 8 gives the final roll-plane pattern calculation, obtained by using the input file which created Fig. 6 and adding cylinders to represent the ET and the cross section of the orbiter's nose in the roll-plane. Figs. 9 and 10 present the same data in expanded form. Shuttle dimensions used in creating the input file are taken from [8].

There are some small discontinuities evident in Figs. 9 and 10. These may be due to the basic limitations in the code's ray tracing procedure or to the fact that computations can only be done at a minimum of 1 degree increments. But this pattern is believed to be reasonable and accurate to within the code's limitations and the simplifying assumptions.

Due to the 25 page limit on this report, there is no room for discussion of the details of the input data file. It is listed as an appendix at the end of this report, and may be interpreted with the use of [7].

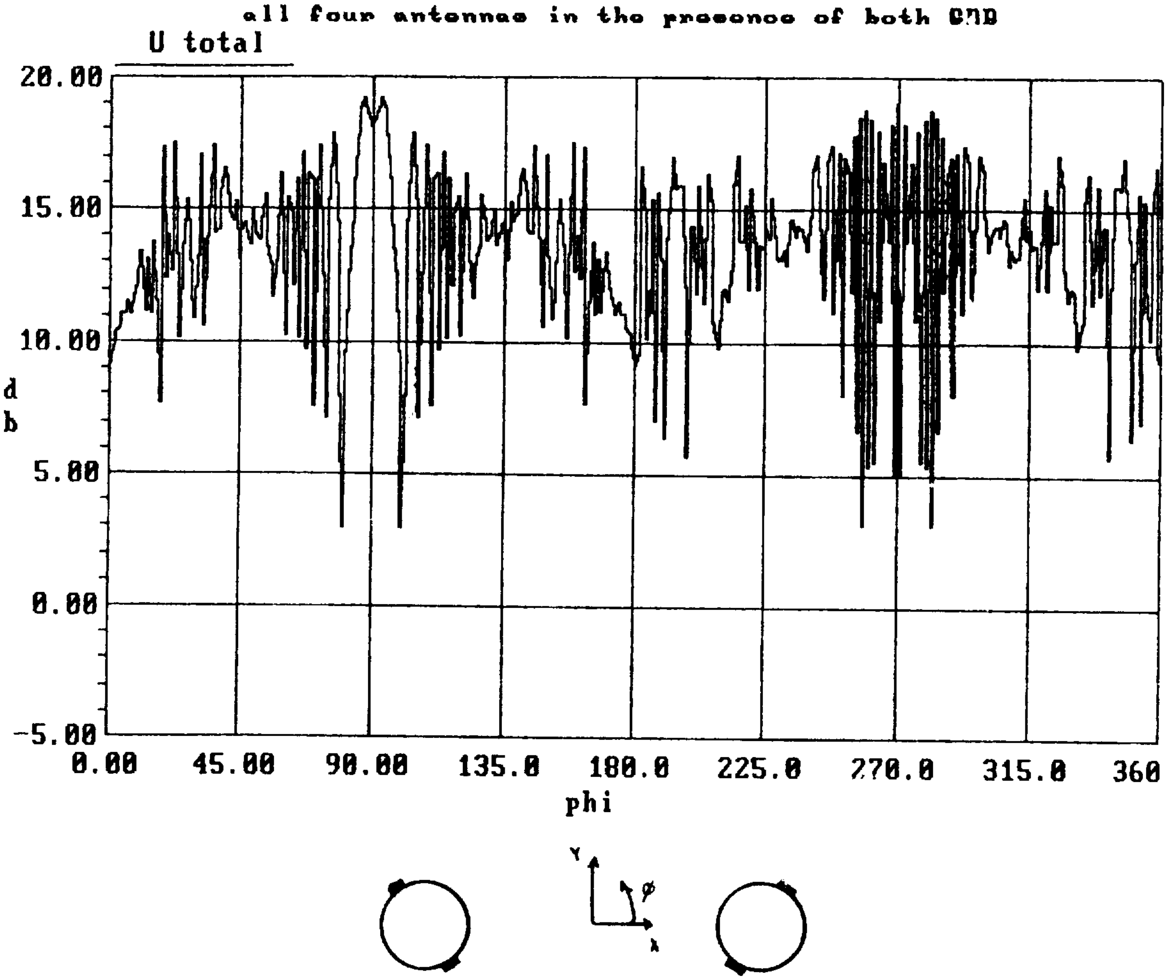


Figure 6: Pattern of all four antennas in the presence of both SRB's.

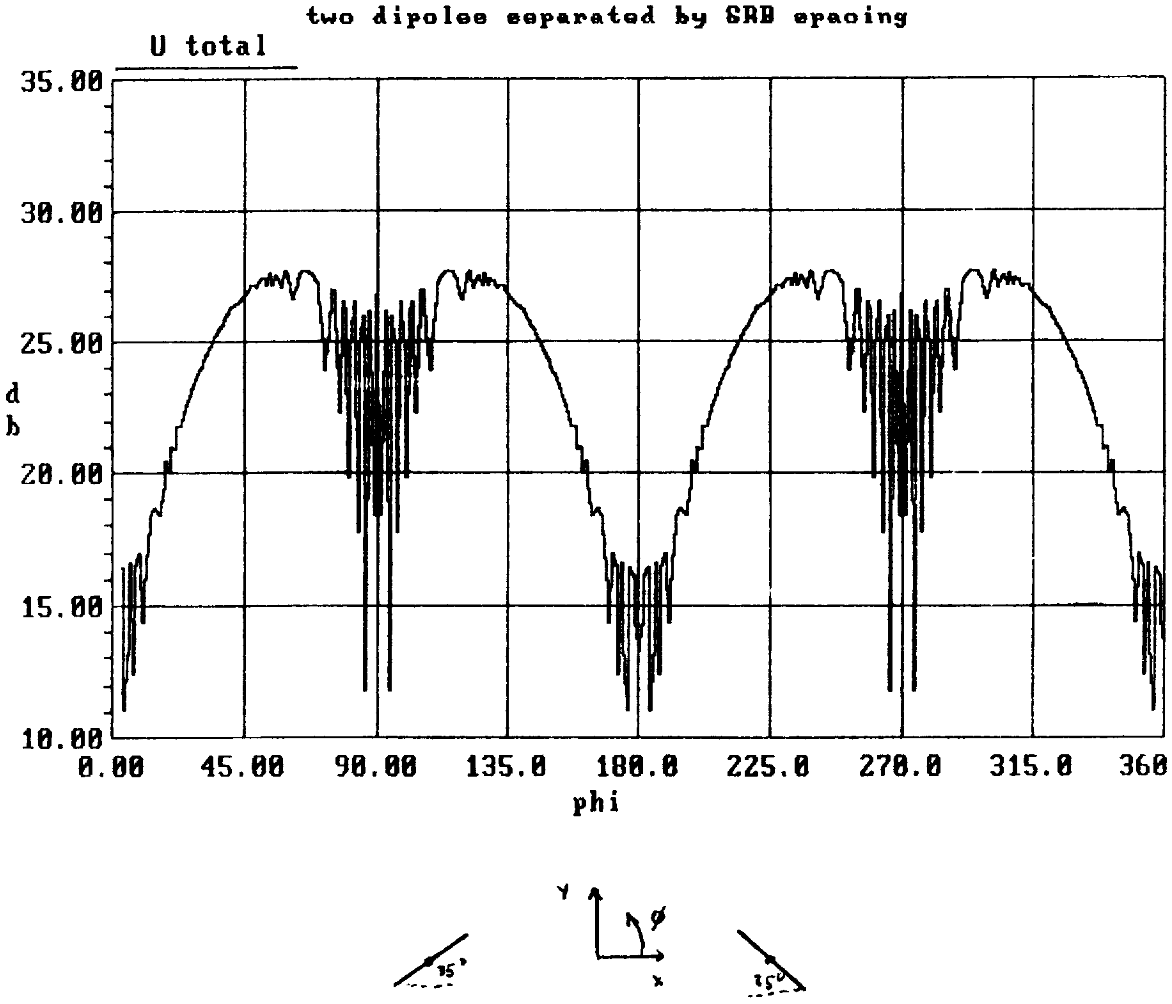


Figure 7. Pattern of two dipoles separated by the distance between the SRB's.

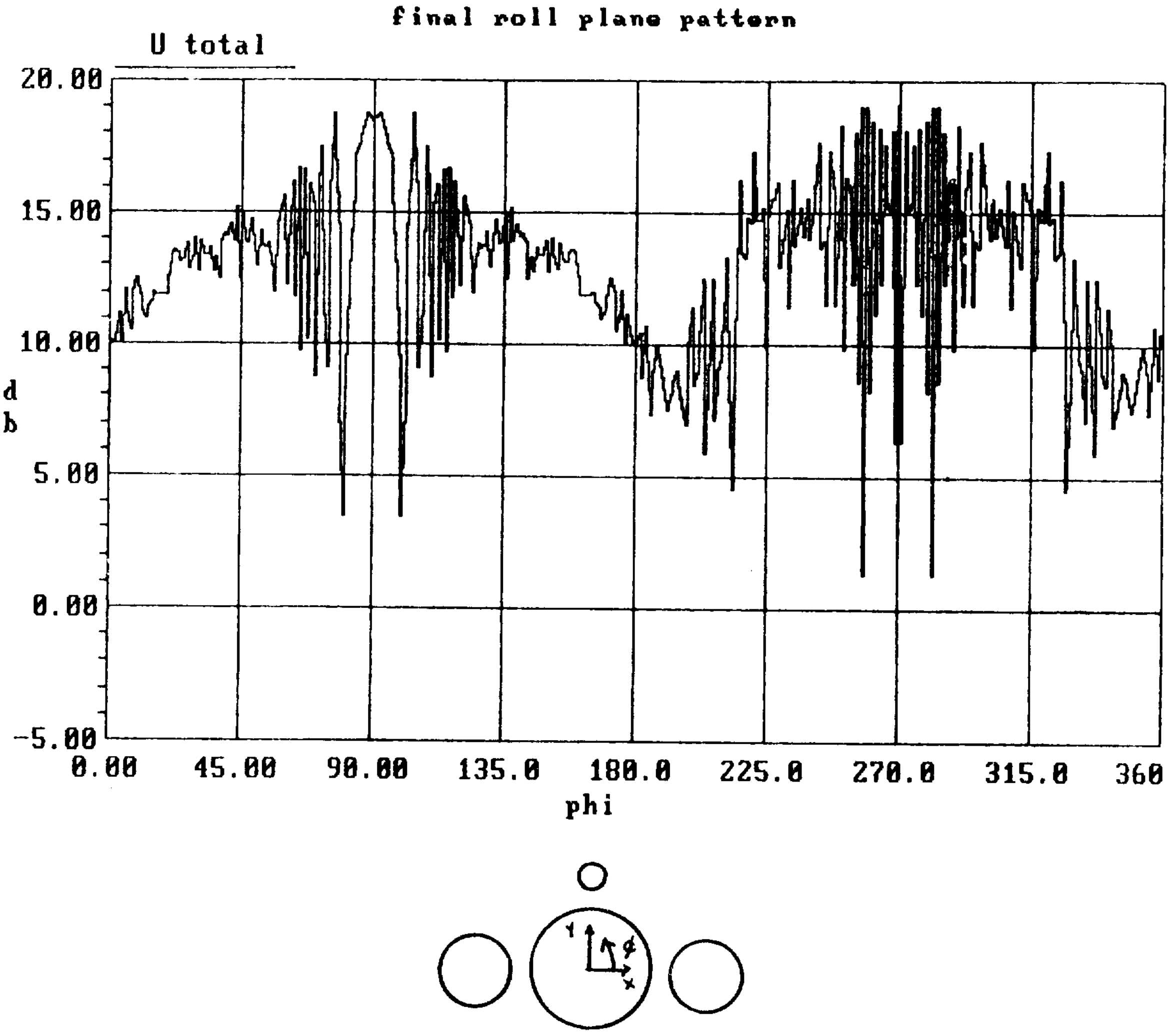


Figure 8. Final result.

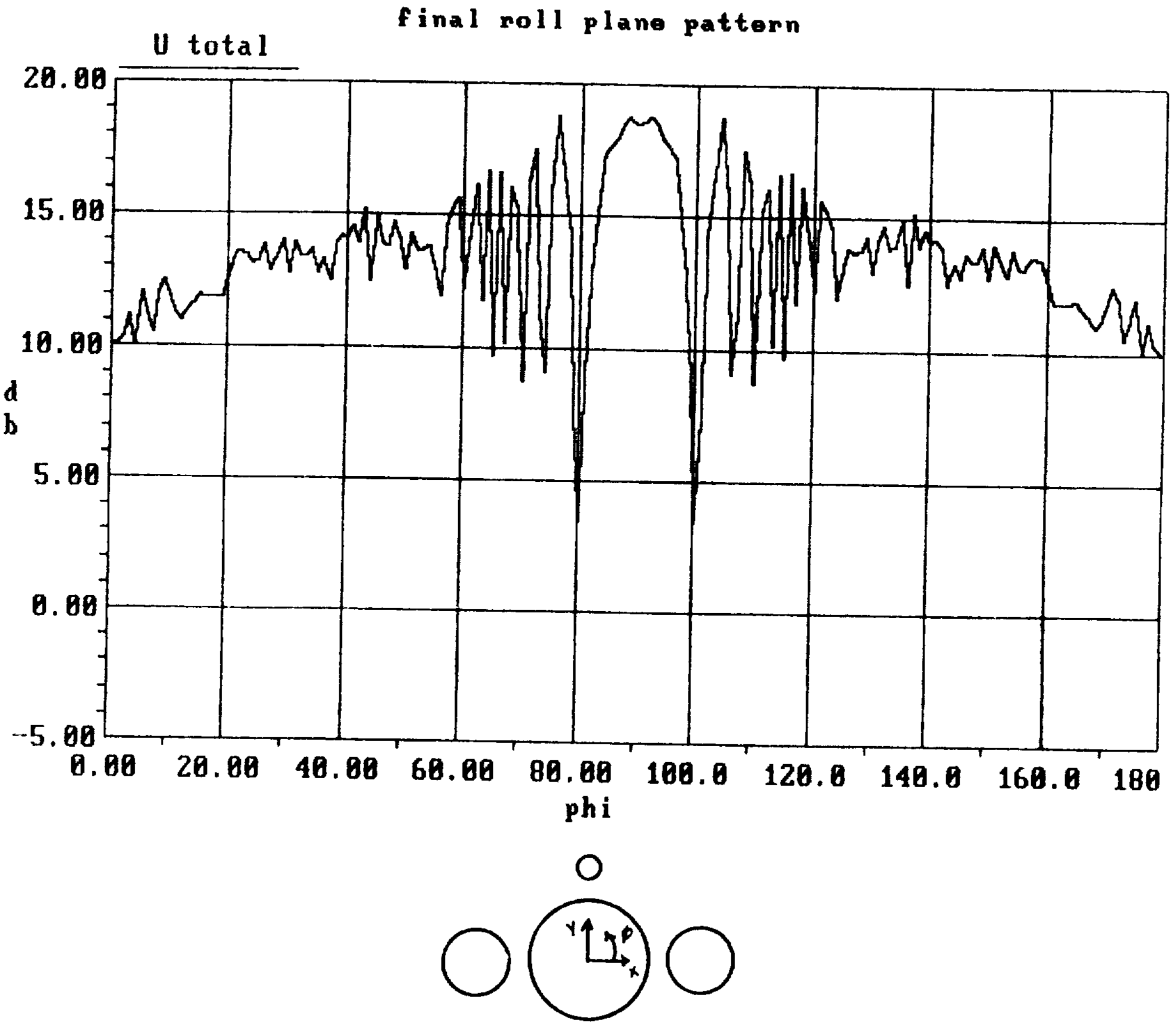


Figure 9. Final result - 0° through 180°.

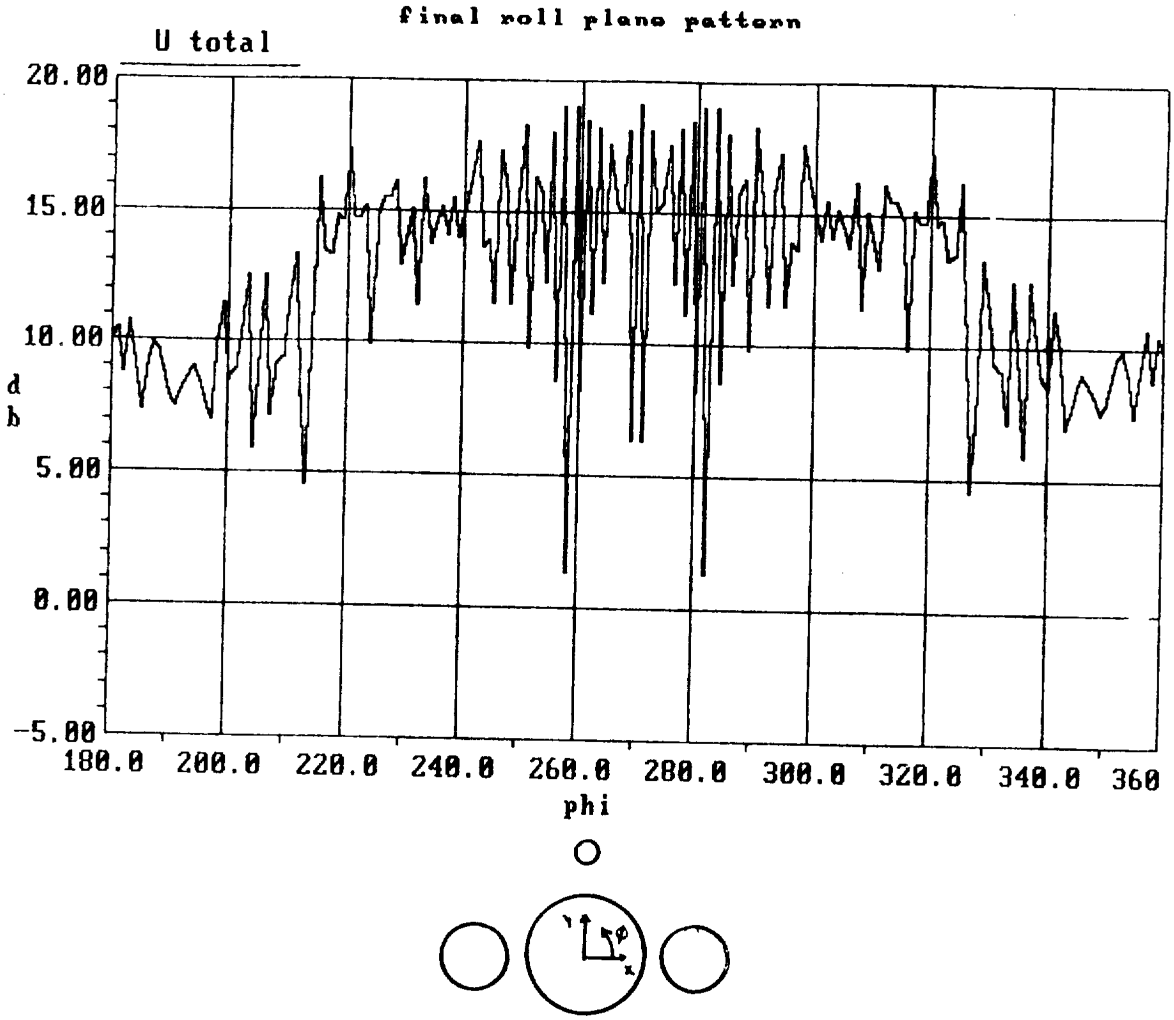


Figure 10. Final result - 180° through 360°.

CONCLUSIONS AND RECOMMENDATIONS

The roll-plane pattern of the radar transponder antennas given in Figs. 8-10 is believed to be reasonable, given the assumptions listed in the Objectives section. The absence of contributions to the roll-plane pattern due to portions of the cluster not in the roll-plane would modify it somewhat, but they are not expected to be significant.

However, if a better estimate of the roll-plane pattern is desired, it is necessary to investigate the effects of the corrugations on the external tank. This problem was examined to some degree [4], but the author stresses that the extent of his investigation was not sufficient to come to a hard conclusion. It appears that the main reason for this was the modeled corrugations were placed on a flat plate, rather than a circular cylinder. This is understandable, since the code used in the study could not handle a problem of this magnitude.

This problem of scattering from electrically large corrugations on a circular cylinder could possibly be solved by a combination of theories used in the examination of frequency selective surfaces (Floquet harmonics [9]) along with the method of moments to solve for induced currents in a periodic cell (one corrugation adjacent to its flat neighbor). This approach was successful in calculation of scattering from a flat array of conducting plates; extension to a cylindrical surface is straightforward but tedious.

Of course, the roll-plane pattern alone is not sufficient to completely describe the performance of the antenna system mounted on the shuttle cluster; a three-dimensional pattern would be necessary. This would not be an easy problem, but is clear that a geometrical optics approach is necessary, and some simplifying approximations would have to be made.

It is also recommended that steps be taken to educate the personnel at the MSFC antenna range on modern techniques to perform analyses such as the one described in this report. There are some very powerful tools available today to aid the electromagnetic engineer perform calculations that he/she could not possibly do by hand and would otherwise have to rely on crude rule-of-thumb methods. It must be stressed that purchasing codes and reading the associated manuals is not enough; proper understanding of the underlying theory is crucial. The computing power that already resides at the antenna range is sufficient; it is recommended that arrangements be made to have the author present several hands-on seminars to MSFC personnel to increase what is now a very small electromagnetic computational capability. This could be done for a small cost (several thousand dollars).

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APPENDIX
DATA INPUT TO BSC FOR FINAL MODEL

```
CM: OUSIM29
CM: ALL CYLINDERS, WITH MULTIPLE INTERACTIONS
CE: LONG CYLINDERS, ROLL PLANE
UN:
1
US:
1
FR:
5.765
CG:
6.36433,0,0
0,0,90,0
1.8293,1.8293
-500,90,500,90
CG:
-6.36433,0,0
0,0,90,0
1.8293,1.8293
-500,90,500,90
CG:
0,0,0
0,0,90,0
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-500,90,500,90
0,6.184,0
0,0,90,0
1.1725,1.1725
-500,90,500,90
SM:
12.5
24
5.3007536,-1.507604,0,.00130095,0,235
5.31141,-1.515068,0,.00130095,0,55
5.306082,-1.511335,0,.0130095,0,145
5.306082,-1.511335,.00650475,.00130095,0,235
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-5.3007536,-1.507604,0,.00130095,0,125
```

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0,1
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F,F,F,F
XQ:
EN:
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