A UHF TRANSPONDER
ANTENNA SYSTEM

By

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PREFACE

The design of antennas for space vehicles presents an interesting and challenging problem due to the severe environments encountered in flight and the space and weight restrictions. This thesis describes the development of an antenna system used on the third stages of the Transit I and Tiros I satellite launch vehicles.

The development of the antenna system was conducted at the Engineering Electronics Laboratory of the Tulsa Division of the Douglas Aircraft Company, Inc., Tulsa, Oklahoma, on contract to the National Agency for Space Administration. The author was responsible for the design and development effort from the preliminary design study to the delivery of four complete systems for installation.

Nearly all antenna design is conducted on a cycle consisting of preliminary calculations, experimental electrical measurements from models, comparison with desired results and calculation of adjustment of the model parameters to achieve more satisfactory results. The design described here is no exception. The irregular and assymmetrical configuration of the ground plane made accurate calculation of the radiating element dimensions impossible. The approach to this problem was to make measurements using an element which would exhibit approximately the proper characteristics on a flat ground plane and then analyze the results to determine what revisions were necessary due to the ground plane configuration. The data from the first measurements showed considerable deviation from the desired conditions and the final antenna configuration was quite different from the first model.

The organization of the body of the thesis is such that the progress of the development program may be traced directly from the statement of the problem to the end result. I hope that this will be of assistance to a reader interested in the methods of antenna development. Frequently the method by which a problem solution is found is more important to an observer than the solution itself.

I would like to express my appreciation to the Douglas Aircraft Co., Inc., for presenting the opportunity for me to work on this project, for financial assistance in my graduate work and for release of this material. I should like to thank Carol L. Crom, Howard H. Williams, and Johnathan Scheidt who assisted in the work described. I especially thank Dr. H. L. Jones and Dr. W. L. Hughes for their suggestions and criticisms in the preparation of this thesis.

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CHAPTER I

INTRODUCTION

The advent of the space age has produced a whole new set of technical problems and avenues for new development for the radar systems and antenna designers. Very accurate information concerning missile and satellite trajectories is required to obtain correlation between vehicle position and other data gathered from the flight. This is particularly important in the case of satellites because long term orbit prediction is desirable to preclude the necessity for frequent tracking to maintain the data link with the vehicle.

The methods for achieving better tracking include increased radar transmitter power, increased antenna gain, better receiver sensitivity, more sophisticated means of reducing the tracking data obtained, and augmentation of the target radar return. All of these means were utilized to obtain the orbit prediction data for the Transit I and Tiros I satellites. The Millstone Hill radar in Massachusetts provided all the attributes mentioned except target augmentation. This radar is an experimental set operated by MIT for radar research and has been used recently in radar mapping of the surface of the moon. Preliminary calculations showed that even the superior performance of the Millstone Hill radar was not sufficient to obtain tracking data at the ranges involved in the satellite launches.

Tracking information from the orbit injection trajectory and the first few orbit passes was required for use by computers for long term orbit prediction. This meant that the radar had to track the small third stage of the launching vehicle or the satellite itself because only the third stage would enter the orbit with the satellite. It was decided that a transponder would be used on the third stage vehicle to provide the necessary assistance to the tracking radar. The transponder would receive the ground radar signal pulse and transmit a similar pulse of fixed characteristics after a precise time delay. A single antenna would be used for both receiving and transmitting to save space and weight on the missile.

The transponder antenna system is the subject of this thesis. Although there are no new discoveries or principles advanced here, the basic antenna developed for the use described above is felt to be novel application of the gamma match antenna principle.

CHAPTER II

PROBLEM STATEMENT

The antenna system discussed in this thesis was designed to function as both the receiving and radiating element for the transponder. The signal received at the antenna is directed to the receiver section of the transponder by a duplexer and the signal from the transmitter section of the transponder is directed to the antenna through another path in the duplexer.

The electrical characteristics required of the antenna system are as follows:

1. Frequency: 440 megacycles per second center frequency with a bandwidth of 2 megacycles.
2. Impedance: The VSWR referred to 50+j0 ohms shall be less than 2:1.
3. Pattern Coverage: Omnidirectional coverage is desirable. Coverage is required at the aspect angles at which the radar views the missile during the launch phase.
4. Polarization: Circular polarization to give maximum coupling to the ground radar antenna is desired. Linear polarization will be accepted.

The mechanical characteristics required of the antenna system are as follows:

1. Weight: Total weight added to the vehicle for this antenna system shall not exceed 2.5 pounds.
2. Size: Size of the antenna system is limited by the engine, fairing, and payload configurations.
3. Strength: The antenna system should withstand normal handling loads without damage and shall withstand the flight environmental conditions listed below without impairment to operating characterisitics during flight:
    - a. Acceleration:

      Forward longitudinal axis- 16 g's
      Positive and Negative Pitch axis- 4 g's
      Positive and Negative Yaw axis- 4 g's
    - b. Vibration:

      4 to 25 cps sinusoidal, 15 minutes
      each axis- 2 g's (rms)
      25 to 700 cps- 9 g's (rms)
      700 to 2000 cps- 15 g's (rms)
      Sinusoidal vibration shall complete one sweep cycle at approximately a constant octave sweep rate.
    - c. Radial accelerations:

      13 g's for 1 minute
      9 g's for 30 minutes

The antenna system shall withstand the following environmental situations without degradation of operating characteristics:

1. Temperature: 0-160 degrees F.
2. Altitude: 0-200,000 feet

3. Humidity:

   a. Storage at 95% humidity at 120 degrees F. for 50 hours.

   b. Operation at 95% humidity at 90 degrees F. for one hour.

CHAPTER III

PROBLEM APPROACH

The choice of antenna system for a particular application must depend upon the space available, the pattern coverage required, the properties of the other antennas with which it must electrically couple and the electrical requirements of the equipment to which it is connected.

The pattern coverage requirement was the first problem considered in the design of this antenna because this factor largely determines the basic antenna type. It was desirable to be able to track the missile no matter what path it may take, which would require an omnidirectional airborne antenna. Coverage was required at the aspect angles presented to the radar site as defined by the trajectory computations. It was determined that the most important aspect angles were in the aft hemisphere from the missile for the Tiros and Transit missions. Since the missile was spin-stabilized about its longitudinal axis, no emphasis could be placed upon coverage for any particular azimuth region.

The major factor to be considered in assuring compatibility of the airborne antenna system with the ground antenna system is that of wave polarization. In this case, the ground radar antenna could have either right or left hand circular polarization at the operator's option. Maximum coupling between antennas is achieved if the airborne antenna is also circularly polarized in the proper sense at all aspect angles encountered in the flight. In practice, circularly polarized antennas are usually circular on only one axis and have varying degrees of ellipticity at other angles. Even so, a circularly polarized antenna seemed to offer the best overall solution to the problem at hand if two pitfalls in its use could be avoided. In many cases, the sense of rotation of the wave is found to be reversed when the antenna is viewed from opposite ends of the axis of circular polarization and complex ground planes may cause distortion of the wave even to the point of reversing its rotational sense in extreme instances.

Complex ground planes are very difficult to treat analytically so the type of antenna system was selected on the basis of the other criteria. The effects of the ground plane were then checked experimentally. A circularly polarized antenna with its axis of circularity coincident with the missile axis was chosen. With this type of system, linear polarization is presented broadside of the missile. As the missile is viewed from decreasing angles off the tail, the polarization will become less elliptical until circular polarization is obtained in the tail aspect. The same variation in ellipticity will be observed progressing from broadside the missile to the nose, but the sense of rotation will be reversed. When the missile antenna has the same sense of rotation off the tail as the ground antenna, some coupling may still be obtained in the forward hemisphere. This is true because an elliptically polarized wave may be represented by two circular waves of opposite rotational sense and different magnitudes. Kraus discusses this analysis on pages 477 and 478.

A turnstile with radiating elements perpendicular to the missile axis is probably the simplest antenna which will provide the characteristics described above at 440 megacycles. It was impossible to use a turnstile consisting of simple crossed dipoles with the feeds on the axis of the missile because of the presence of the engine. A close approximation of a crossed dipole turnstile was obtained by locating four monopoles at 90 degree intervals around the engine case. Opposite elements were fed in phase in space to give the effect of dipoles.

The 90 degree phase angle between dipole currents required to produce circular polarization may be obtained in several ways. One dipole may be displaced from the other along the perpendicular axis by a quarter wave length and fed in phase, or the dipoles may be in the same plane and fed 90 electrical degrees out of phase. The first method offers the advantage of eliminating the reversal of rotation sense from front to back but requires more space and, in this case, more weight than the second method. The second method was chosen for use in this system because of its lesser requirements for space and weight. These types of turnstiles and others less suitable for this application are described by Kraus on pages 424 to 428.

The only space available on the third stage vehicle for installation of the transponder and its antenna system was a conical metal device over the nose of the engine case. This was adequate for the transponder packages, but offered little space and practically no suitable ground plane for the antenna system. A four inch wide cylindrical metal skirt was riveted to the conical section to serve as a ground plane. The aft edge of this cylindrical skirt was rolled to achieve the necessary stiffness with thin metal. The weight of the skirt was included in the total weight of the system which was limited to 2.5 pounds. The four inch width of the skirt was determined to be the minimum required to provide space to mount the monopoles and meet the ground plane requirements.

The antenna elements and cabling system must be properly matched to obtain the required impedance match between the transponder and the antenna system. Since there are a limited number of standard coaxial cables available, the cable system was designed first to make the best use of these cables. Then the antenna elements were designed to match the requirements of the cable system.

CHAPTER IV

CABLING DESIGN

The choice of the basic antenna type (monoplanar turnstile made up of monopoles) provided the requirements upon which the cabling system was based. The system impedance viewed from the duplexer must be within a 2:1 voltage standing wave ratio referred to $50+j0$ ohms. Equal power distribution to the four monopole elements was required to assure a symmetrical pattern and circular polarization. Antennas on opposite sides of the missile had to be an odd multiple of 180 electrical degrees out of phase to provide antenna currents in phase in space. The pairs of monopoles had to be 90 degrees out of phase to provide the required circular polarization. It was desirable to keep the cables as short as possible and to avoid the use of additional elements such as stub tuners in order to keep the weight and power absorption losses as low as possible. An idealized cabling system may be formulated from the above criteria.

The following cable and antenna impedances were determined by proceeding from the duplexer to the radiating elements and considering the characteristics of the next components necessary to maintain the desired impedances and phase relationships at each cable junction. Reference to Figure 1 will simplify this discussion. Cable 1 must have 50 ohms impedance to match the transponder. The impedance of the two pairs of antennas must combine in parallel at antenna 1 to provide a 50 ohm input impedance; therefore the impedance of each pair at this point should be

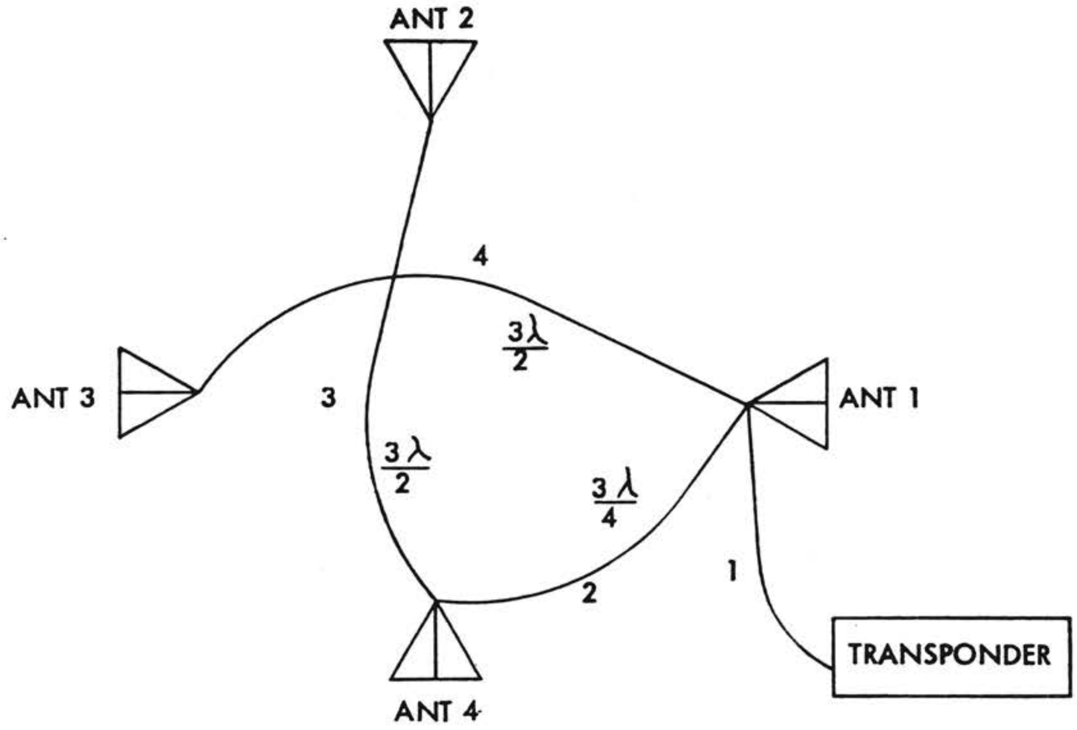


FIGURE 1 BASIC DIAGRAM OF ANTENNA SYSTEM

100+j0 ohms, which provides equal power division at this point. Cable 2 must be an odd multiple of 90 degrees in length to provide the proper phasing between antenna pairs. Its impedance must be 100 ohms to prevent transforming the impedance of the antenna 2 and 4 combination. This allows all antennas to have the same impedance. The impedance of cables 3 and 4 is not critical because a cable which is a multiple of 180 electrical degrees in length will cause no transformation. As mentioned above, these cables must be an odd multiple of a half wave in length to maintain the proper space phase of the antenna currents. The antenna impedance must be 200+j0 ohms to produce 100+j0 ohms in parallel and maintain equal power division.

The idealized cable system was used as the basis of a practical system using available coaxial cable. No 100 ohm cable was available, so 93 ohm RG-62/U was chosen for cable 2. A VSWR of 1.1:1 would then be presented to the transponder with antenna impedances of 186 ohms. Fifty ohm RG-58/U was chosen for cable 1, 3, and 4. The 3 or 4:1 mismatch on cables 3 and 4 was tolerated because the cables were short and the attenuation due to standing waves was quite low. The use of 50 ohm cable here made possible the accurate measurement of the electrical length of cables 3 and 4 and their associated connectors. This is discussed in the Appendix. The RG-58/U and RG-62/U cables were chosen from among others of the same electrical characteristics as a compromise of light weight, ease of handling, experience of the technicians who must work with the system, and quick availability of the cable and necessary connectors. Type TNC connectors were used to obtain their good reliability under vibration.

Accurate calculation of the required cable lengths was complicated by the use of cables and connectors having different velocities of propagation, variations in the velocity factors of the cables, and difficulties in accurate determination of the effective lengths of the connectors.

Details of the antenna cabling harness are shown in Figure 2. Since the ground plane skirt is 20 inches in diameter, cables 3 and 4 could be about 1.5 wave lengths long and cable 2 could be about 0.75 wave lengths long to satisfy the system requirements. One wave length at 440 megacycles per second is about 17.69 inches in RG-58/U and about 22.51 inches in RG-62/U cable. The velocity factor for the TNC connectors with teflon dielectric was assumed to be about 0.695. The mechanical length of cable 3 and 4 was calculated as follows:

$\lambda_T =$ wavelength at 440 mc in teflon

$$\lambda_T = \frac{11811}{440}(.695) = 18.67 \text{ inches}$$

$\lambda_P =$ wavelength at 440 mc in poly-ethylene

$$\lambda_P = \frac{11811}{440}(.659) = 17.69 \text{ inches}$$

$$\frac{2d}{\lambda_T} + \frac{c}{\lambda_P} + \frac{b}{\lambda_T} - \frac{a}{\lambda_T} = 1.5 \qquad (1)$$

$$c = \lambda_P \left[1.5 - \frac{2d+b-a}{\lambda_T} \right]$$

$$c = 17.69 \left[1.5 - \frac{2(.28)-0.11}{18.67} \right]$$

$$c = 26.11 \text{ inches}$$

The length of cables 3 and 4 from the end of plug dielectric at one end to the end of plug dielectric at the other end is 26.11 + 2 (.28) = 26.67 inches.

The electrical length of a cable made to this dimension was checked by methods described in the Appendix and found to be too long. This error was attributed to a slightly different propagation velocity in the cable

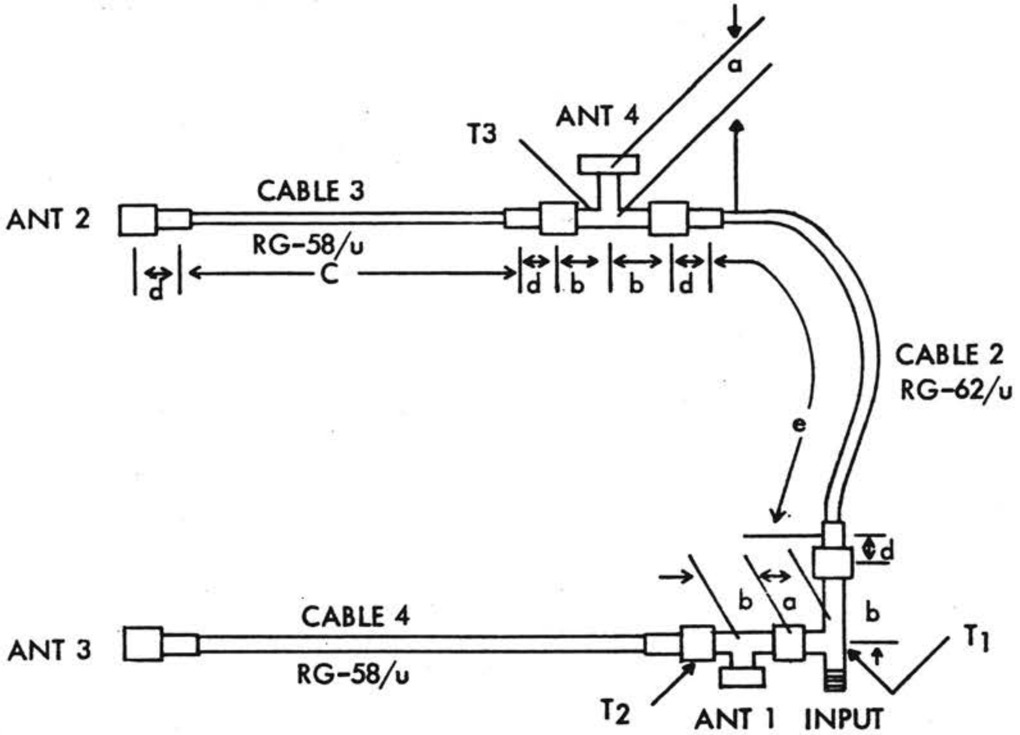


FIGURE 2 DETAIL OF ANTENNA CABLING HARNESS

than that used in the calculations. The correct length for cables 3 and 4 was found to be 26.50 inches after correction for this error.

Determination of the proper length for cable 2 would not be so straight forward if the transformer effects of the 50 ohm connectors were considered. These transformer effects could cause unequal power division between pairs of antennas if they were pronounced enough. It was felt that a compromise might be necessary between accuracy of phasing and impedance match to obtain the best possible antenna pattern. For these reasons, the approximate length of cable was calculated disregarding the transformer effects and the final length was determined by comparing antenna patterns made with cables of various lengths. The approximate length of cable 2 was calculated as follows from Figure 2:

λ_{SP} = wavelength at 440 mc in semi-solid poly-ethylene

$$\lambda_{SP} = \frac{11811}{440}(.84) = 22.51 \text{ inches}$$

$$\frac{e}{\lambda_{SP}} + \frac{2d}{\lambda_T} + \frac{2b}{\lambda_T} - \frac{a}{\lambda_T} - \frac{b}{\lambda_T} = 0.75 \qquad (2)$$

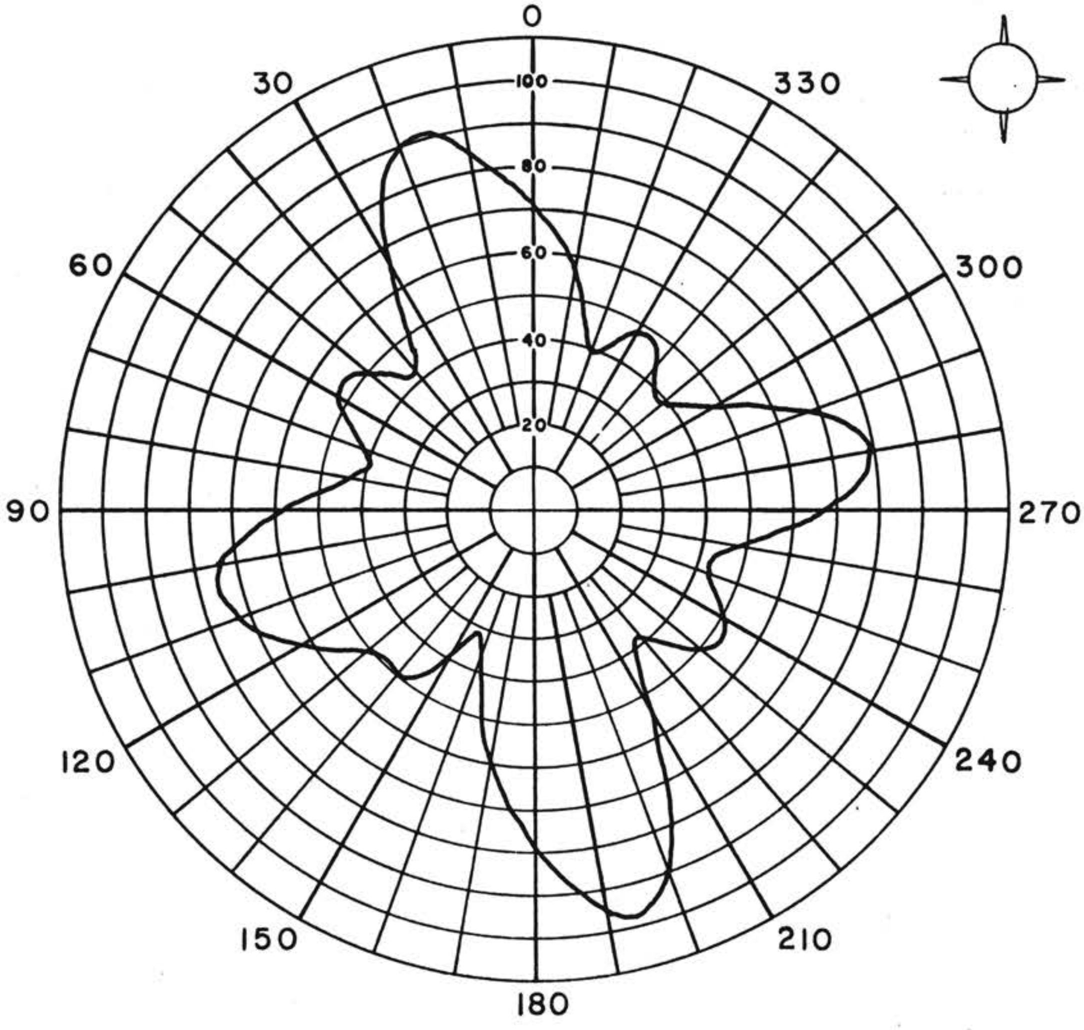
$$e = \lambda_{SP}\left[0.75 - \frac{2d+b-a}{\lambda_T}\right]$$

$$e = 22.51\left[0.75 - \frac{2(.28)-0.11}{18.67}\right]$$

$$e = 16.24 \text{ inches}$$

Calculated cable length from end of plug dielectric at one end to end of plug dielectric at other end = 16.9 inches.

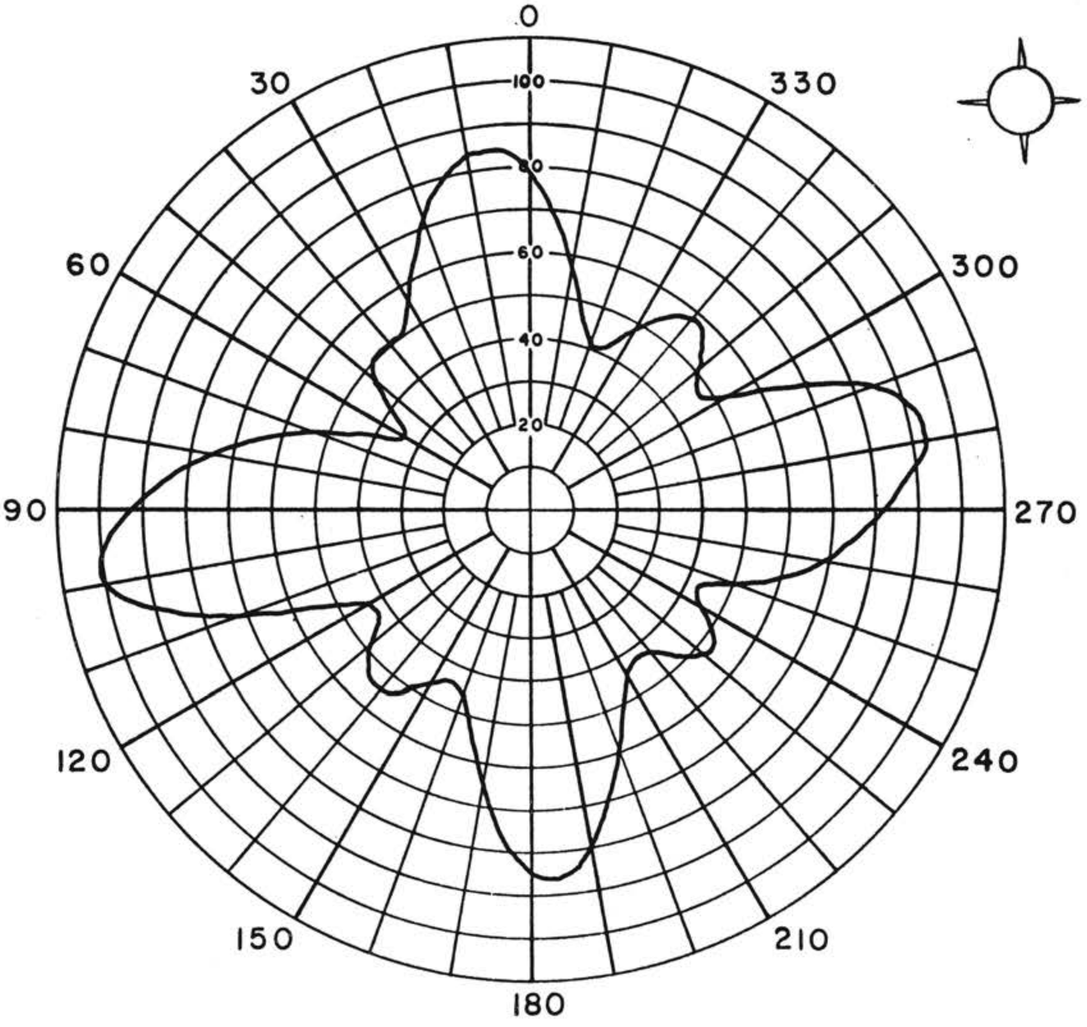
Development of cable 2 had to be done after antennas of the proper impedance were obtained so that valid antenna patterns could be made for evaluation of the effects of varying the cable length. The proper cable length was selected from the patterns in Figures 3, 4, and 5 to be 17.30



ROLL PLANE RADIATION PATTERN

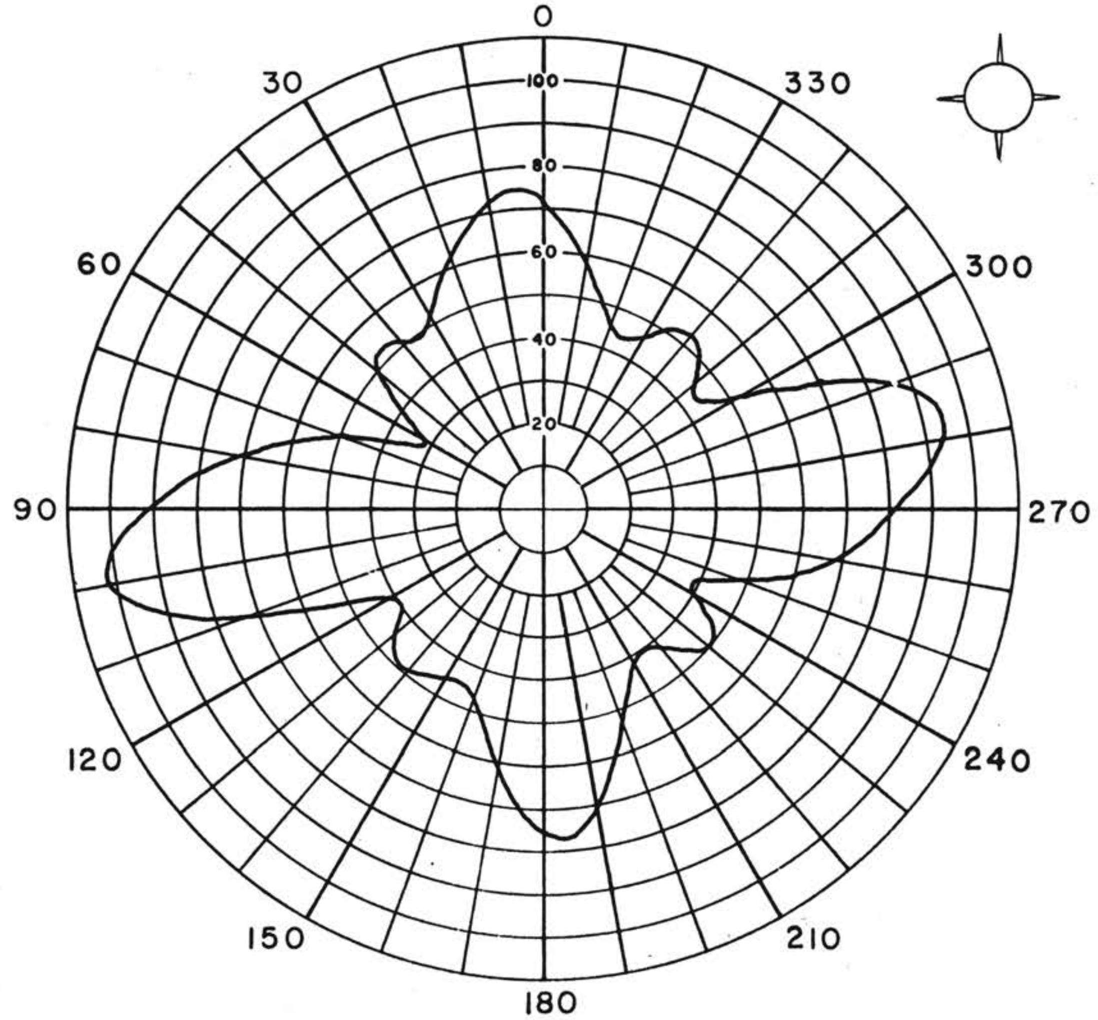
FULL SCALE MODEL AT 440 mc

FIGURE 3 ANTENNA SYSTEM RADIATION PATTERN CABLE 2 = 17.15 inches



ROLL PLANE RADIATION PATTERN FULL SCALE MODEL AT 440 mc

FIGURE 4 ANTENNA SYSTEM RADIATION PATTERN CABLE 2 = 17.30 inches



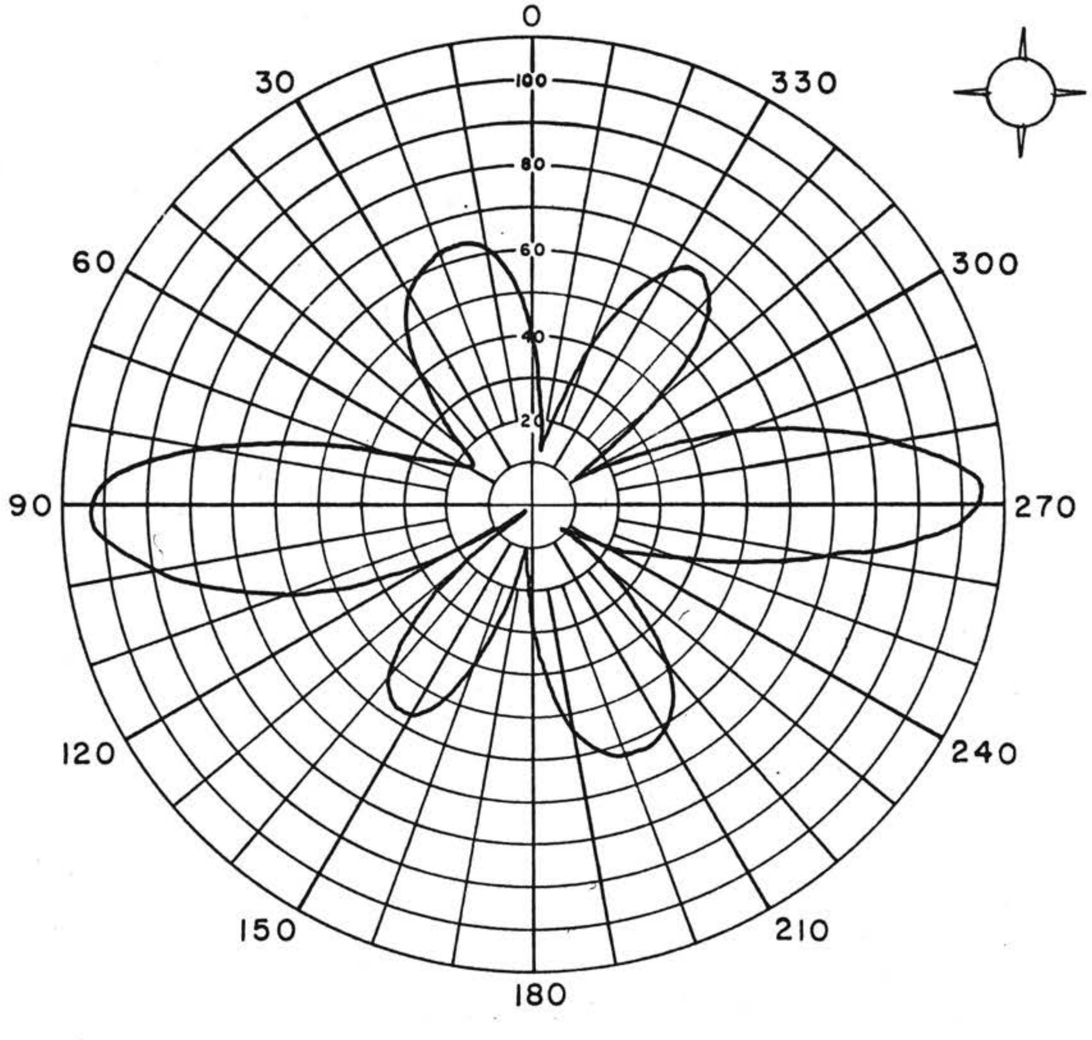
ROLL PLANE RADIATION PATTERN FULL SCALE MODEL AT 440 mc

FIGURE 5 ANTENNA SYSTEM RADIATION PATTERN CABLE 2 = 17.45 inches

inches. It is noted from these patterns that the major effect of small variations in cable length is a difference in power division between pairs of antennas. This is evident from comparison of the amplitudes of major lobes 90 degrees apart on the patterns.

The angle between adjacent major lobes does not vary appreciably between pairs of antennas. An extreme case of the effect of improper length of cable 2 is shown in Figure 6 which is a pattern made with cable 2 too long by 0.5 inches. The impedance match at T2 was so poor that one pair of antennas received practically all the power. The minor lobes are mostly due to the separation of the monopoles producing phase interference at the angle of the null between major and minor lobes.

The cable system design was predicated upon the antenna impedance being 186 ohms resistive at the junction in T2 and T3. The impedance at the antenna terminals must be inductive to achieve this match because of the section of tee between the junction and the antenna to which the tee is connected. The length of the tee between the antenna and the junction is 0.61 inches or 0.033 wavelength. Reference to a Smith chart shows an antenna impedance of 120+j85 ohms is required.



ROLL PLANE RADIATION PATTERN FULL SCALE MODEL AT 440 mc

FIGURE 6 ANTENNA SYSTEM RADIATION PATTERN CABLE 2 = 17.9 Inches

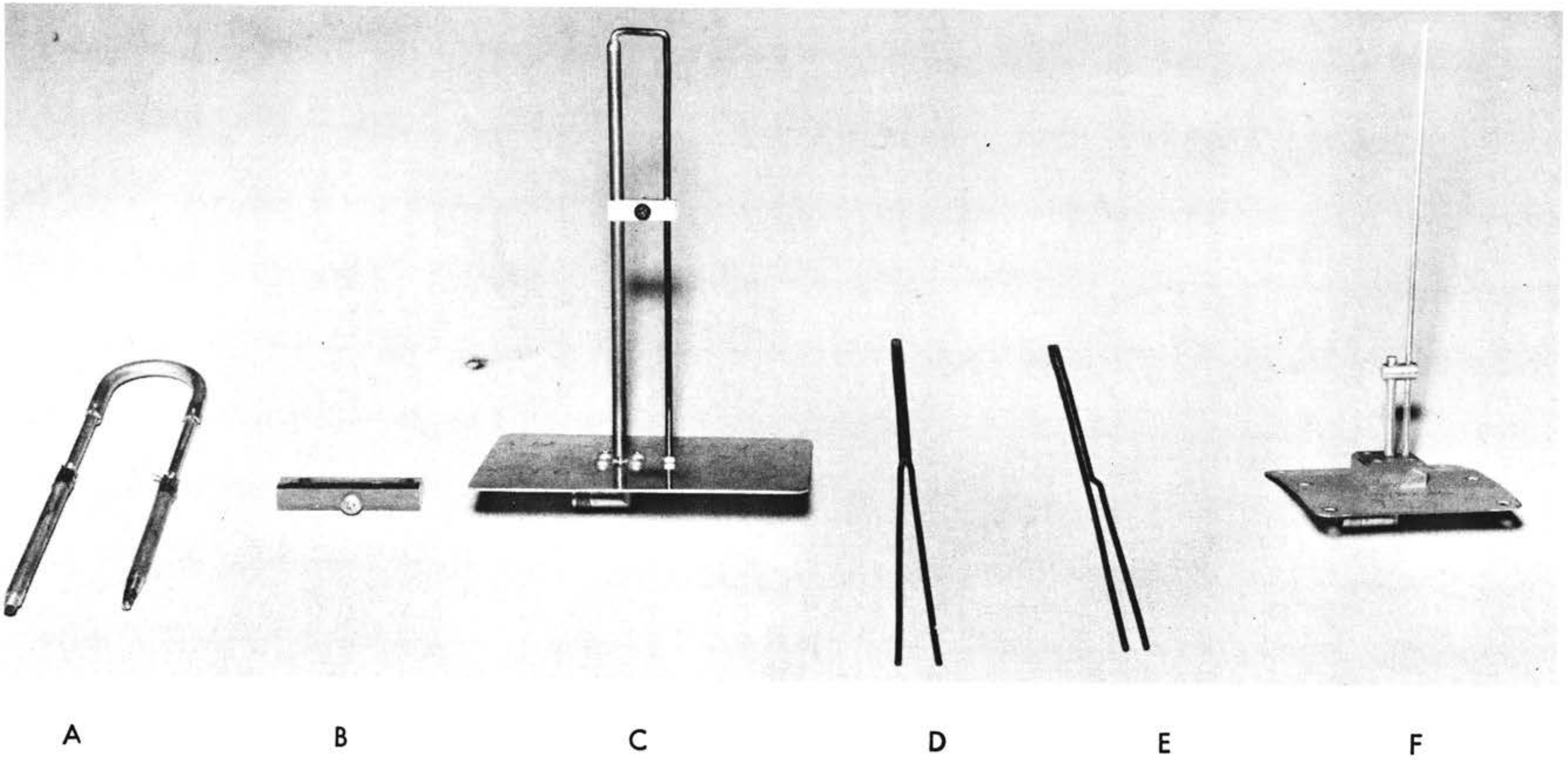
CHAPTER V

ANTENNA DESIGN

The design of the radiating element presented the most difficult design problem in the system development. This was true because the ground plane configurations about the antenna locations were dissimilar, which affected the antenna impedances differently; and because the individual antenna impedances were critical for proper operation of the system. The measurement of the antenna element characteristics was complicated by the coupling between antennas around the missile, even though no transmission line was connected between them. The latter difficulty was of nuisance value, but the dissimilar ground plane configurations required physical differences in the antenna elements to maintain the proper impedances and system operation.

The first type of antenna investigated for use in this system was the folded monopole. It appeared to be suitable for this application because its impedance is characteristically about 150 ohms and can be adjusted over quite a large range by varying the diameters, length and spacing of its elements. The cabling system design established the required antenna impedance of 120+j85 ohms. Also, the folded monopole was attractive because it can be made mechanically strong and light. The first antenna was built to allow preliminary measurements and to establish a reference for further development on the ground plane. This antenna, (A, Plate I) was constructed of 0.25 inch tubing with 1.5 inches separation

PLATE I ANTENNA INVESTIGATED DURING DEVELOPMENT PROGRAM



between the vertical elements. The length was adjustable from about 5.75 to 7 inches by telescoping sections in the elements. The impedance of this antenna, mounted in one of the antenna positions on the ground plane, was found to be highly capacitive at all lengths in the range of adjustment. For example, with an antenna length of 6.5 inches, the impedance was 98-j84 ohms at 440 mc. with no payload on the missile. With the Tiros payload installed, the impedance was 145-j145 ohms.

The current in the folded monopole can be considered to be composed of radiation current and transmission line current. This theory was developed by German and Brooks and the resulting admittance expression is treated in detail in this thesis. The transmission line current can be controlled, within the limits of the monopole, separately from the radiation current by use of a shorting element between the vertical elements of the antenna. This was seen to be useful in this case because the first antenna tested was capacitive. Shortening the transmission line should make its contribution to the total impedance more inductive. Element B, Plate I, was used as a short for element A. Experimentation with elements A and B showed that manipulation of the short would control the susceptance with little effect on the conductance and that inductive phase angles could be obtained near that required for the system under study; however, the impedance obtained at these angles was too high. Further corrections in the antenna configuration were determined by reference to the admittance expression from German and Brooks.

Derivation of Admittance Expression for Folded Monopole

The coaxial feed is replaced by three radio-frequency generators as shown in Figure 7.

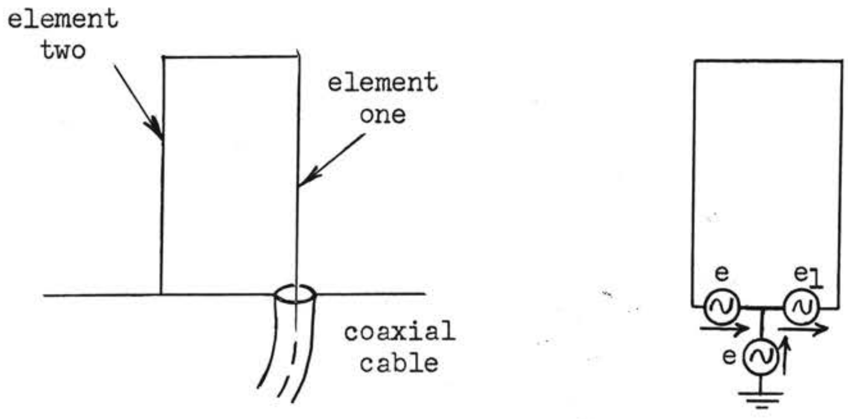
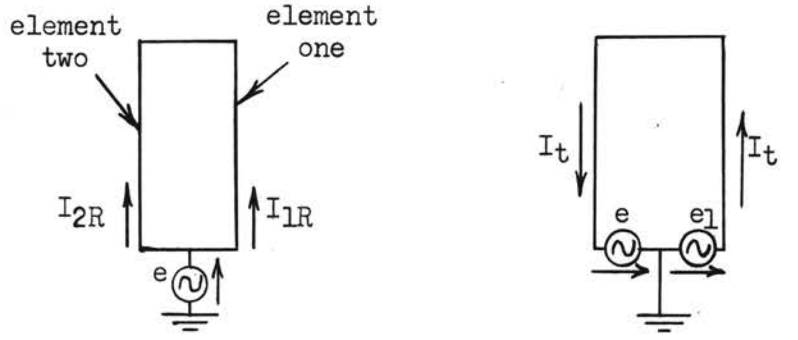


Figure 7. A Folded Monopole and Equivalent Circuit

These generators are purely imaginary and are stipulated to have zero impedance. All three generators are operated in phase with the polarities indicated in Figure 7. The total voltage (e_t) applied between ground and the driven element (element 1) is ($e+e_1$). Notice that this is also the voltage between element 2 and element 1 so that element 2 is always ground potential, as is the case in the true folded monopole situation. The generators have been placed as shown so that the transmission line and radiation components of antenna current may be considered separately and then added, by means of the superposition theorem to obtain the current entering the lower end of the driven element.

Assume that there is voltage only on the lower generator as in Figure 8 a. This generator is feeding the two elements in parallel. If Y_R is the input radiation impedance of this composite radiator, the lower generator will supply a total current of eY_R to the antenna. This current will divide inversely between element 1 and element 2 as the impedances it sees in these elements. The current in element 1 is designated I_{1R}



a. Radiation Mode b. Transmission Mode

Figure 8. Circuits for Modes of Antenna Current

and the current in element 2 is designated I_{2R}. Note that these currents are instantaneously flowing in the same direction. Therefore:

$$I_{1R} + I_{2R} = eY_R \tag{3}$$

Now assume there is no voltage in the lower generator. Under this condition, Figure 8b, the voltage $(e+e_1)$ is impressed on the shorted transmission line composed of the two elements. If the two elements are unequal in diameter, they will present unequal impedances to the two generators; therefore, the generators must be unbalanced in order to make the currents in the two conductors equal and opposite, as is the case in the actual antenna, and at the same time maintain the point between the generators at ground potential. The current in this transmission line is designated I_t with an instantaneous direction outward in one element and inward in the other. From the transmission line equation:

$$I_t = (e_1 + e)\, Y_c \coth \gamma L \tag{4}$$

where Y_c is the characteristic admittance of the transmission line, L is the distance from the shorted end, and γ is the propagation constant. The coaxial feedpoint admittance is the ratio of the current entering element 1 to the total voltage applied to the lower end of element 1.

$$Y = \frac{I_{1R} + I_T}{e + e_1} \qquad (5)$$

Defining the radiation current ratio as

$$n = \frac{I_{2R}}{I_{1R}}$$

(3) becomes

$$I_{1R} = \frac{eY_R}{1+n} \qquad (6)$$

Since the elements are in parallel, in close proximity to one another and generally under similar conditions, it is assumed that I_{1R} and I_{2R} are in phase so that n is a real number. The ratio of the currents in two parallel conductors of unequal size is found from logarithmic potential theory. If D is the distance between the centers of the elements, R_1 is the radius of element one and R_2 is the radius of element 2,

$$n = \frac{I_{2R}}{I_{1R}} = \frac{\log_{10} \frac{D}{R_1}}{\log_{10} \frac{D}{R_2}} \qquad (7)$$

Substituting (4) and (6) in (5), the feedpoint admittance is:

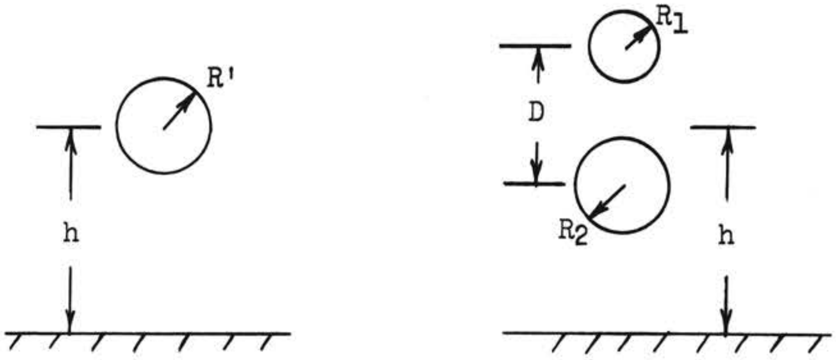
$$Y = \frac{\frac{eY_R}{1+n} + (e_1 + e)Y_c \coth \gamma L}{e + e_1}$$

$$Y = Y_R \left(\frac{1}{1+n}\right)\left(\frac{e}{e+e_1}\right) + Y_c \coth \gamma L \qquad (8)$$

The term Y_R is the admittance that a radio frequency generator would see when connected to an equivalent vertical radiator which is fed against ground. The equivalent cross section of the two elements in parallel may be found by assuming the conductors are parts of transmission lines far from the earth and having equal characteristic impedances. The impedance of the equivalent radiator is

$$Z_c' = 138 \log_{10} \frac{2h}{R'} \qquad (9)$$

Where h is the distance from the center of the equivalent line to ground and R' is the radius of the equivalent line as shown in Figure 9 a.



a. Equivalent Line b. Parallel Conductor Line

Figure 9. Radius of Equivalent Cylindrical Antenna

Remembering that, as before

$$n = \frac{I_{2R}}{I_{1R}} ,$$

the impedance of the parallel lines in Figure 9b, is

$$Z_c = \frac{138}{1+n}\left(\log_{10} \frac{2h}{R_1} + n \log_{10} \frac{2h}{D}\right)$$

Setting $Z_c' = Z_c$, as $h \rightarrow \infty$,

$$\log_{10} \frac{2h}{R'} = \frac{1}{1+n} \left[\log_{10} \frac{2h}{R_1} + \log_{10} \left(\frac{2h}{D} \right)^n \right]$$

$$\log_{10} \left(\frac{2h}{R'} \right)^{1+n} = \log_{10} \left[\frac{(2h)^{1+n}}{R_1 D^n} \right]$$

$$(R')^{1+n} = R_1 D^n$$

$$R' = (R_1 D^n)^{\frac{1}{1+n}} \qquad (10)$$

The admittance of this equivalent cylindrical radiator of radius R' fed against ground may be approximated by methods discussed by Schelkunoff and Friis or from Hallen's work.

The voltage ratio, $\frac{e}{e+e_1}$, is found by determining the position of the neutral plane between the elements of the antenna and calculating the individual impedances. The cross section of the transmission line and the equivalent circuit is shown in Figure 10.

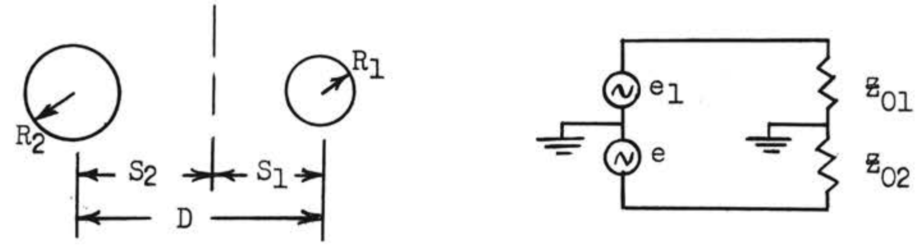


Figure 10. Cross Section of Transmission Line and Equivalent Circuit

The spacing between the conductor centers and the neutral plane was determined by German and Brooks to be

$$S_1 = \frac{D^2+(R_1{}^2-R_2{}^2)}{2D} \qquad (11)$$

$$S_2 = \frac{D^2-(R_1{}^2-R_2{}^2)}{2D} \qquad (12)$$

The characteristic impedance between the conductors and the neutral plane are, from transmission line equations,

$$Z_{01} = 60 \cosh^{-1} \frac{S_1}{R_1} , \qquad (13)$$

$$Z_{02} = 60 \cosh^{-1} \frac{S_2}{R_2} , \qquad (14)$$

The voltage division is

$$\frac{e}{e+e_1} = \frac{Z_{02}}{Z_{02}+Z_{01}} \qquad (15)$$

The second part of the admittance expression, (8) above, is the term due to the transmission line component. If the transmission line is considered lossless, a good approximation in this case, the term $Y_c \coth \gamma L$ may be replaced by $-jY_c \cot \frac{2\pi L}{\lambda}$ where λ is the wavelength on the line and L is the length to the short between the elements.

The admittance expression for a folded monopole, when the above derivations are substituted, becomes

$$Y = Y_R \left(\frac{1}{1+n}\right)\left(\frac{Z_{02}}{Z_{02}+Z_{01}}\right) - jY_c \cot \frac{2\pi L}{\lambda} \qquad (16)$$

From the equations above it can be seen that the impedance of antenna can be decreased by reducing the spacing between the elements and by making the radius of element one larger and the radius of element two smaller. Antenna C, Plate I, was constructed using these principles. Element one of this antenna was 0.25 inch tubing while element two was 0.10 inch copper wire. The spacing between the elements was 0.75 inches. The length was 6.25 inches. The required impedance could be obtained at all four antenna locations with antenna C by moving the short and bending the elements to obtain different spacings. These variations were necessary because of the symmetry of the ground plane which affected the impedance at each antenna location differently.

A study of the mechanical properties of Antenna C and the manufacturing processes required to build it revealed some shortcomings for the application at band. It was noted that element one, the feed element was the heavier of the two and yet had the weakest attachment to the bracket. A major portion of the support for element one had to come from element two which was smaller and therefore less rigid. It was felt that a lighter, stronger arrangement could be made which would exhibit the same electrical properties.

It was noted that there is no need for two conductors above the short on the folded monopole. When the portion of the feed element above the short is removed, the antenna takes the form of half a gamma match dipole mounted above a ground plane.

Gamma Match Element Development

Antennas D and E were built and their impedances were measured on the full scale missile mock-up. Antenna D and E exhibited the proper impedance after some bending of the lower elements. The impedance was found to be very sensitive to the spacing between the elements due to their close proximity. This characteristic made these elements unsatisfactory due to the difficulty in maintaining the necessary tolerances during construction of the several sets of antennas required and due to the possible adverse effects on the system performance if the antenna impedance should vary due to the distortion from the severe acceleration and vibration to which the system would be subjected.

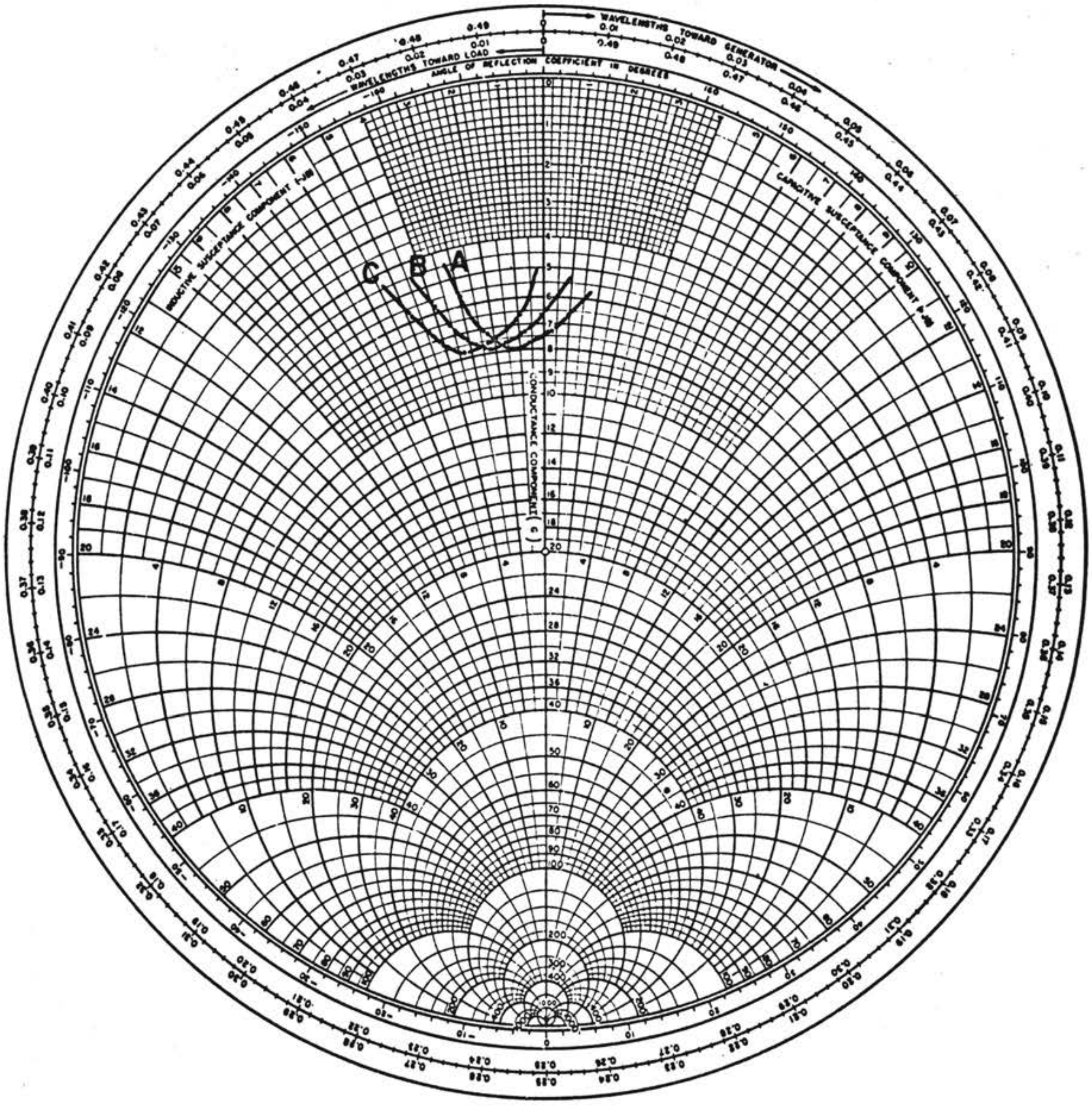
The final configuration, Antenna F in Plate I, was developed to provide good mechanical strength and for ease in producing the antennas of slightly different dimensions required for the different locations around the ground plane. As mentioned previously, the ground plane configurations were not identical for any two of the antenna locations so that slightly different antenna dimensions were required for each antenna location to obtain the necessary impedance. Adequate adjustment was available by varying the length of the long element and the location of the shorting bar between the elements. This allowed use of the same stock parts in all the antennas with the different configurations being obtained during the assembly work.

It was noted that the admittance expression for the folded monopole, equation 16, seemed suitable for the gamma match stub if the length, L, in the transmission line term is taken to be the distance from the ground plane to the short between the two elements rather than the total length of the antenna. It was determined by experiment that the antenna exhibits the proper variations in impedance as the parameters are varied. Figure 11 is an admittance chart with curves to show admittance variations with changes in the antenna and the shorting bar position.

The difficulties of applying the admittance equation to the gamma match antenna for determination of an admittance number lie in left term of the expression. The ratio, n, of the radiation currents in the two antenna elements will probably be affected somewhat by the asymmetry of the current paths where feed element is shorted to the other element. This effect is probably minor, however, to the error introduced when computation of the admittance, Y_R of the equivalent cylindrical radiator is attempted.

The major difficulty in calculating Y_R arises from the approximations required to compute an equivalent radius for the entire length of the gamma match antenna. Schelkunoff and Friis, and Hallen provide theoretical

ADMITTANCE COORDINATES—20-MILLIMHO CHARACTERISTIC ADMITTANCE



CURVE A L = 2.25 inches CURVE B L = 2.0 inches CURVE C L = 1.875 inches

ANTENNA LENGTH IS INCREASING FROM CURVE A TO CURVE C.

FIGURE 11 GAMMA MATCH STUB ADMITTANCE FOR VARIED ANTENNA LENGTH WITH CONSTANT TRANSMISSION LINE SECTION LENGTH, L.

equations and experimental tables, respectively, which have been found to yield good approximations of antenna admittance providing a good estimate of the radius and length of the equivalent cylindrical antenna is available. The radius R' obtained from equation (10) above applies only to the region below the short between the elements. The model existing after substitution of a cylinder of R' radius for the lower region has a cylinder of the same diameter as the fed element protruding from the top of the lower cylinder of radius R'. A single equivalent cylinder must be determined for this model.

Schelkunoff and Friis provide an equation for the approximate equivalent radius of a cylindrical element with varying cross section (page 426). If $r(Z)$ is the radius of the antenna at distance Z from the base, the radius, a, of the equivalent cylinder is found from

$$\log a = \frac{1}{L}\int_0^L \log r\,(Z)\,d\,Z \qquad (17)$$

where L is the antenna length.

Trial calculations of the gamma match antenna admittance were made using the admittance expression for the folded monopole. The radius of the equivalent cylinder was determined from equations (10) and (17) as described above. The admittance of the equivalent cylinder was calculated from equations developed by Schelkunoff and Friis, page 415 and 416. The equations were developed for dipoles and result in twice the impedance of the stub which is desired.

$$\frac{2}{Y_R} = Z_i = -jK\cot BL + \frac{R+jX}{\sin^2 BL}$$

where:

$$K = 120\left(\log\frac{\lambda}{2\pi a} + 0.116 + BL\right)$$

$$R = 60\ \mathrm{Cin}\ 2BL + 30(\mathrm{Si}4BL-2\mathrm{Si}2BL)\ \sin 2BL + 30(2\mathrm{Cin}2BL-\mathrm{Cin}4BL)\ \cos 2BL$$

$$X = 60\ \mathrm{Si}\ 2BL + 30(2\mathrm{Si}2BL-\mathrm{Si}4BL)\ \cos 2BL + 30(2\mathrm{Cin}2BL-\mathrm{Cin}4BL-2\ \mathrm{Cin}BL + 2\ \log 2)\sin 2BL$$

B = phase constant

The final result of the calculations for 440 mcs, was an admittance of 0.00599 mhos at -81 degrees. The measured admittance of this antenna on a flat ground plane was 0.0091 mhos at -35 degrees. The correlation between the calculated and measured data was not good enough to be particularly useful in design even though the admittances fall in the same sector of a Smith Chart. The errors involved in the calculations described combined to yield a fairly inaccurate result. The inadequacy of the theoretical calculations for prediction of the admittance of the gamma match stub does not reduce the value of the basic admittance equation (16) in guiding the modification of an experimental antenna to achieve a desired impedance.

Results of Development Program

The development effort described above yielded a set of four antennas with the required impedance of 120+j85 ohms for the four antenna locations. When the cabling was connected as in Figure 2, the resulting system exhibited a VSWR of 1.2:1 which is well within the required 2:1 ratio. The antenna was tested in the acceleration and vibration environments listed in Chapter II. No failures were noted during or after the tests.

The system performed satisfactorily during both the Transit I and Tiros I satellite launch attempts. The third stage of the Transit vehicle failed to fire so that the satellite did not orbit. The tracking information obtained allowed early verification of the failure. The Tiros satellite attained a near perfect orbit. The third stage launch vehicle was tracked from horizon to horizon during the launch and for three successive orbits thereafter. The transponder and antenna system functioned at least as well as expected and tracking was discontinued when sufficient data was obtained.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The monoplanar turnstile was found to be most suitable for the application at hand. The turnstile was constructed of four monopoles spaced at 90 degree intervals around a cylindrical ground plane. Proper current phasing was achieved by the interconnecting cable harness constructed from standard cable and connector components.

The radiating element was evolved from a folded monopole to the final gamma match quarter wave stub configuration. The gamma match stub was particularly valuable in this application because its impedance may be easily adjusted by varying the lengths of the feed element and the fed element. This quality was important because the ground plane configuration affected each antenna differently so each antenna had to be adjusted separately.

Design of the radiating element was aided by use of the folded monopole admittance equation developed by German and Brooks. This equation was found to describe variations in the admittance of the gamma match stub due to variations in the element dimensions.

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APPENDIX

MEASUREMENT TECHNIQUES

The cabling between opposing antennas in the turnstile was measured by connecting the test equipment as shown in Figure 12. Since the currents in the opposite antennas were to be in phase in space, the currents at the antenna inputs had to be in phase opposition or 180 degrees out of phase. This was checked by tuning the signal generator to obtain a null on the VTVM and comparing this frequency with the desired 440 megacycles.

Antenna impedance measurements were made with the equipment connected as shown in Figure 13. All data were corrected for the length and attenuation of the cable from the bridge to the antenna. The frequency meter was used to check the oscillator frequency when any change was made in the system to detect any frequency shift due to loading. All final measurements and antenna tuning were performed on the 30 foot wood impedance tower using actual missile interstage sections and third stage engine with full scale payload mock-ups. Plate II shows one such setup with the Tiros payload model.

Full scale system pattern performance was recorded for the major axis roll plane only since the missile and payload were too large to be handled by the pattern range fixture in any other plane. System pattern performance at other viewing angles was recorded using model techniques. The theory of antenna modeling techniques for pattern measurements is discussed fully by Crom. One third scale models of the third stage engine,

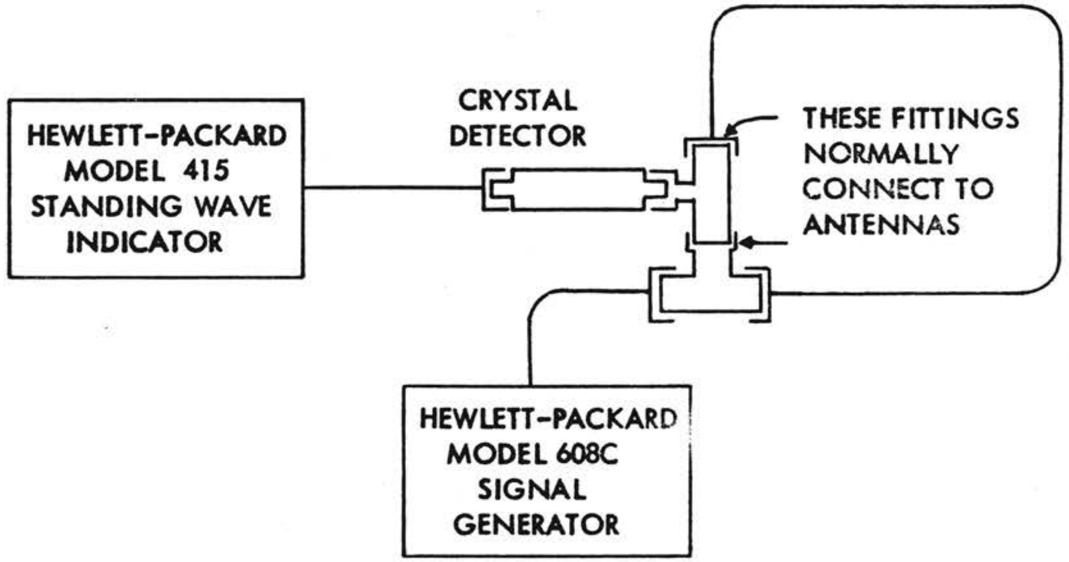


FIGURE 12 TEST SCHEMATIC FOR DETERMINING ELECTRICAL LENGTH OF CABLES 3 AND 4.

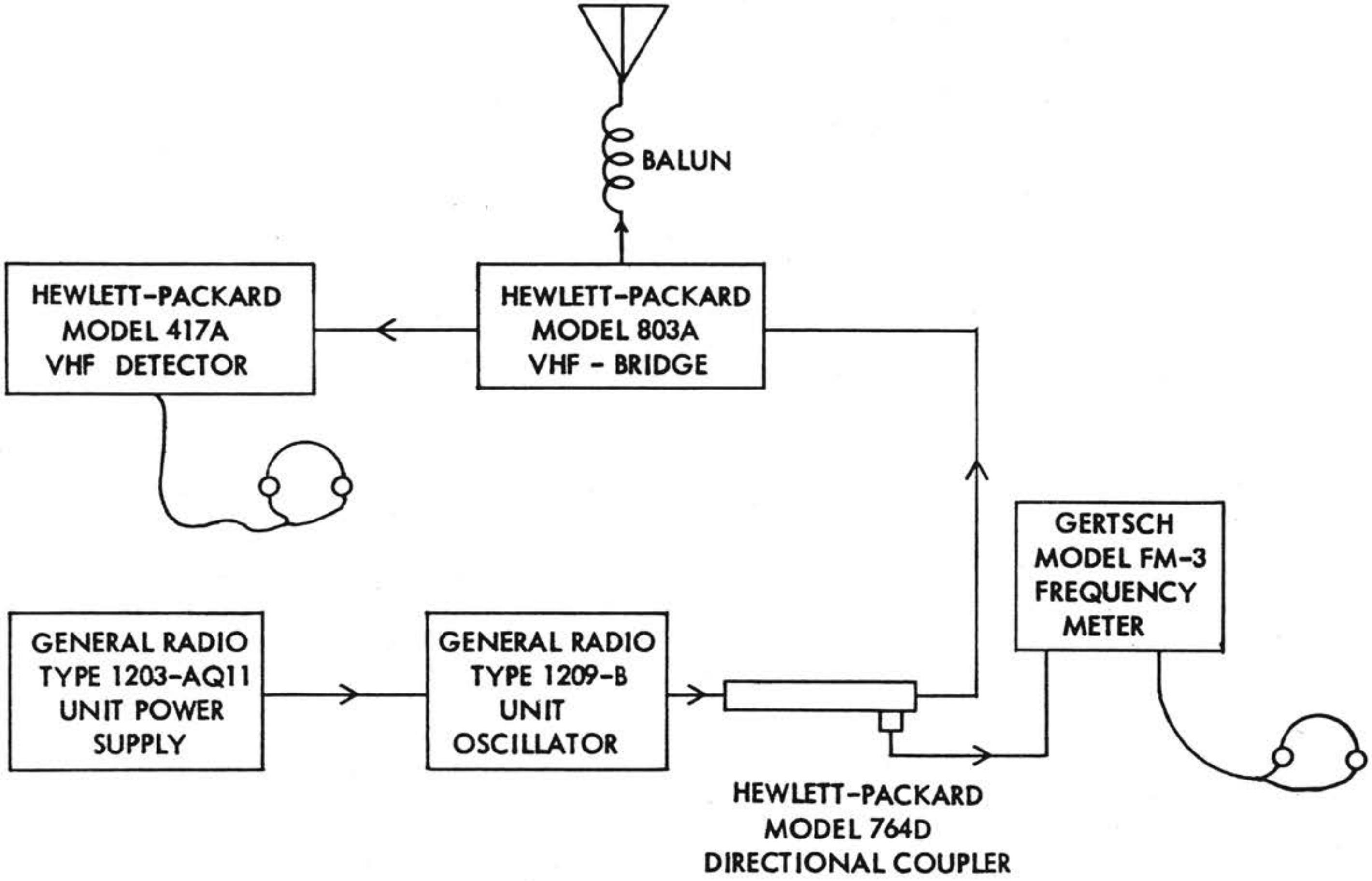
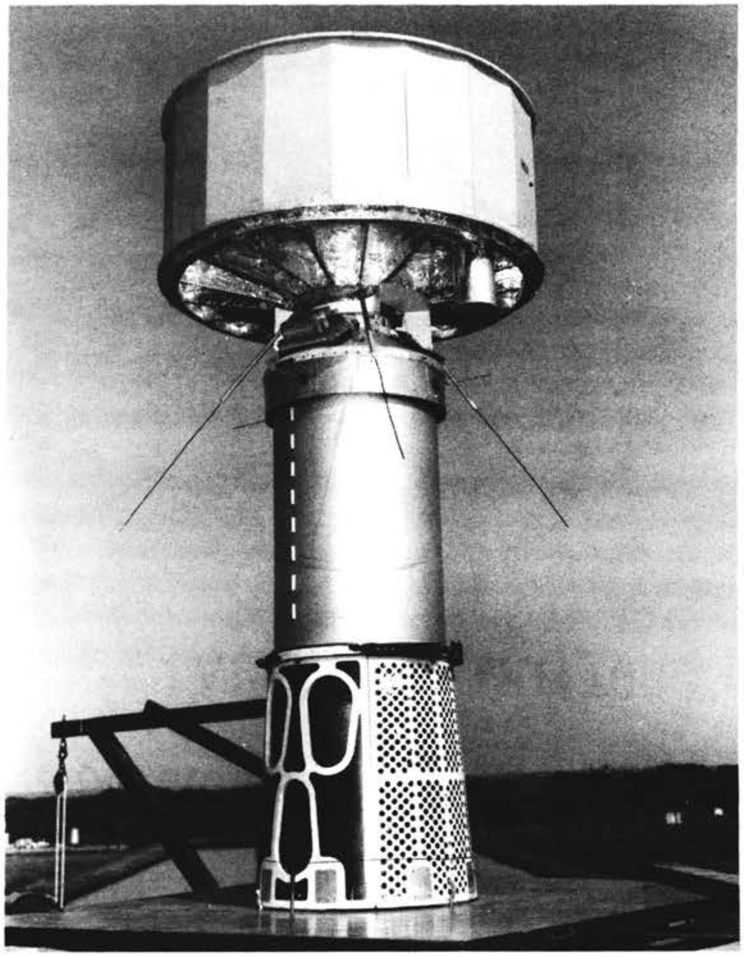


FIGURE 13 TEST EQUIPMENT DIAGRAM FOR ANTENNA IMPEDANCE MEASUREMENTS

PLATE II FULL SCALE THIRD STAGE MODEL WITH TIROS PAYLOAD



payloads and interstage section were employed for complete pattern performance determination including pattern gain and polarization plots to verify the system adequacy for the predicted trajectories of the missile. The small size of the model made accurate scaling of the antennas and cabling impossible. The model antennas were wire stubs fed through an arrangement of tuners and cables to insure proper phasing and power division. The feed arrangement is diagrammed in Figure 14. Plate III shows the model Transit payload and model third stage with Tiros payload installed. The general arrangement of components for pattern recording is shown in Figure 15. The theory and techniques of models and antenna pattern measurements are described by Crom and by Kraus, pages 444 to 486.

CABLE 2 IS $\frac{\lambda}{4}$ LONGER THAN CABLE 1.

CABLES 3 AND 4 AND CABLES 5 AND 6 ARE EQUAL LENGTHS.

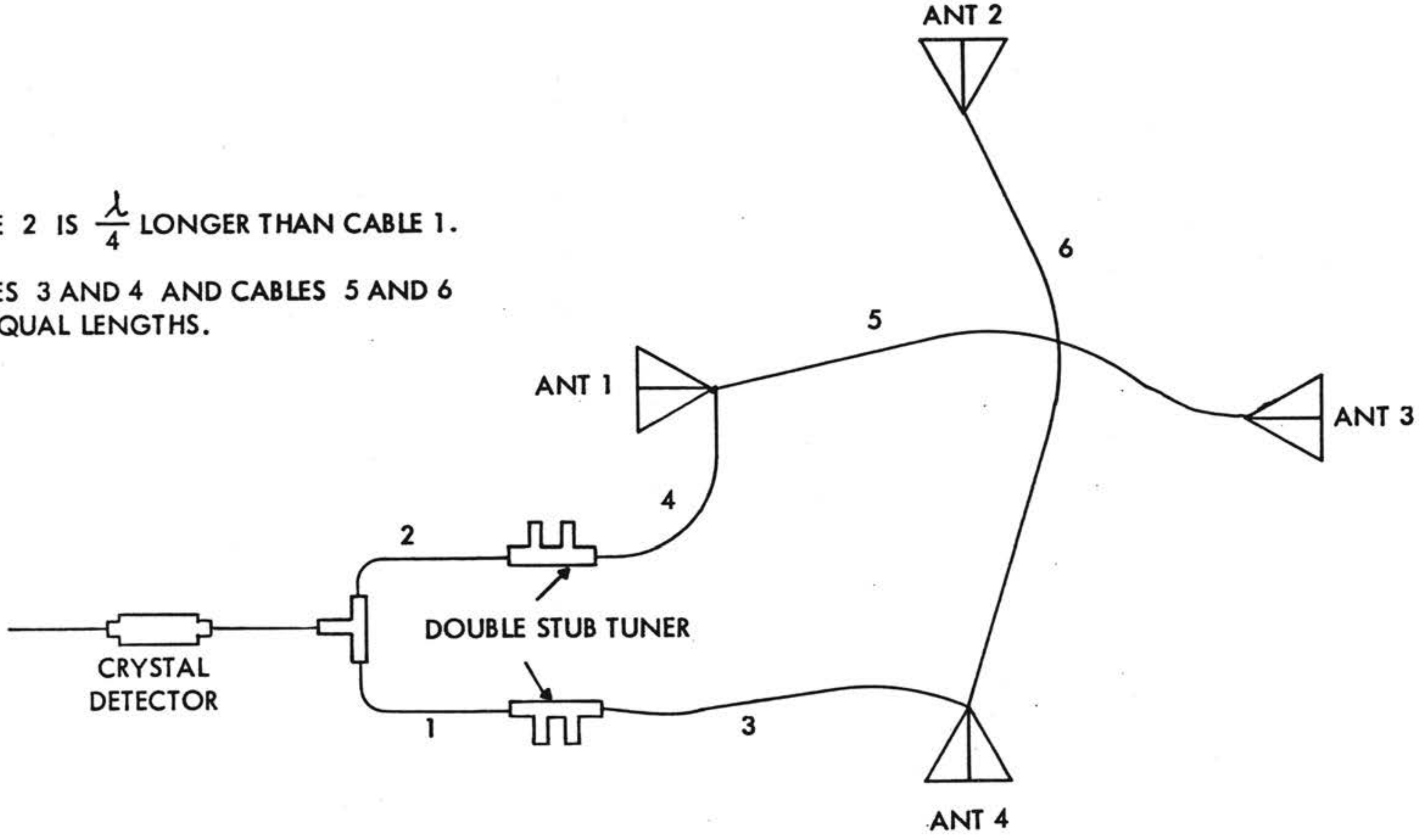
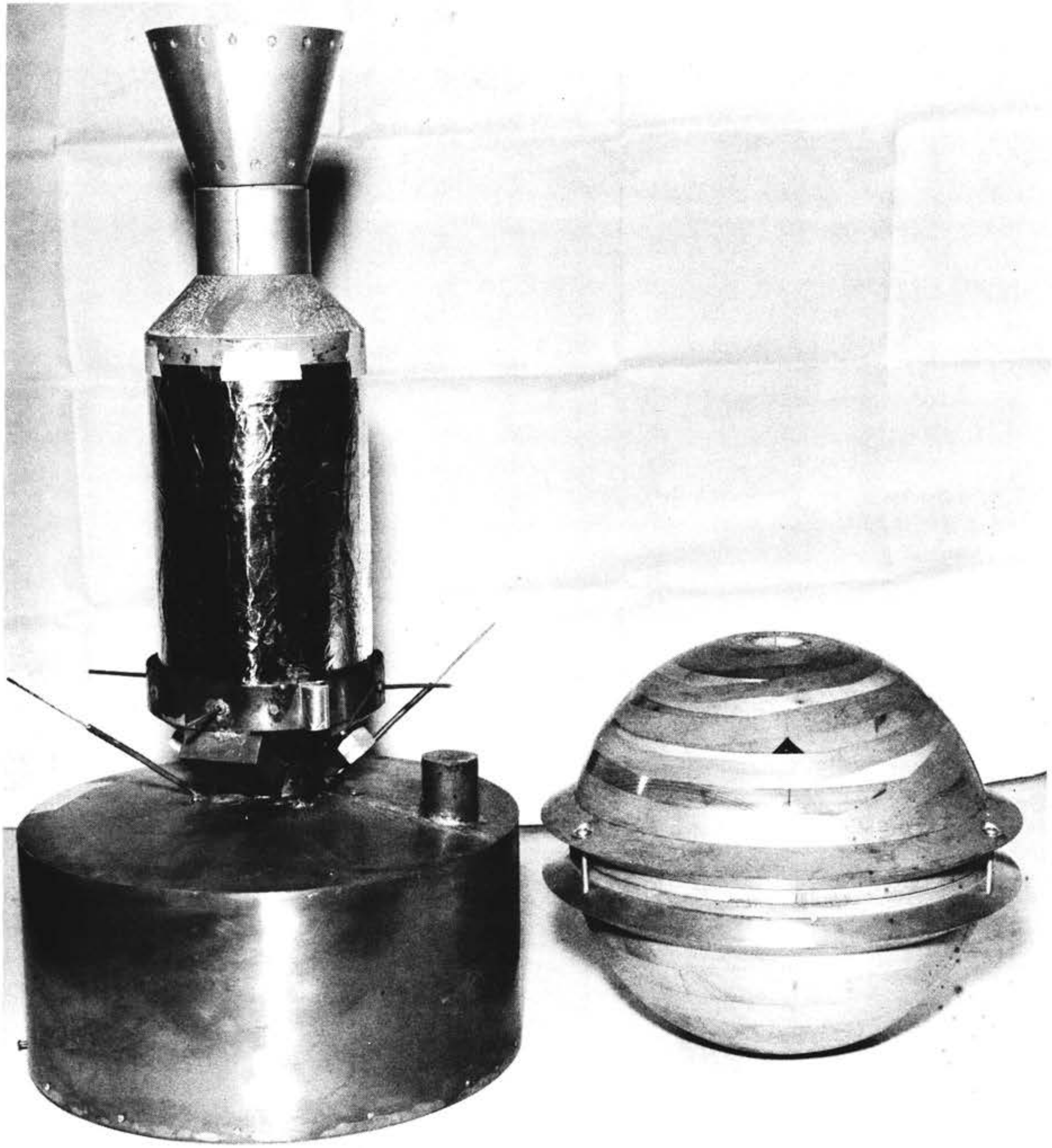


FIGURE 14 ANTENNA CABLING FOR MISSILE SCALE MODEL FOR PATTERN MEASUREMENTS

PLATE III ONE-THIRD SCALE MODEL FOR PATTERN MEASUREMENTS



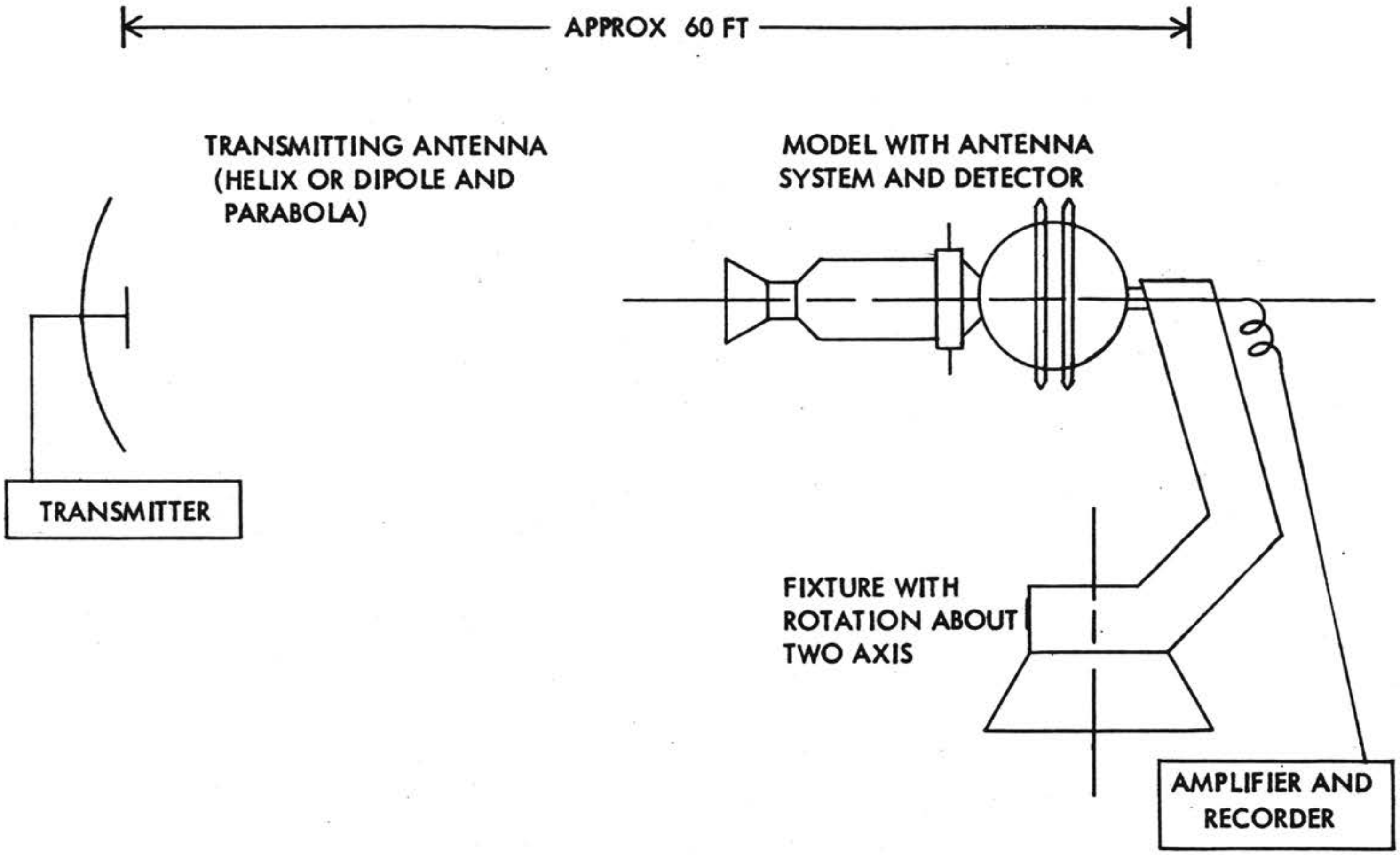


FIGURE 15 BASIC PATTERN RANGE CONFIGURATION

VITA

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