NRL Report 6907

Satellite Turnstile Antennas

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August 6, 1969

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Washington, D.C.

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ABSTRACT

The construction of an rf anechoic chamber at NRL presented an opportunity to study, in detail, satellite turnstile antennas. This study was conducted in three phases: research, prototype development and testing, and flight model satellite tests. As a result of this program it was found that the satellite size and shape and the rf harness had a profound effect on the pattern. Tests on the flight model satellites confirmed observations made during the research and development phase.

PROBLEM STATUS

This is an interim report; work is continuing on the problem.

AUTHORIZATION

NRL Problems A01-17, A01-20, and R04-16
Project A37-538-002/652-1/F019-01-01

Manuscript submitted March 10, 1969.

SATELLITE TURNSTILE ANTENNAS

INTRODUCTION

The turnstile antenna is a useful antenna for satellite applications. It consists, basically, of two dipoles oriented orthogonal to each other and fed in phase quadrature.

The construction of an rf anechoic chamber at NRL presented an opportunity to study this antenna under a closely controlled, simulated outer-space environment. The study was conducted in three phases: antenna research, satellite mockup test and development, and flight model satellite tests. In the research and development phase, basic antenna models were constructed, and various parameters were varied to determine their effect. In the next phase, satellite mockups were constructed to verify theory and to try to optimize the design. Finally, the flight model satellite was tested, as a final check, just before launch. Two satellites are discussed as example of this process. They are Solar Explorer B (Explorer 37) and Timation I, both designed and constructed by NRL.

HISTORY

The turnstile antenna, although developed long ago as an omnidirectional antenna for vhf broadcast use, has proven to be one of the most useful antennas for spacecraft use. It was first reported in 1936 as a good antenna for omnidirectional horizontal coverage, and by stacking several turnstiles to reduce the power in the vertical direction, a gain could be realized. This early paper describes the basic properties and characteristics of a turnstile antenna as well as some practical examples. Present-day FM and television broadcast stations often use stacked turnstile arrays for their transmitting antennas. With the advent of Sputnik on October 4, 1957, and Explorer I on January 31, 1958, a new application presented itself for the turnstile antenna. These and other small satellites require omnidirectional coverage, which the trunstile antenna provides in its relatively simple configuration.

THEORY

The turnstile antenna consists of two dipoles oriented orthogonal to each other and fed in phase quadrature. An alternate form is four quarter-wave stubs in turnstile form, which are fed by a network with each stub fed 90 degrees in advance with respect to the one next to it. Thus, if the first stub is the reference, the second will be 90 degrees advanced from the reference, the third will be 180 degrees advanced from the reference, and the fourth will be 270 degrees advanced from the reference. This is the usual form of satellite turnstile antennas.

Considering the dipole form, the pattern produced by an infinitesimal dipole in the plane of the trunstile is that of a rotating dipole pattern, rotating at a rate of ω, where ω is the frequency of the signal. The field of the turnstile can be described mathematically as the sum of the driven dipoles:

$$E = \sin \phi \cos \omega t + \cos \phi \sin \omega t = \sin (\phi + \omega t),$$

where ϕ is the angle in the plane of the turnstile. In the axial direction, the field has a constant magnitude as stated by

$$E = \cos^2 \omega t + \sin^2 \omega t = 1.$$

For half-wave dipoles, the dipole pattern is slightly sharper, and circularity is off by ±5% or approximately 1 dB. The formula for the half-wave dipole is

$$E = \frac{\cos (90° \cos \phi) \cos \omega t}{\sin \phi} = \frac{\cos (90° \sin \phi) \sin \omega t}{\cos \phi}$$

Since the pattern is that of a rotating dipole, the polarization would be horizontal in the plane of the turnstile and circular in the axial direction. Going from the axial direction to the normal direction, the polarization will be elliptical.

THE ANECHOIC CHAMBER

The application of this type of antenna to artificial earth satellites has been studied in the NRL rf anechoic chamber for the past 2 years. Experiments have been run on many satellite models and antenna configurations. When a satellite is proposed, a sheet metal prototype is built and tested. The flight model is also tested after it is completely assembled, just prior to launch. In addition, research and development studies are conducted to provide the necessary background to design better satellite antennas. All of this work has been done in the vhf satellite frequency band of 136 to 138 MHz.

The anechoic chamber is a tapered chamber 120 ft long, 32 ft high, and 32 ft wide (Fig. 1). Its useful frequency range extends to 90 MHz, and in the 136- to 138-MHz band reflected signals are at least 40 dB below the transmitted signal.

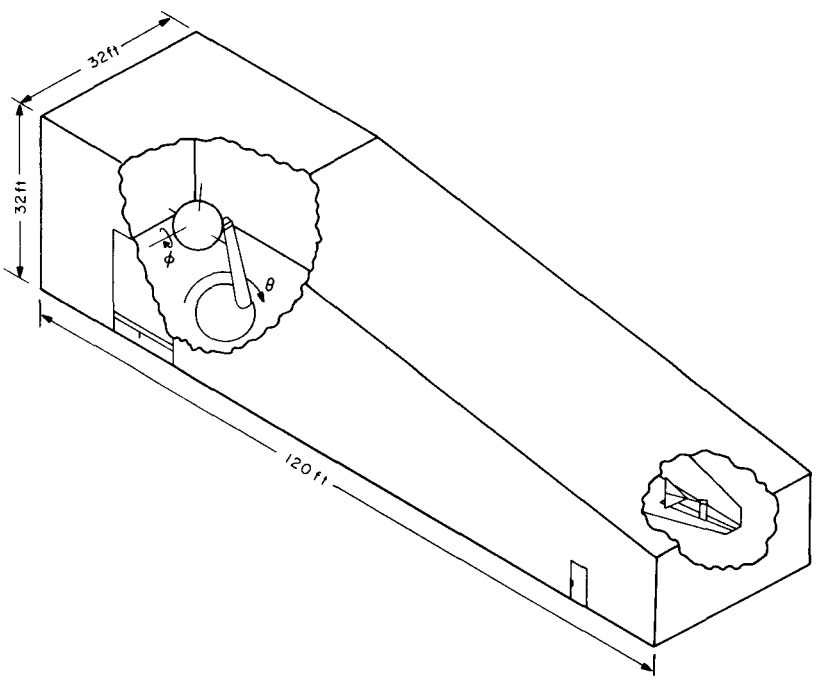


Fig. 1 - Rf anechoic chamber

In operation, a cross-polarized Yagi antenna is placed in the tapered section of the chamber and connected through a phase-determining network to a signal generator. This antenna is used as a signal source by which the test antenna is excited. The phase network can be switched to produce any of the four principal polarizations: vertical, horizontal, left-hand circular, or right-hand circular. In the normal mode of operation the test antenna is connected via a coaxial cable through a receiver to a recorder. The paper drive of the recorder is driven by a synchro system connected to the rotation of the test antenna.

Two other methods of operation use the test antenna as the transmitting antenna, driven with either a remote signal generator or a small battery-powered oscillator mounted on the test antenna. Due to the law of reciprocity, changing the direction of propagation caused no change in the pattern, but there are sometimes other considerations; these will be discussed later. The use of the battery-powered oscillator eliminates the coax wire from the test area, but it has been found that the presence of the cable causes very little distortion in pattern measurements.

Test antenna models are mounted in the chamber so that they may be rotated over the whole sphere. The two orthogonal rotations used are in the plane of the turnstile (ϕ) and about the axis of the turnstile (θ) (Fig. 2).

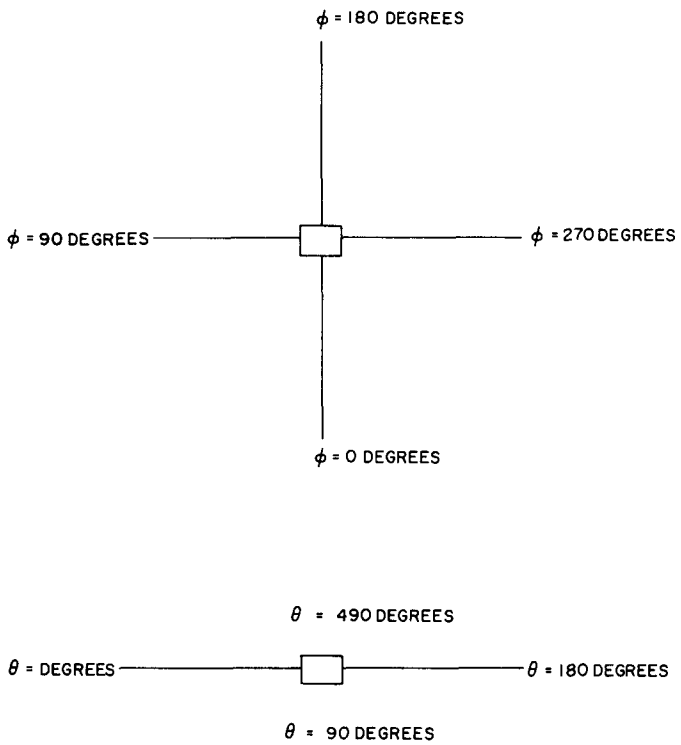


Fig. 2 - Coordinate system for a turnstile antenna

In addition to the standard antenna patterns, a unique recording system is used, whereby the test antenna is rotated automatically over the whole sphere while the signal strength is printed on a typewriter every few degrees. The signal strength is recorded

in decibels below a set reference level (usually 0 dB). This type of pattern allows the display of three different variables at one time and is referred to as a radiation distribution plot (RDP).

BASIC TURNSTILE TESTS

A basic turnstile antenna system was constructed to verify the theory and to test the effects of varying different parameters. The system consisted of a 14-in. sphere with four adjustable-length antennas mounted around the center. The antenna length was adjustable from 7-1/2 in. to 30 in. and was equipped with a broadband hybrid system to feed the antennas with the correct phase relationships. The antennas were adjusted to be a quarter wavelength long at the operating frequency. A second turnstile was also built with a 3-by-4-in. box holding 21-in.-long antennas.

Four RDP patterns are usually run on a test antenna, one for each of the four principal polarizations. Figure 3 shows some cuts from these RDP patterns. Figures 3a through 3d are θ cuts, showing the variation as the turnstile was rotated from top to side to bottom, and Fig. 3e is a ϕ cut, showing the variation when the trunstile was rotated on its axis. Figure 3a is the θ pattern for vertical polarization, which is parallel to the axis of the turnstile. At $\theta = 0$ degree the turnstile polarization is horizontal; therefore, the turnstile is cross polarized and a null exists. At the top and bottom ($\theta = \pm 90$ degrees) of the turnstile, there is a 3-dB loss due to the change from circular to linear polarization. Figure 3b is the θ pattern for the horizontal polarization, which is parallel to the plane of the turnstile. This pattern will vary either very little or by approximately 1 dB, depending on whether a cut is taken at the location of the antenna stubs or between the stubs. Figure 3e is the corresponding ϕ cut, which shows the variation of the pattern caused by the use of quarter-wave length stubs instead of stubs infinitesimally short. The nulls occur between the antenna stubs.

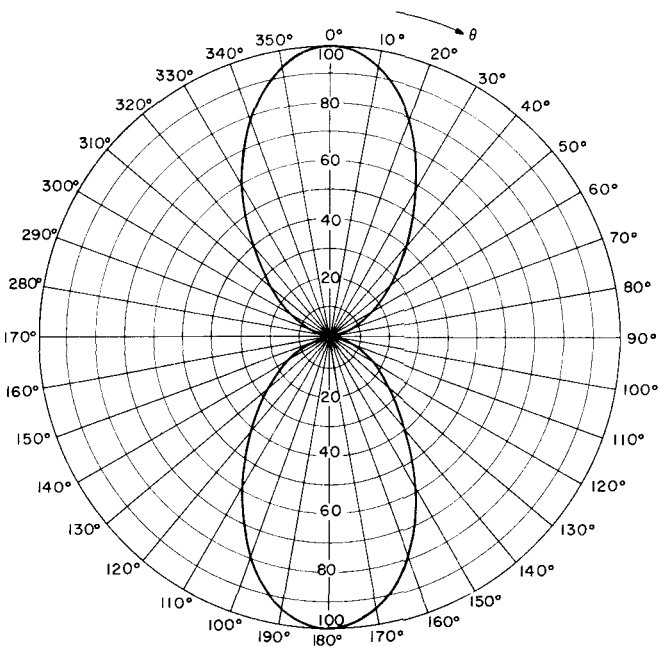


Fig. 3a - θ antenna pattern for vertical polarization (power plot)

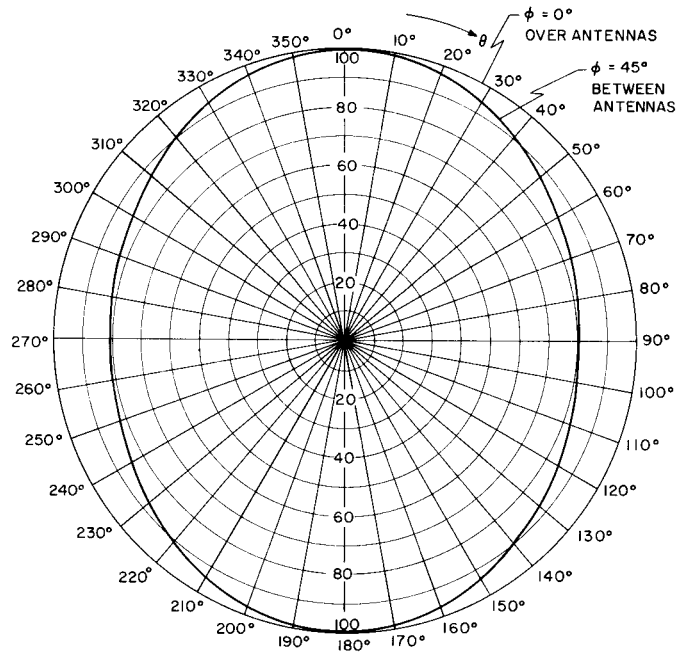


Fig. 3b - θ antenna pattern for horizontal polarization (power plot)

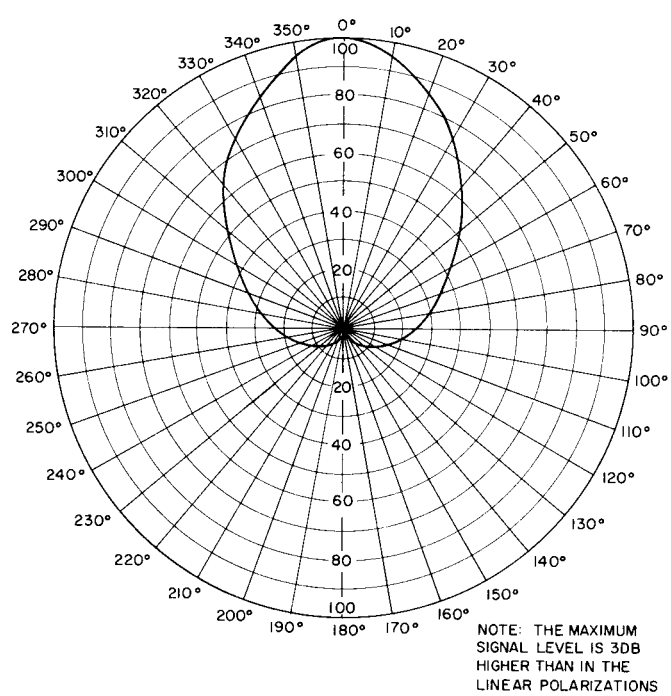


Fig. 3c - θ antenna pattern for left circular polarization (power plot). The maximum is 3 dB higher.

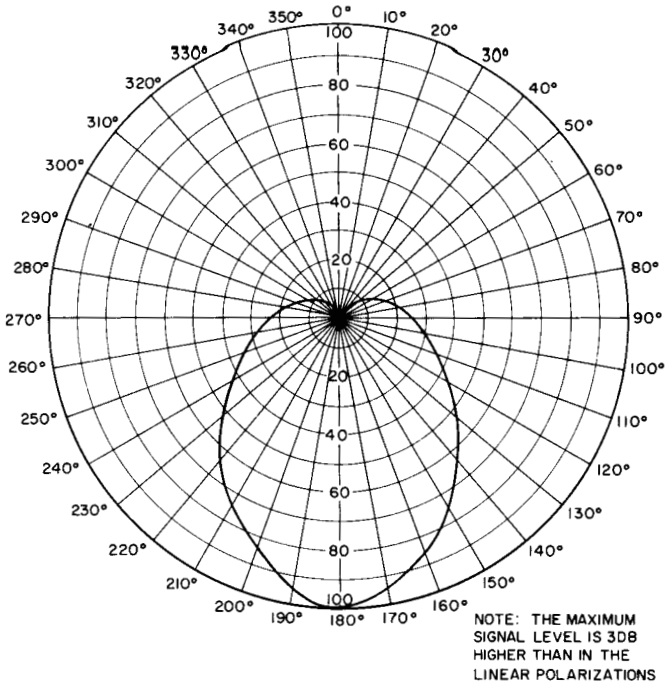


Fig. 3d - θ antenna pattern for right circular polarization (power plot). The maximum is 3 dB higher.

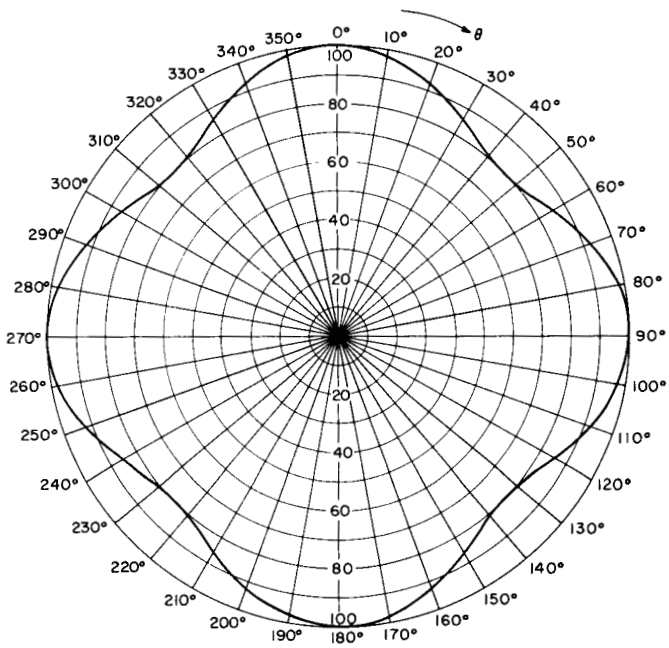


Fig. 3e - ϕ antenna pattern for horizontal polarization (power plot)

The other two polarizations are shown in Figs. 3c and 3d. On one end of the turnstile, the maximum signal exists, while at the side of the turnstile (θ = 0 degree), there is a 3-dB loss due to the change from horizontal polarization on the turnstile antenna to circular polarization. On the other end of the turnstile, the antennas are cross polarized and a null exists.

For the rest of this report only the horizontal polarization will be discussed. While the other polarizations are also important, the consideration of only one polarization will allow comparisons to be made when various effects are studied.

PHYSICAL EFFECTS

When a turnstile antenna is placed around a satellite, instead of on a very small center structure, several variables modify the basic pattern. The two biggest variables introduced are the ratio of the size of the satellite to the antenna length and the manner in which the antennas are connected. Other significant factors are booms, antennas, or other metal objects sticking out from the satellite. On the other hand, it has been found that the angle of the antennas with respect to the turnstile plane is not as important nor is the change in conductivity of the satellite skin, which is caused by the mounting of solar cells. The solar cells produced no measureable change as long as they were mounted on metal panels.

To determine the effect of the ratio of the satellite size to the antenna size, the scaling theory was used. A model may be scaled by increasing the frequency while simultaneously decreasing the antenna length according to the formulas F scale = nf original and L scale = L original/n, where F is the frequency, n is the scale factor, and L is the length of the antenna, which is a quarter wavelength in this test. The 14-in. sphere previously mentioned was used for this test.

The graph in Fig. 4 shows the increase in the variation of the pattern (null to max) as the ratio of satellite size to antenna size is increased. Very little deterioration was noted as the ratio varied from infinitesimal to 1:1. The total change in variation was only 1 dB. A change in the ratio from 1:1 to 1.6:1 caused the nulls to deepen an additional 5 dB, and when the ratio was increased to 1.8:1 the nulls jumped an additional 12 dB for a total deterioration of 19 dB more variation than the best turnstile pattern.

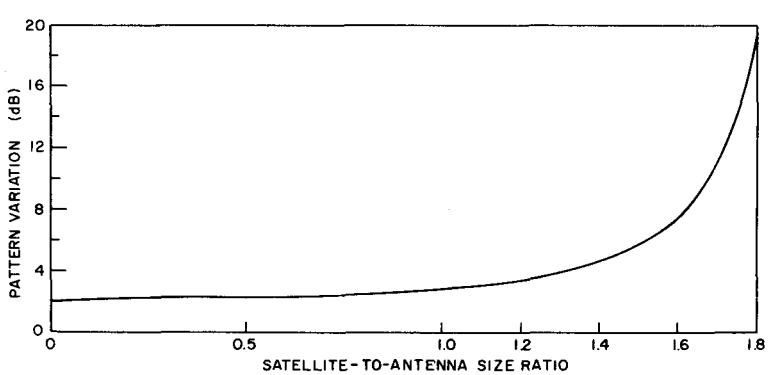


Fig. 4 - Signal variation as a function of satellite-to-antenna size ratio

These tests show that a satellite with a quarter-wavelength diameter or smaller should have a very good pattern, a satellite between a quarter-wavelength diameter and 3/8-wavelength diameter will suffer almost an order of magnitude power losses in the nulls, and satellites larger than 3/8-wavelength diameter will have very deep nulls.

The above discussion applies to spherical or approximately spherical satellite shapes. If the satellite shape is irregular, such as a box-shaped satellite, and if the size is a quarter wavelength long or longer, significant distortions can occur, which would be very difficult to predict.

Antennas or booms of approximately the same length will have a profound effect on the antenna pattern, sometimes improving it and sometimes making it worse. Very long gravity gradient booms will also affect the pattern, especially if they are not symmetrically placed with respect to the turnstile antenna, but it is very difficult to measure the effect due to practical problems encountered in mounting such a long boom on a satellite model. The longest boom capable of being simulated in the anechoic chamber (using scaling factors) is 28 ft.

ELECTRONIC EFFECTS

Satellites built by NRL use multiple receivers and transmitters and therefore require a complex rf harness to connect them to one antenna system. It is important to connect each antenna stub exactly 90 degrees in phase separation from its adjacent antenna stubs. This is normally accomplished with a lumped-element hybrid consisting of coils and capacitors to develop the required phase relationships. There are two inputs to this hybrid to allow two mutually orthogonal circular polarizations to be available at the same time from the turnstile. Ideally both of these input ports should be terminated with a 50-ohm characteristic impedance at the operational frequency. However, usually notch filters and bandpass filters are used to isolate receivers and transmitters. These filters look like shorts at certain frequencies and therefore unbalance the phase network and cause larger variations in the antenna patterns. Remedies to this problem include keeping all rf cables as short as possible to prevent impedance transformations and the use of isolators and circulators at the inputs of the hybrid to preserve a 50-ohm system while providing the necessary isolation. This rf harness also causes problems due to the use of tees and isolators. Therefore, it is a nonreciprocal network, and since it has a profound effect on the antenna pattern, the signal used to make the pattern must always travel in the same direction as the signal in the satellite. Usually flight transmitters are used as the signal source for the transmitter pattern, and for receiver patterns the system coaxial cable is connected to the harness at the point where the flight receiver is normally connected.

SOLAR EXPLORER B

An example of several of the parameters discussed above is Solar Explorer B, built by NRL and launched by NASA on March 5, 1968, as Explorer 37 (Solrad 9). Figure 5 shows the satellite mounted in the anechoic chamber for testing. It is a 12-sided cylinder, 30 in. in diameter and approximately 27 in. high. There were two turnstile antenna systems, each with four 21-in.-long antennas. One system had two transmitters connected to it, and the other had one transmitter and two receivers connected to it. All of the experimenter's detectors were mounted flush with the skin of the satellite so that the only significant metal objects above the skin of the satellite is the antenna system.

Work on this satellite was begun at approximately the time when the anechoic chamber became operational and was the first satellite for which a comprehensive program of development test and evaluation was performed. Initial tests were performed with a sheet

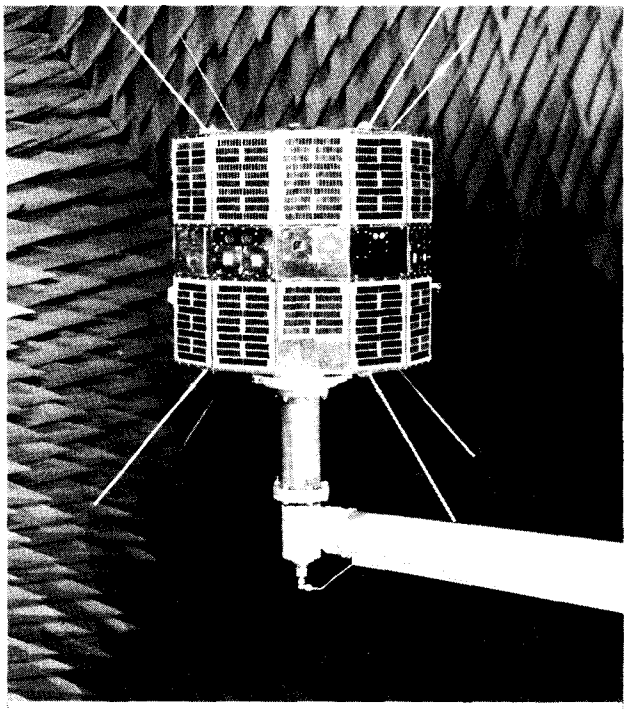


Fig. 5 - Solar Explorer B in the anechoic chamber

metal mockup with a simple balanced hybrid system. This prototype model was flexible enough to permit experimentation with antenna connections and locations. The flight payload was thoroughly tested in the anechoic chamber with all of its electronics and rf harness in working order.

Three distinct effects could be noted on this satellite: the size, the existence of another set of antennas, and the rf harness. The ratio of the satellite size with respect to the antenna size is about 1.6:1, but this ratio is complicated by the nonspherical shape, although its symmetrical shape is better than an irregular shape.

The first pattern run was with one turnstile antenna system mounted at about the middle of the side of the satellite. For a satellite-to-antenna ratio of 1.6:1, Fig. 4 indicates the variation should be about 7 dB. However, the measured value in this case was 8 dB, the difference probably being due to the cylindrical shape. The pattern, however, was properly shaped for a turnstile with four nulls between the antennas.

The next step was to run patterns on a prototype with both antenna systems in place. All parts of the hybrid systems except the signal output port were terminated with a 50-ohm load. The resultant horizontally polarized RDP is shown in Fig. 6a. In this case the interaction of the two antenna systems caused the nulls to decrease to the point where the variation was only 4 dB. The pattern shape is still that of a normal turnstile with four nulls between the antennas. As expected, the upper and lower turnstile systems produced the same patterns.

The flight model satellite was tested using each of the three transmitters in turn as a signal source to make the RDP patterns. In this test, the interaction of the rf harness

became evident; despite the fact that the transmitters were within 1 MHz of each other, each transmitter produced a distinctly different pattern. Most of the difference was in the shape of the null rather than the depth of the null. Figure 6b is a horizontally polarized RDP of one of the transmitters. The nulls became worse with average variations of 8 dB, and there was a severe distortion of the shape of the pattern with two deep nulls and two lesser nulls each shifting slightly from their expected positions.

In summary, the cylindrical shape caused an improvement in the pattern over what would normally be expected; the addition of a second turnstile antenna system caused a further improvement, but the interaction of the rf harness caused a degradation of the pattern with the net result being close to what normally would have been expected.

TIMATION I

Another satellite constructed by NRL and tested in the anechoic chamber was Timation I, launched on May 31, 1967 (Fig. 7). This was a rectangular satellite 17 in. by 30 in. by 10 in. with one turnstile antenna connected to one transmitter and two receivers. The satellite is gravity-gradient stabilized by means of a 60-ft-long boom extending downward from the center of the satellite. In addition, there was a 400-MHz dipole on the bottom of the satellite. Four 19-in. antennas were used, one at the top center of each side.

A prototype and the flight model were tested in the chamber. On the prototype it was discovered that the gravity-gradient boom and the 400-MHz antenna caused no noticeable degradation of the pattern, probably due to their size and location away from the turnstile antennas. The satellite antenna-size ratio indicates a pattern variation of 4 dB from Fig. 4, if the satellite antennas were more regularly spaced. However, the pattern run on the prototype shows a severe distortion of the normal pattern with a total variation of 9 dB (Fig. 8a). The number of nulls was reduced from four to two; the nulls that would be expected between antennas alternately disappeared or were deeper than expected. Had the antennas been mounted in the middle of the sides, a better pattern would have been obtained, but mechanical considerations prevented this type of mounting.

The tests run on the flight model with all its electronics and rf harness indicated both a change in the antenna pattern and a deepening of the nulls. The nulls were shifted by approximately 20 degrees and the pattern variation increased to 16 dB (Fig. 8b). It is useful to note that the nulls occurred in the plane of the turnstile (θ = 0 degree), and once the satellite was stabilized, this part of the satellite is never seen by an earth ground station. The ground station looks at the bottom of the satellite (θ = -90 degrees) to ± 60 degrees off axis. Most of the nulls are outside this area with only a small but deep null of 13 dB observable after stabilization.

CONCLUSION

The antenna study produced a better understanding of the satellite turnstile antenna. Several general effects were noted. The basic turnstile antenna is a good choice for omnidirectional coverage with 4-dB nulls. These nulls, however, can be deepened when the antenna is placed on a satellite. Some of the factors affecting the pattern are: the satellite size and shape, the rf harness connected to the antenna, and the satellite projections. The most profound effect on the pattern was due to the satellite size and shape.

The study of two flight model satellites showed that the more symmetrical the shape, the better the pattern will be. Tests on the flight model satellites confirmed observations made during the research and development phases.

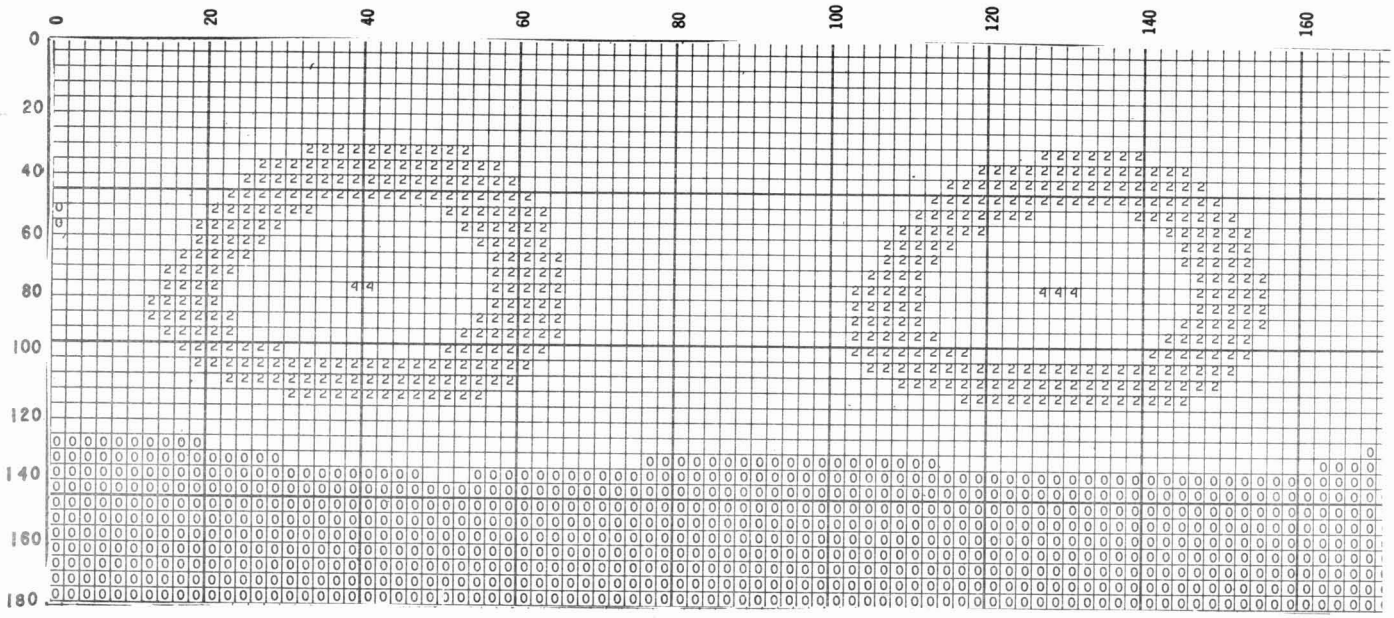


Fig. 6a - Solar Explorer B prototype ant

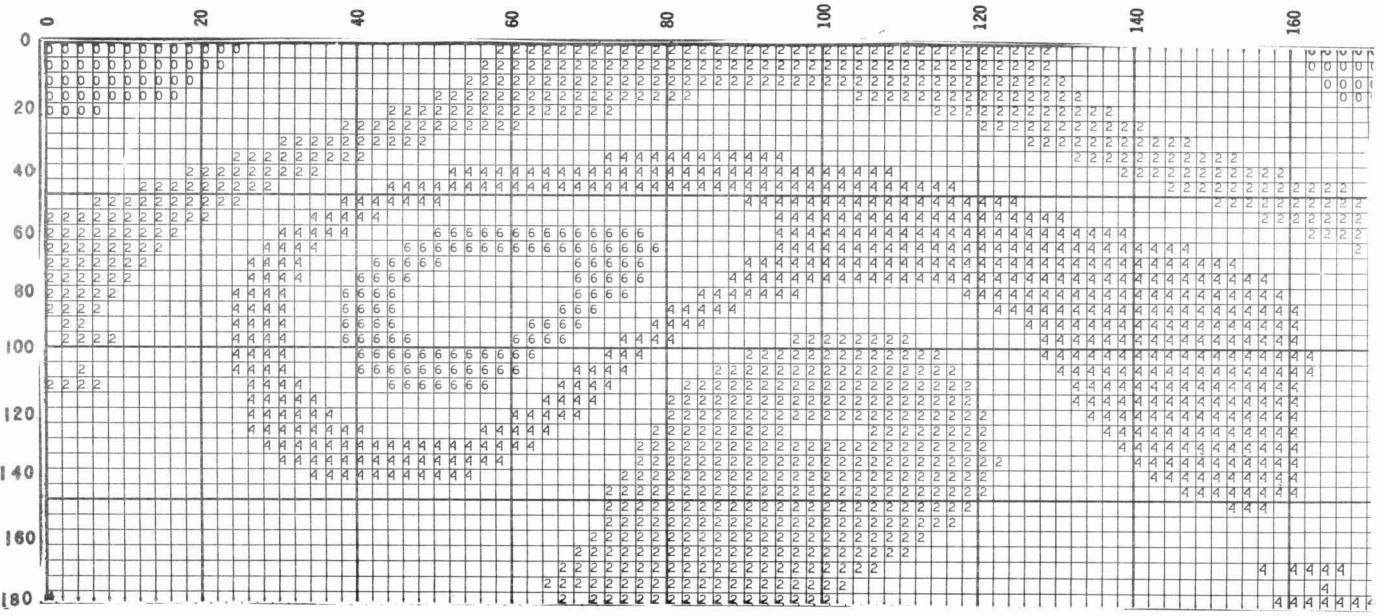
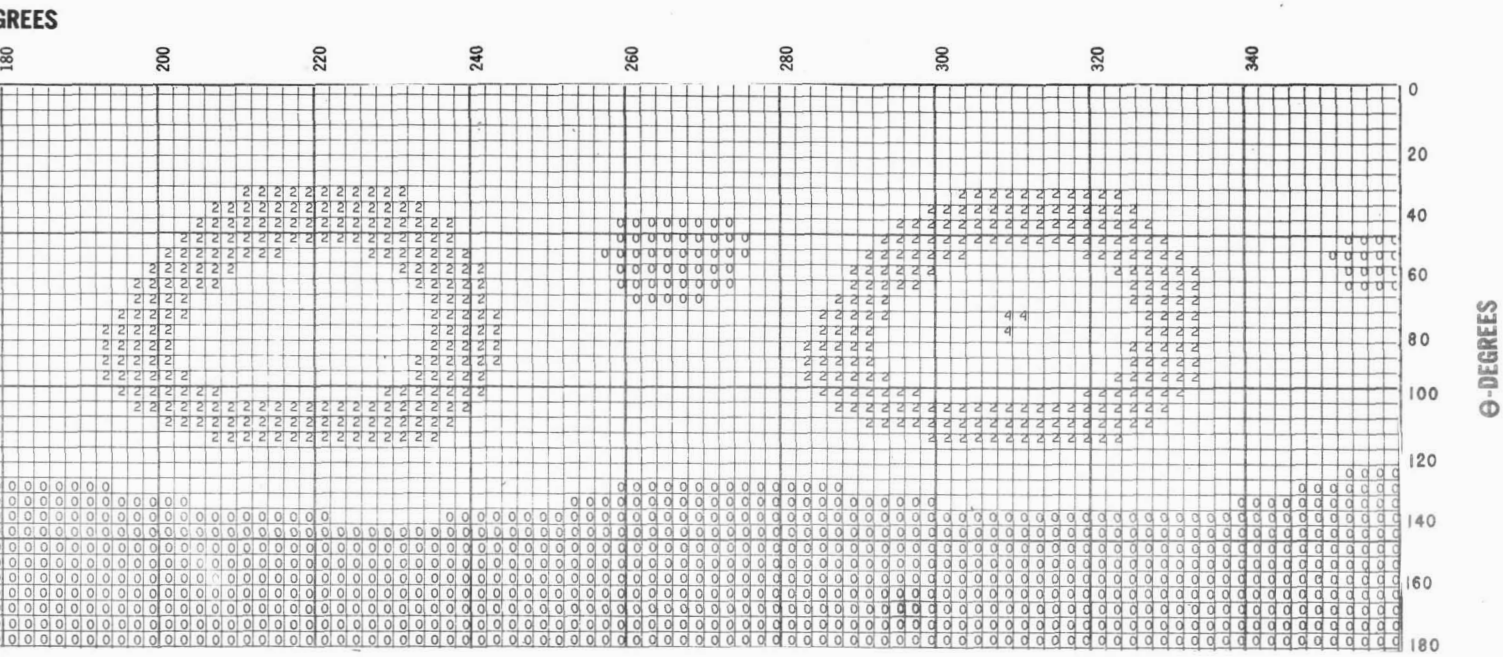
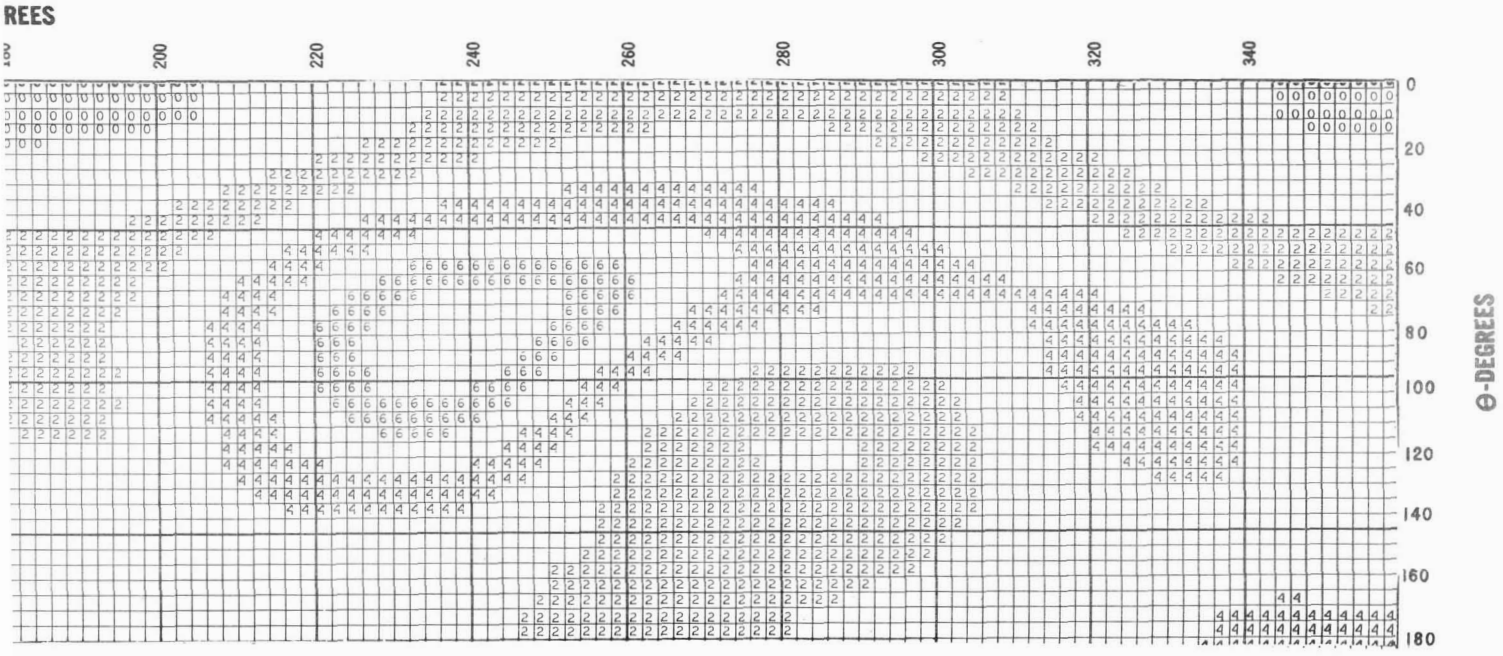


Fig. 6b - Solar Explorer B flight mode a:



pattern (decibel plot). Zero is the highest level.



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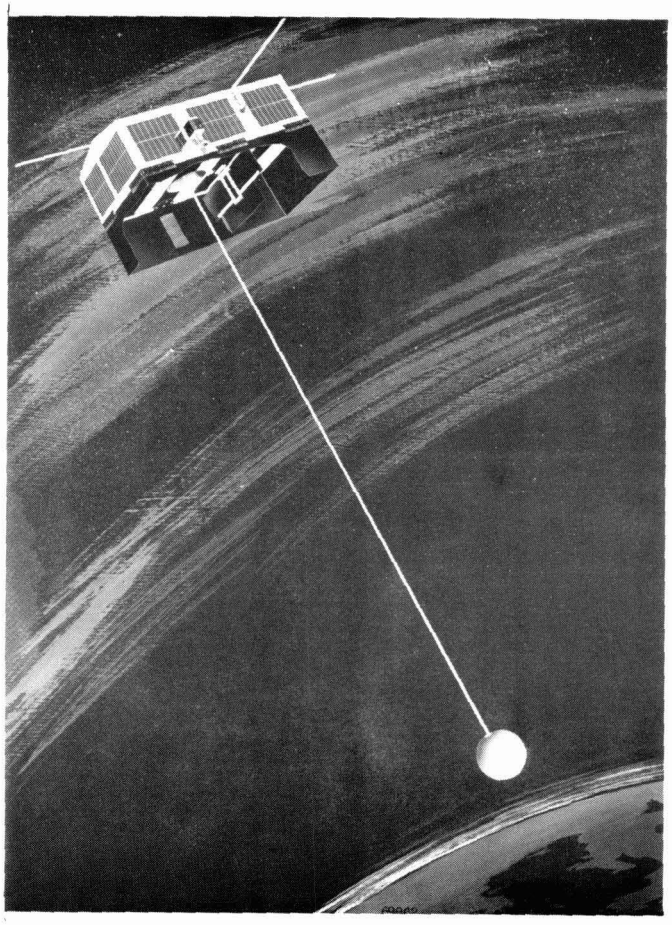


Fig. 7 - Timation I in orbit

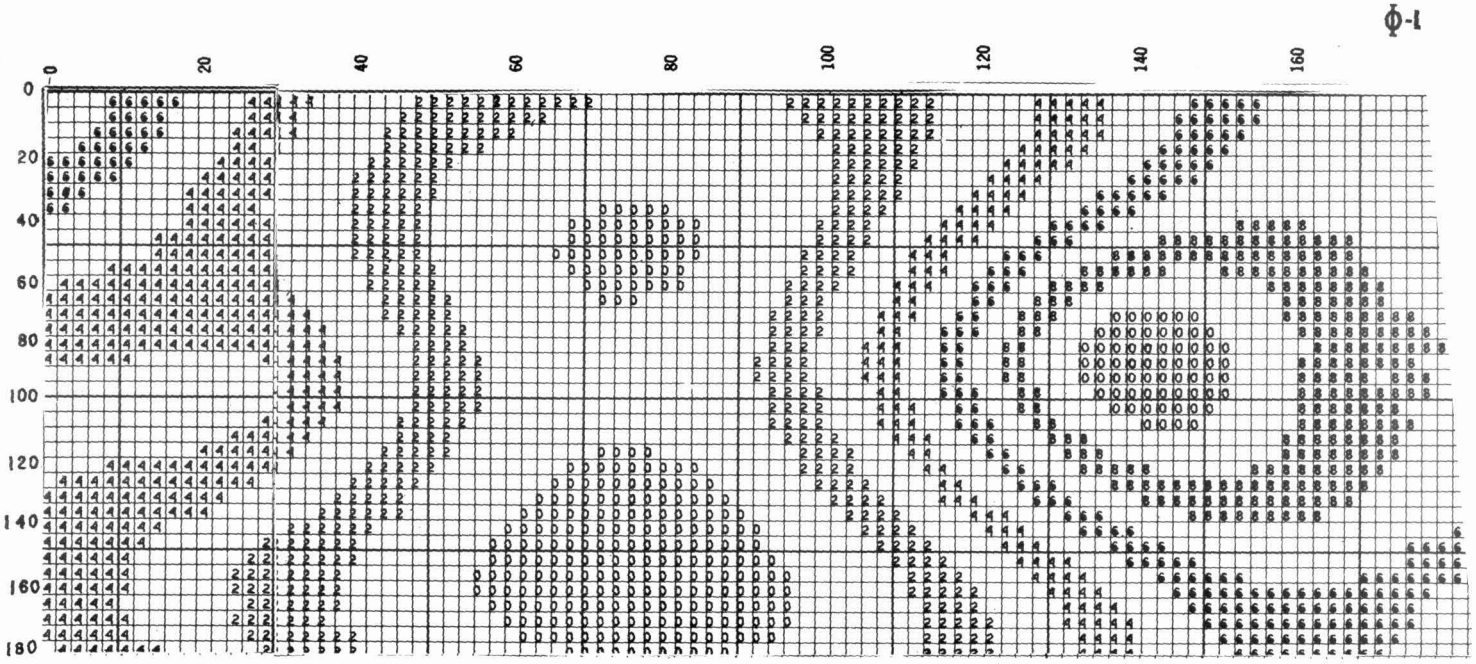


Fig. 8a - Timation I prototype antenna patte

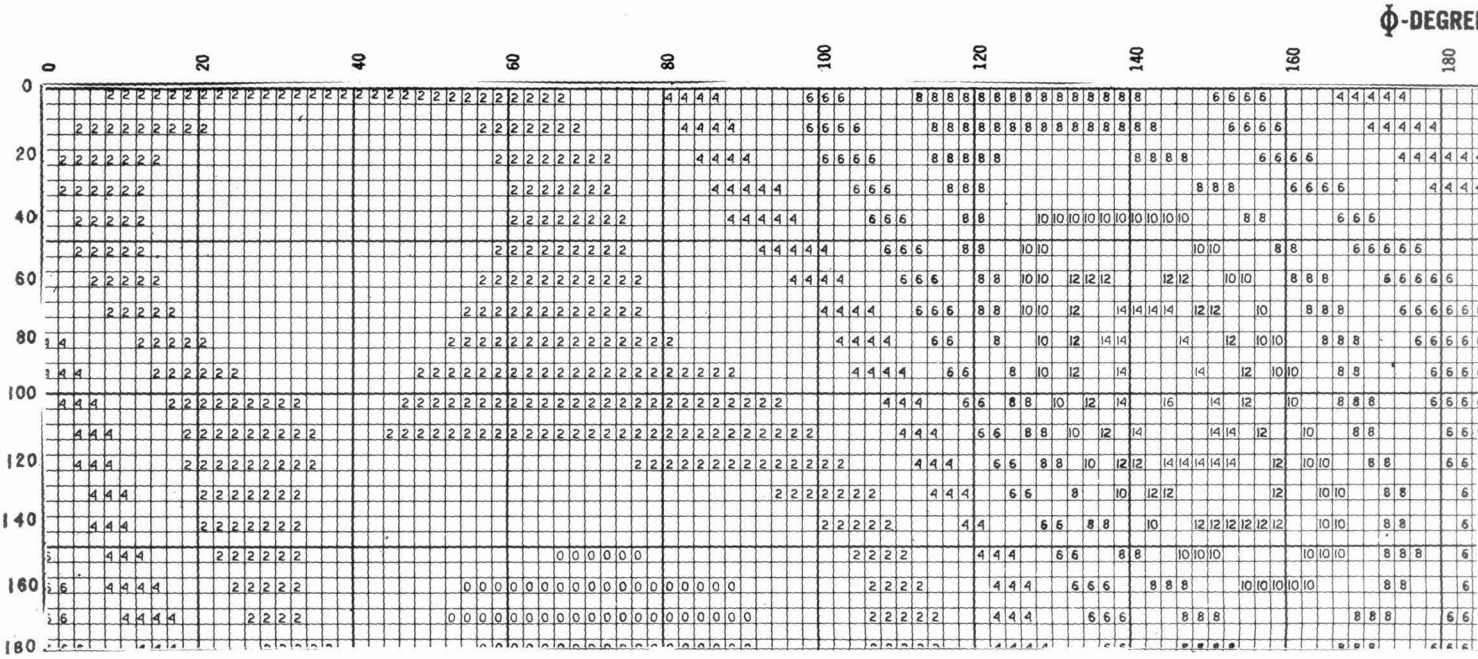
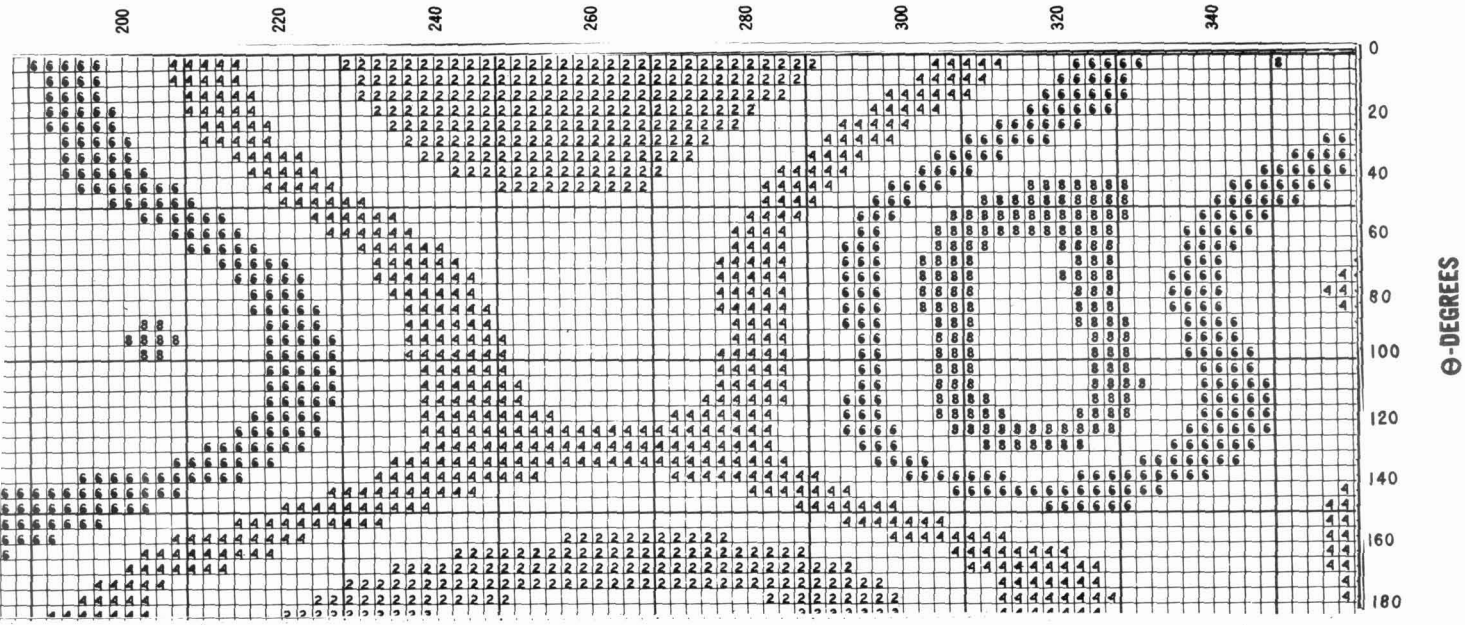


Fig. 8b - Timation I flight model antenna patt



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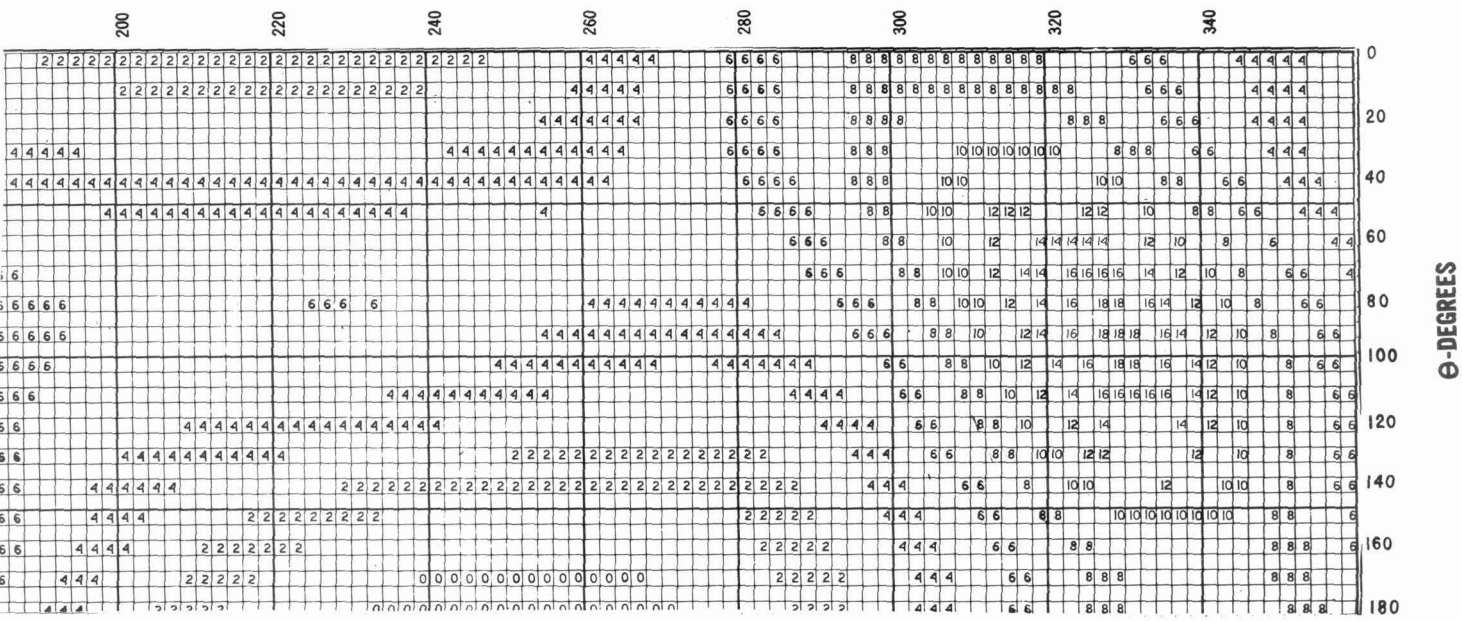

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ACKNOWLEDGMENTS

The author gratefully acknowledges the guidance of John Poole, under whose direction the anechoic chamber was constructed, and of Philip R. McCray and Henry Rogers, who assisted in running the tests that this report is based on. Without the encouragement and leadership of Lenard Hearton, this report would not have been written.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

SATELLITE TURNSTILE ANTENNAS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Interim report; work is continuing on the problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

Stephen Nichols

6. REPORT DATE August 6, 1969	7a. TOTAL NO. OF PAGES 22	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. NRL Problems A01-17, A01-20, and b. PROJECT NO. R04-16 A37-538-002/652-1/F019-01-01 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6907 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Naval Air Systems Command), Washington, D.C. 20360

13. ABSTRACT

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S/N 0101-807-6801

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