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Antennas for the Gemini VHF-UHF Polarization Experiment (D-14)

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CONTENTS

ABSTRACT

An experiment was conducted to measure the spatial and temporal distribution of free electrons in the lower layers of the ionosphere. This study used a Gemini spacecraft as a platform from which signals at 133.9 Mc and 401.7 Mc were transmitted.

A single antenna (a boom-mounted colinear-fed dipole) was used to transmit linearly polarized signals at both of the desired frequencies. The effort in designing this antenna was centered chiefly on attempts to achieve polarization purity in the transmitted signal. The proximity of the Gemini spacecraft acting as a reflector introduced an undesirable component of cross-polarization to the signal. By careful design and orientation of the antenna-spacecraft configuration, this cross-polarized component was minimized.

The spacecraft-launched signals were received on 28-foot parabolic antennas at two separate ground stations. The reflectors and pedestals were commercially manufactured. Dual-frequency crossed-dipole feeds were designed and built for these reflectors.

PROBLEM STATUS

This is a final report on one phase of the problem.

AUTHORIZATION

NRL Problem R07-13
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ANTENNAS FOR THE GEMINI VHF-UHF POLARIZATION EXPERIMENT (D-14)

INTRODUCTION

Since free electrons in the ionosphere have a pronounced effect on the transmission of rf signals through that medium, a knowledge of the physics of the ionosphere is of extreme importance in detecting, tracking, and communicating with space and trans-horizon targets. Earlier experiments to determine the spatial and temporal distribution of electrons in the ionosphere had been conducted by the Search Radar Branch using the 150-foot antenna at the Chesapeake Bay Division of the Laboratory to study radar returns from Echo II. The results of these experiments may be found in other NRL reports (1,2). As an extension of these experiments to studies of the lower regions of the ionosphere, an experiment was conceived in which the signals were to be transmitted from a Gemini spacecraft and received at stations on the earth's surface. Since the altitudes of the Gemini orbits were to be under 200 nautical miles, as compared to an orbital altitude of approximately 1000 nautical miles for Echo II, this technique would permit measurements of the inhomogeneities in the lower regions of the ionosphere without their being masked by the much greater variations in the upper regions.

The present report describes the design and testing of the antennas employed in the Gemini experiment. Only a brief description of the experiment itself will be included in order to delineate the problems associated with antenna design. The transmitters used in the experiment are described in another report (3), and a thorough treatment of the experiment, its objectives, and its results will be presented in a future NRL Report by other authors.

In brief, the aim of the experiment was to determine the spatial and temporal dependence of fine-scale inhomogeneities in the lower layers of the ionosphere. According to well-known physical principles, a linearly polarized electromagnetic wave has its plane of polarization rotated as it passes through a medium containing free electrons in the presence of a magnetic field. This effect is known as Faraday rotation, and its magnitude is a function of (a) the frequency of the propagated wave, (b) the direction of propagation with respect to the orientation of the magnetic lines of force, (c) the magnetic field intensity, (d) the distance traversed through the ionized medium, and (e) the free-electron density in the medium. Of these, factors (a) through (d) are known, or can be calculated from the known geometry of the transmitter and receiver positions. Therefore if the actual Faraday rotation itself is measured for an experimental signal, the free-electron density, factor (e), can be calculated.

In the implementation of this experiment an orbiting Gemini spacecraft was used as a platform from which signals of known polarization could be launched. Two signals were transmitted, one at 133.9 Mc (vhf) and the other at 401.7 Mc (uhf). The degree of rotation of the polarization is indirectly proportional to the square of the transmitted frequency. The vhf signal therefore undergoes a greater degree of rotation as it passes through the ionosphere, and the measure of this rotation provides a precise (or vernier) determination of the electron density. The amount of rotation of the uhf signal is less by a factor of 9 (because of the 3:1 frequency ratio), and this signal is used to resolve ambiguities of $n\pi$ rotations of the vhf vernier signal.

The signals were received on the island of Kauai in Hawaii or on Antigua in the British West Indies. These two sites were chosen, among the limited number available, because their locations with respect to the proposed orbits of the Gemini vehicles were such as to provide a reasonable amount of data at a variety of elevation angles.

This report will first present a description of the design, construction, and testing of the vehicle antenna. This will be followed by a description of the ground-station antennas and of the design, construction, and testing of the feeds for these antennas.

THE VEHICLE ANTENNA

The major requirement for the antenna on the Gemini vehicle was that it launch a signal of pure linear polarization of known orientation. In theory any linear polarization could be used if the orientation of the space vehicle (and therefore of its antenna) with respect to a receiving station on the surface of the earth were known very precisely for all points along the observed orbit. From this information the expected polarization at the receiving station could be calculated for each point. But even if the space-vehicle orientation were known with sufficient precision (which it would not be), the computational problem to process such data would be extremely burdensome. The practical way around this difficulty is to choose an orientation for the space-borne antenna such that the polarization of the signals that would be received at the ground station in the absence of Faraday rotation is invariant with the position of the vehicle along its orbit. A consideration of the geometry of an orbiting linear radiator and a point on the earth's surface will reveal that the only way to maintain this constancy of polarization is to orient the orbiting antenna vertically, i.e., pointed toward the center of the earth. In this way any deviations from a purely vertically polarized signal at the ground station can be ascribed to Faraday rotation.

The transmission of a signal of pure vertical polarization is of course only an idealization and would not be obtained in practice. The proximity of the spacecraft with its complexly curved surface was expected to introduce some degree of crossed polarization into the transmitted signal. This cross-polarized component would present itself as an error in the measurement of polarization angle at the receiving station, the amount of error being dependent on the viewing angle to the spacecraft but independent of the degree of rotation suffered by the signal as it traversed the ionosphere. However the percentage accuracy of the readings at the receiving site would be a function of the total Faraday rotation and can be expressed as $100 \times \xi/\Omega$, where ξ is the angular error due to cross polarization in the transmitted signal and Ω is the total rotation angle. At vhf the rotation angles Ω could be between zero and several thousand degrees. If a relative accuracy of $\pm 1\%$ were desired and Ω were $25°$, ξ would have to be less than $\pm 0.25°$. This value of ξ represents a ratio of direct-to-cross-polarized components (E_θ/E_ϕ) in the transmitted signal of 229:1 (i.e., the cotangent of $0.25°$), or 47 db. If Ω were of the order of $500°$, ξ would be $\pm 5°$ for the same relative accuracy of $\pm 1\%$. This represents an E_θ/E_ϕ ratio of 11.4:1, or 21 db. It was realized from the start that polarization ratios of about 47 db would probably have been impossible to attain in practice, although 21 db certainly seemed reasonable. Therefore no specific design goal was set for polarization purity, but the general goal was to obtain as high a ratio of E_θ/E_ϕ as possible.

Mechanical requirements in the design of the vehicle antenna were that it be lightweight and small. Actually size was no real constraint for the operational phase when the Gemini spacecraft was in orbit, but during launch no part of the antenna could protrude beyond the skin of the spacecraft where it would affect the aerodynamic properties of the launch vehicle. This requirement dictated either a radiator of inherently flush design such as a cavity or slot or a radiator retracted below the skin of the vehicle during launch to be unfurled in orbit.

Initial Designs Investigated

Perhaps the most direct approach, and therefore the one which was initially tried, was to use a simple monopole antenna projecting from the surface of the vehicle. The monopole could be of such design that it could be retracted into the spacecraft during launch. Several commercial models of retractable whip antennas are available. Such units have been used frequently on orbiting vehicles and are in fact used for communications antennas on the Gemini spacecraft. They consist in general of a coiled metal ribbon which is unfurled either by releasing the inherent spring energy of the coil with a suitable latch, or by unwinding it from a motor-driven spool.

An ideal monopole above an infinite ground plane should have essentially all its radiated energy polarized parallel to the element throughout all space above the ground plane, with little or no crossed polarization (i.e., that radiation which is perpendicular to the orientation of the monopole). In the practical application here, the outer skin of the Gemini spacecraft formed the ground plane for the monopole. This surface is obviously not a plane, much less is it infinite. How much this curvature of the ground plane would degrade the purity of the desired unipolarized linear radiation was investigated by actual measurement.

A one-tenth-scale model of the Gemini spacecraft was constructed of sheet copper and fitted with a monopole which could be adjusted in length to operate at either of the scaled frequencies (1339 Mc and 4017 Mc). This model, shown in Fig. 1, was mounted such that a series of patterns could be made to investigate the direct- and crossed-polarized radiation levels from all aspect angles to be expected in the actual experiment. The results were disappointing. At both frequencies cross-polarized levels were high — generally running between only 5 and 20 db below the peak of the direct-polarized beam pattern. Obviously surface currents circulating over the complex curvatures of the vehicle were radiating at undesirable polarizations.

A related approach was to mount a dipole on a boom protruding from the rear of the spacecraft model, with the dipole perpendicular to the boom such that it would be vertical to the surface of the earth in flight. Since the rear of the actual Gemini spacecraft is a much less curved surface, it was hoped in this way to avoid the curvatures of the vehicle itself and thereby reduce the cross-polarized radiation. (Actually in our model this rear surface was simpler still, being constructed merely of a flat disk.) However this approach gave no better results. The cross-polarized patterns, though different in shape, still showed peaks in the same general range as in the tests with the monopole.

A cavity-backed slot had also been considered. Such a configuration should have a physical advantage over protruding monopoles and booms in that, because the aperture is inherently flush, the problems of unfurling or erection can be avoided. However the restricted space for installation would have limited the aperture size to 3 by 9 inches. A resonant cavity of this size at 133.9 Mc would have to be severely loaded. As well as making the antenna quite heavy, such loading would be expected to be very lossy. Because of such apparent disadvantages this approach was abandoned and no pattern measurements were made on the configuration.

The results of the tests on these experimental antenna models, while not providing a usable antenna design, did indicate that the outer skin of the spacecraft was to be avoided as a ground screen. The outer skin could be avoided by locating the radiating element so that very little of its radiated energy would be directed toward the vehicle. This was the approach that led to a successful design for the vehicle antenna.

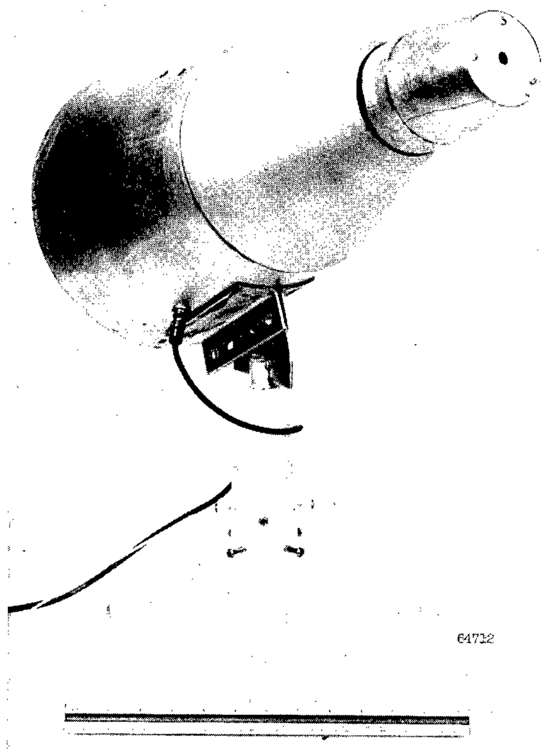


Fig. 1 - One-tenth-scale model of the Gemini spacecraft and monopole antenna for transmitting a linearly polarized signal

Final Design

Figure 2 shows how the element, a boom-supported colinear-fed dipole, was mounted with respect to the spacecraft. The antenna was attached at the end of a retractable boom by which, from a preorbital position beneath the skin of the Gemini spacecraft, it could be reeled out to about 7 feet from the vehicle. The boom, which was used here only to support the actual radiating element, is a modified DeHavilland type A-32 motorized STEM unit. In this device the boom is a multilayer metal ribbon which when stowed is wound on a storage drum. For erection the motor is energized and the ribbon, because of preforming by heat treatment, curls as it unfurls to form a circular tube with the edges of the material overlapping by approximately 180°. Although the motorized unit is a standard DeHavilland device, the boom was modified for this application. It was modified because a study by McDonnell Aircraft determined that beryllium copper should be used as the boom material with an outer coating of silver in place of the standard stainless steel. This modification equalized the temperature gradients on the structure in its space environment and thereby limited the sunlight-induced deflection of the boom to a maximum value of 0.35°F.

Figure 2 also illustrates the design objective of supporting the dipole at a distance from the spacecraft. The dotted curve outlines the general pattern of the dipole, which in the three-dimensional view is doughnut shaped. The objective was to locate the spacecraft in the shadow cone off the feed end of the dipole.

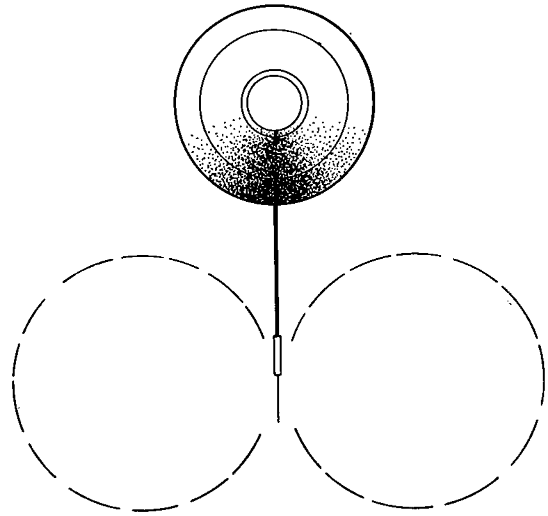


Fig. 2 - Boom-supported dipole mounted on the Gemini spacecraft (nose view)

Figure 3 is a general drawing of the antenna itself. A and B are the upper and lower radiating elements respectively, and C is the supporting boom. The feed point for the antenna is at D, where the inner conductor E of the final section of coaxial line which feeds the antenna is attached to the upper element and the outer conductor connects to the lower element. Incorporated in E is a line transformer for impedance-matching purposes. F is a dielectric-loaded choke which is quarter-wave at 133.9 Mc and three-quarter-wave at 401.7 Mc and isolates the radiating structure from the supporting boom. G is the mechanical coupling connecting the antenna to the boom. The antenna is fed through a type RG-188/U coaxial cable H which terminates inside coupling G at a set of mating TNC connectors.

The type RG-188/U coaxial cable was selected for its flexibility, which allowed it to withstand repeated winding and unwinding. The end of this cable inside the spacecraft is coiled on a DeHavilland-designed drum from which it feeds out as the boom unfurls. The cable is so wound that neither end of the cable twists as the drum rotates, and the need for a rotary joint is thus avoided.

Because of the weight of the overall antenna-boom structure and because of the limited space available for installation on the Gemini spacecraft, it was deemed necessary to use a single antenna for operation at both of the desired frequencies. Thus the feed line was connected to the two transmitter outputs through a diplexer. At the two frequencies separated by a ratio of 3:1 the antenna was required to have (a) adequate coverage on vertical polarization at all angles from which, in flight, the antenna would be viewed from the ground station; (b) a high ratio of direct-to-cross (vertical to horizontal) polarization at these angles; and (c) a good impedance match to the 50-ohm feed line. The design technique pursued to achieve these objectives was predominately experimental. The tenth-scale model of the spacecraft used in the earlier experiments was employed with an appropriately scaled antenna and boom (Fig. 4) to establish the optimum configuration which would yield the desired objectives for the antenna patterns (a and b, above). The coordinate system employed in measuring the antenna patterns is shown in Fig. 5a. This is the conventional spherical coordinate system and is centered on the point at which the axis of the boom intersects the spacecraft axis. The positive z-axis is oriented toward the center of the earth, and the spacecraft axis lies in the x-z plane. It was necessary to cant the vehicle down 17° so that the astronaut could see the earth's horizon through the cabin

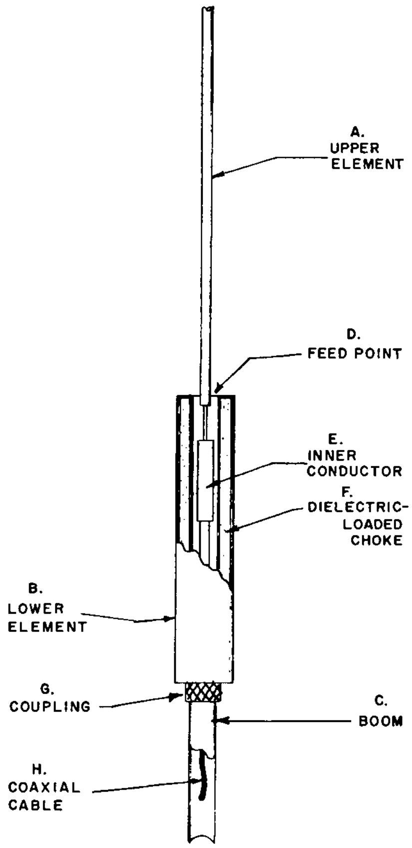
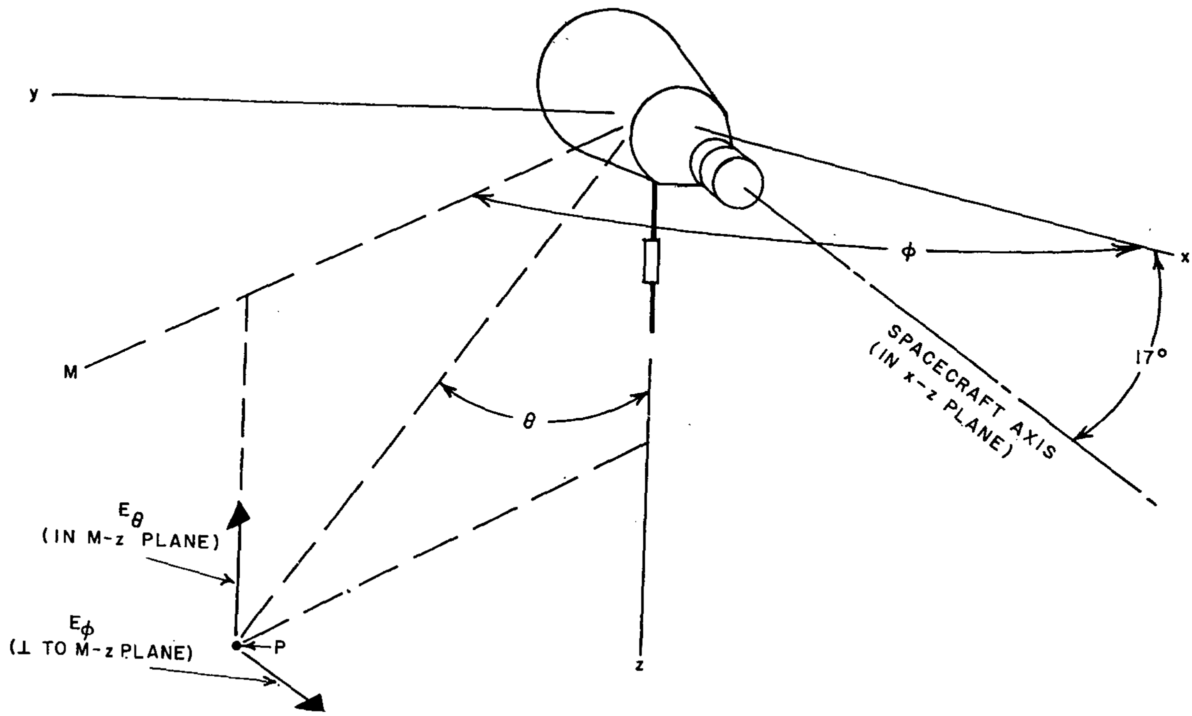


Fig. 3 - Functional drawing of the Gemini vehicle antenna

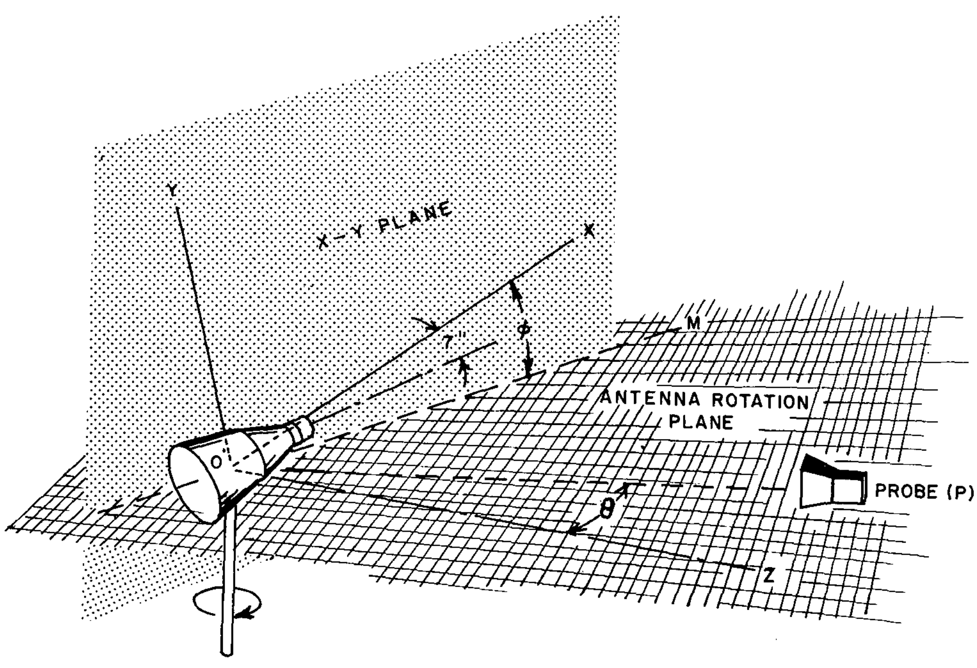
Fig. 4 - One-tenth-scale model of the Gemini spacecraft fitted with the boom-mounted colinear-fed dipole

window to obtain visual reference for attitude control. P represents a probe point in the antenna field. Measurements were made of the direct-polarized vector E_θ and the crossed-polarized vector E_ϕ. The patterns were measured as a function of θ in the plane defined by the line of sight OP and the z axis. A series of these patterns as a function of θ were recorded for 15° increments of ϕ. The relationship of these coordinates to the actual geometry of the measurements is perhaps made more evident by Fig. 5b. Here the measurement plane of Fig. 5a (containing OP and the z axis) is shown and labeled as the "antenna rotation plane." The x-y plane, always perpendicular to the antenna axis and rotating with the vehicle as θ is varied, intersects the antenna rotation plane on line OM. Here ϕ can be seen to be the angle between OM and the x axis and is measured, as it was in Fig. 5a, in the x-y plane. The E_θ and E_ϕ fields were measured with probe P which lies in Fig. 5b with its axis on the rotation plane. It may appear from Fig. 5b that the swing of the antenna, as the model was rotated, would introduce a measure of parallax into the recorded patterns. Actually the distance OP was great enough to make this parallax negligible. At any rate, what was desired to be measured was not the pattern of the dipole alone, but the overall pattern of the dipole, boom, and spacecraft.

Early in the tests it became apparent that the lengths of the upper and lower radiating elements would be critically dictated from pattern considerations alone within the limitations imposed by the physical size of the antenna in its stowed configuration. In other words, the element lengths could not be adjusted for the purpose of matching the antenna at either of the two operating frequencies. Rather, once the lengths were chosen to give the most desirable patterns, the resultant mismatches would have to be corrected



(a) Coordinate system



(b) Orientation for measurements

Fig. 5 - Coordinates employed for the antenna pattern measurements

by a properly designed coaxial line transformer inside the lower element (shown at E in Fig. 3). The upper and lower dipole element lengtns and the length of the extended boom are the three parameters over which complete control should have been exercised to establish good E_θ and E_ϕ patterns. However, structural limitations imposed size limitations on two of these, with the result that only one parameter, the upper-element length, provided any real freedom for adjustment. The boom length was limited to approximately 8 feet by considerations of the structural deflection of the boom with the weight of the antenna at its outer end. The antenna itself, including the coupling to the boom, was limited in its stowed configuration to an overall length of 16 inches. The lower element, because it contained the dielectric-loaded choke and matching transformer, was necessarily rigid and could not exceed this limitation. The upper element could conceivably be folded in its stowed position, one or several times, so that its operational length need not be limited to 16 inches.

No problem was encountered in obtaining good direct-polarized (E_θ) patterns from the antenna over a range of parameter values. Desirable cross-polarization (E_ϕ) characteristics on the other hand were very difficult to achieve. Boom length, although limited as mentioned above, was adjusted to some extent in an attempt to lower the cross-polarized radiation level. The results were not completely clear-cut, but a slight improvement was obtained when the boom length was (in full scale) 85 inches. Since this represents approximately one and three wavelengths at 133.9 and 401.7 Mc respectively, the resonant length of the boom was apparently helping to isolate leakage currents on the boom from the skin of the spacecraft. This indicated that the surface of the vehicle was being excited both by currents on the boom and by direct radiation from the antenna. It is probable that a boom of an even greater multiple of half-wavelengths would have provided still lower E_ϕ levels because of the additional isolation which would have been obtained from direct radiation. However no experimental verification of this was pursued, since the aforementioned structural limitations prevented the use of a much longer boom.

As stated previously the only variable which could be freely adjusted to obtain reasonably low levels of E_ϕ was the upper-element length. After a series of trials during which this length was varied in steps from (in full scale) 15 inches to 45 inches, the lowest E_ϕ levels were found to occur at a length of 30 inches. With the 14-inch lower-element length the total antenna was then 0.5λ at 133.9 Mc and 1.5λ at 401.7 Mc, asymmetrically fed at a point one-third the distance along its length.

Discussion of Results

The direct- and cross-polarized patterns at 133.9 Mc and 401.7 Mc (1339 Mc and 4017 Mc when scaled) are shown in Figs. 6 through 19. The horizontal axis on the patterns represents the angle θ and the vertical axis represents relative power level. Each pattern contains an inset drawing of the spacecraft to aid in visualizing the measurement coordinates. In each of these views the antenna is seen end-on (that is, at $\theta = 0°$) and is depicted as a dot within a circle. The angle ϕ is shown as having two values, one to the right of $\theta = 0°$ and another to the left. In actuality the angle ϕ was not changed during the measurement of any one pattern; the effect of a change in ϕ arises from the convention adopted in measuring the angles θ and ϕ in the spherical coordinate system. In the view of the coordinate system shown in Fig. 5b it can be seen that one-half the pattern can be recorded by rotating the antenna so that the angle θ assumes values from 0° to 180° measured in the direction shown in the diagram. The other half of the pattern can be recorded either by continuing the rotation in the same direction, thus allowing θ to assume values increasing from 180° to 360° or by changing the angle ϕ to its supplement (180° - ϕ) and retracing the same range of θ(180° to 0°). Either method gives an identical pattern. The first method is the physical way in which the patterns were actually recorded. However it is more convenient here to represent the patterns according to the second method.

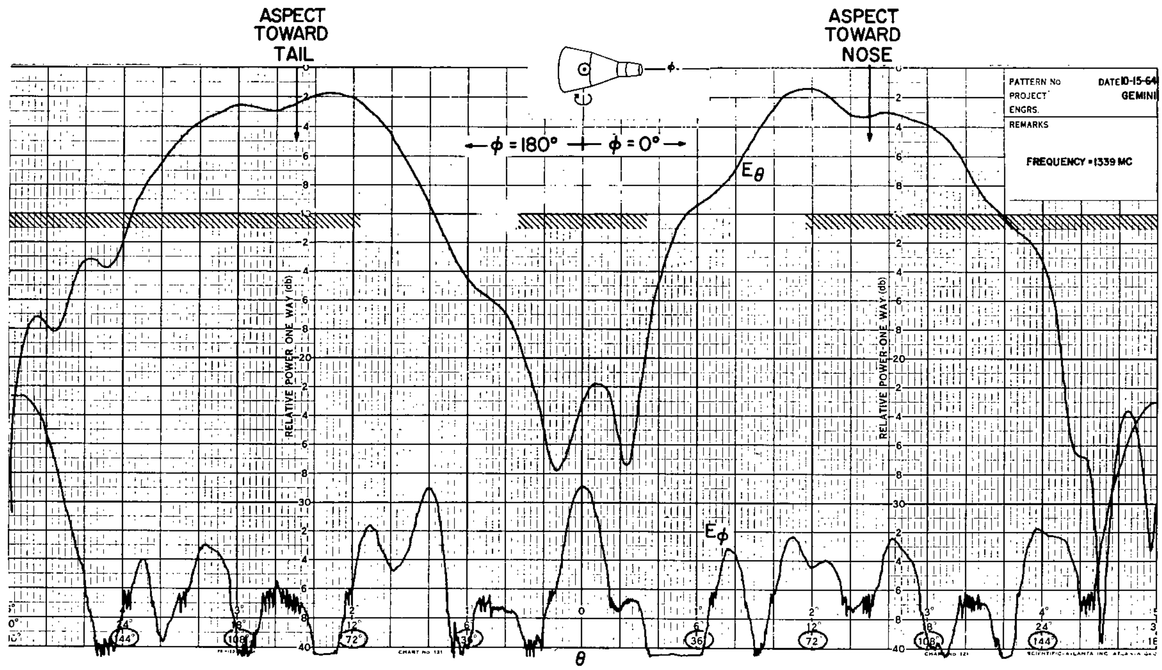


Fig. 6 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with ϕ = 0° and 180°

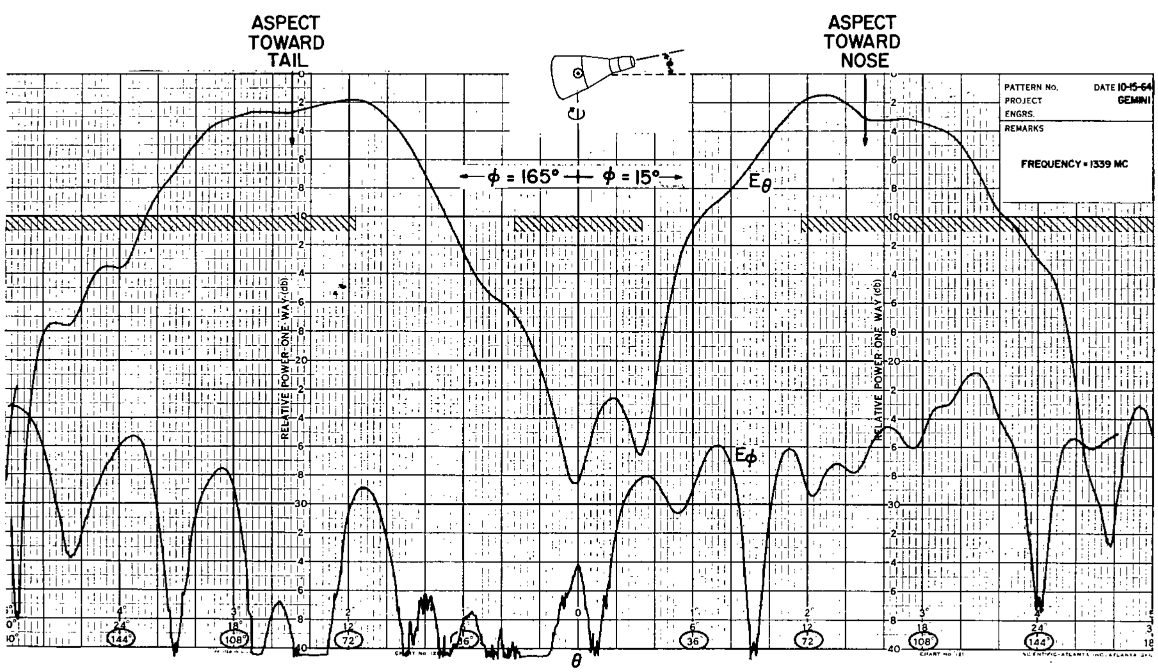


Fig. 7 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with ϕ = 15° and 165°

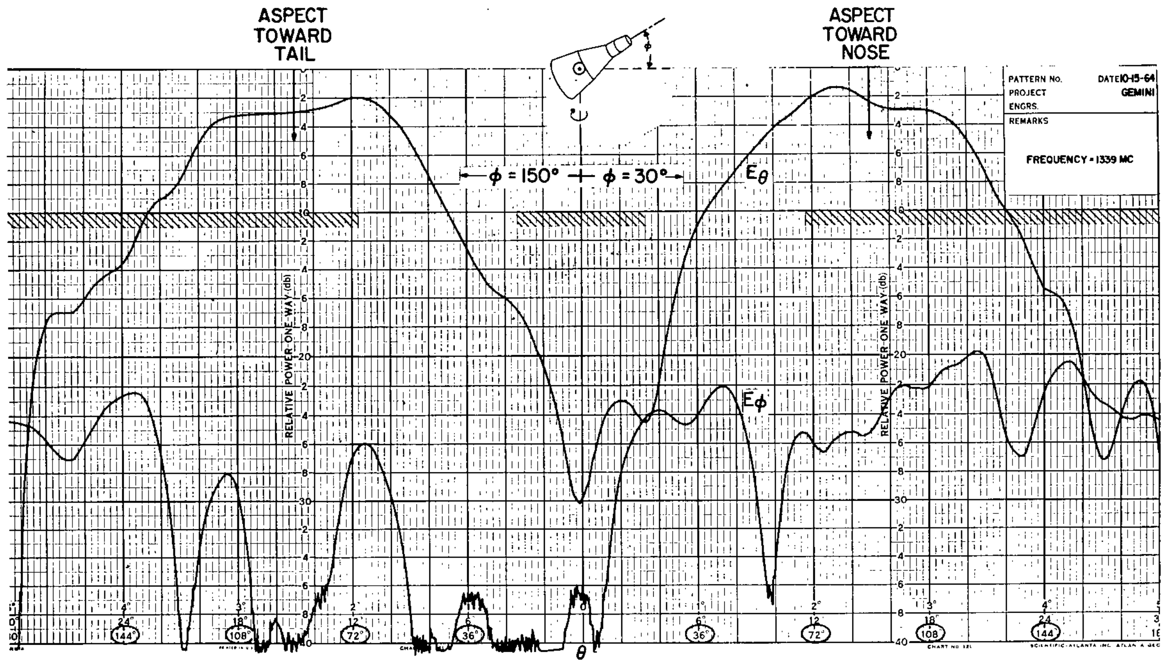


Fig. 8 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with ϕ = 30° and 150°

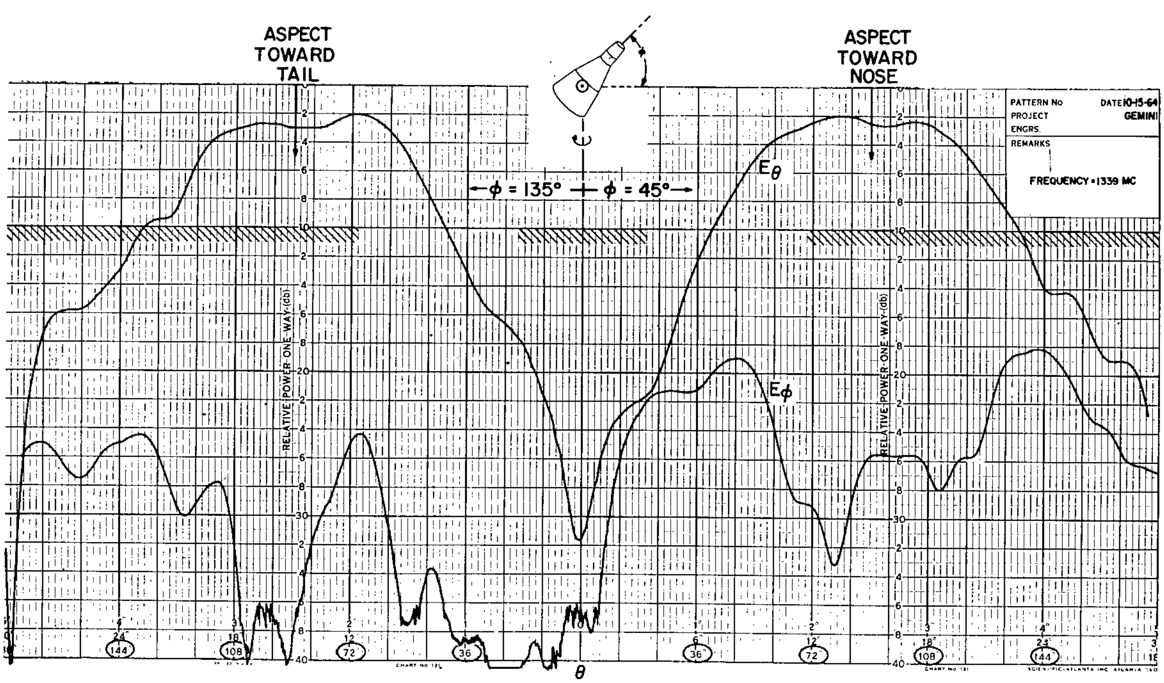


Fig. 9 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with ϕ = 45° and 135°

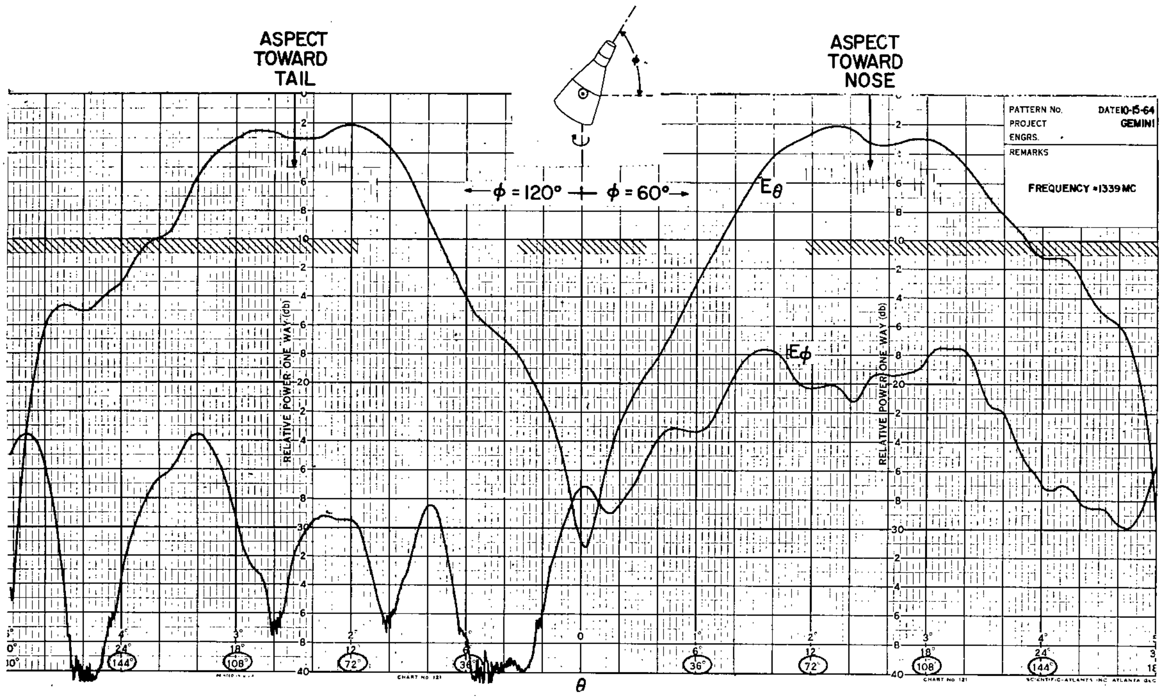


Fig. 10 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with $\phi = 60°$ and $120°$

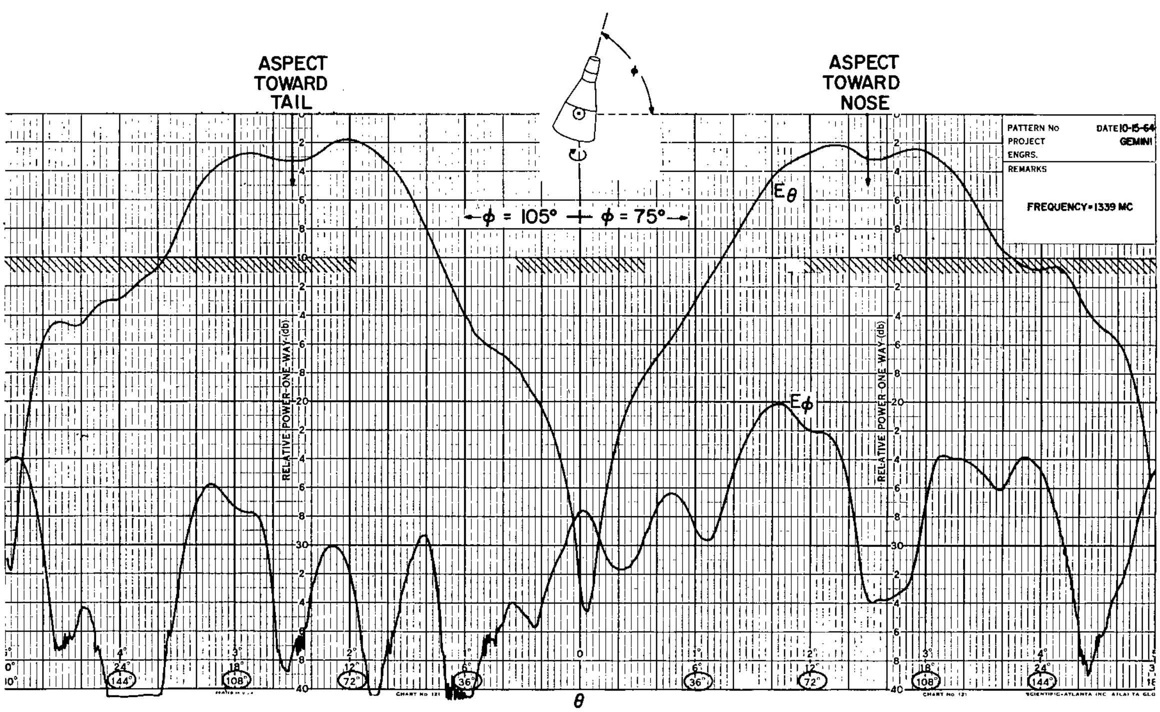


Fig. 11 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with $\phi = 75°$ and $105°$

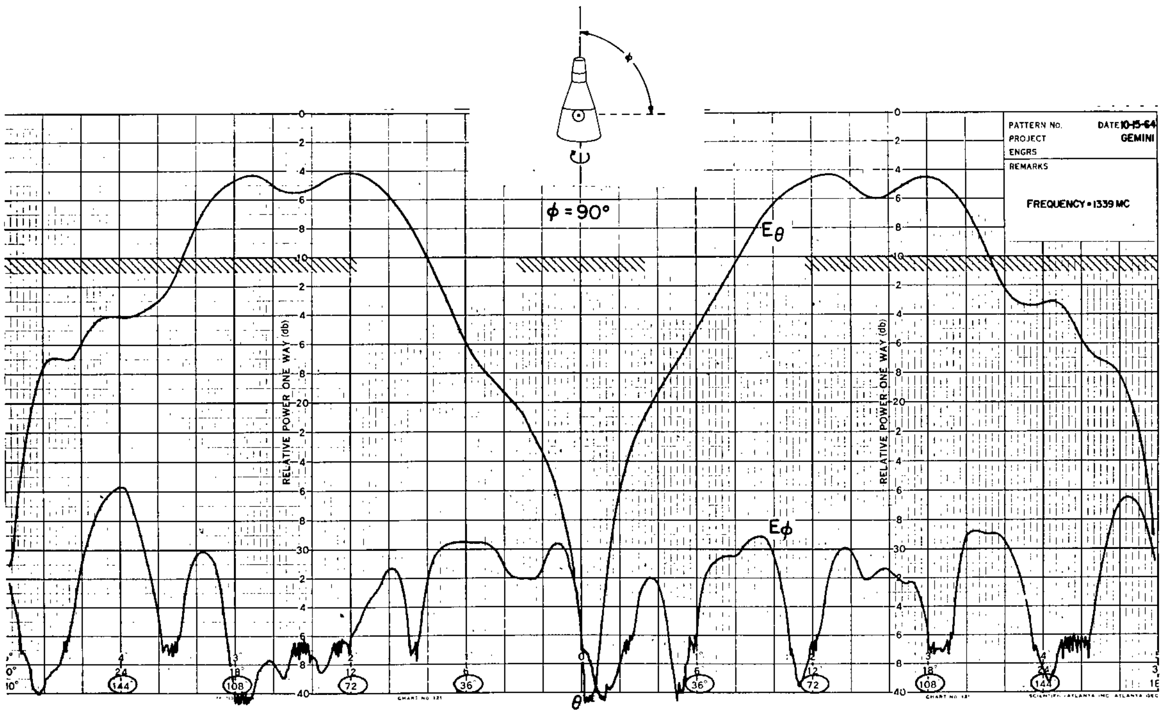


Fig. 12 - Direct- and cross-polarized patterns of the model antenna at 1339 Mc with $\phi = 90°$

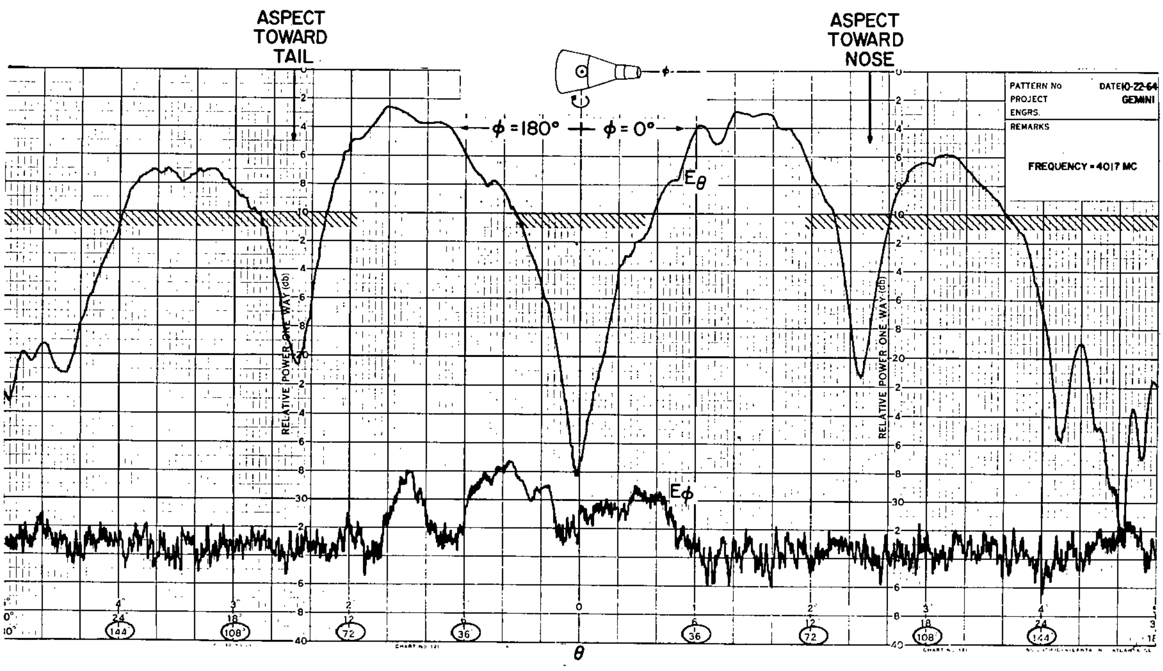


Fig. 13 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with $\phi = 0°$ and 180°

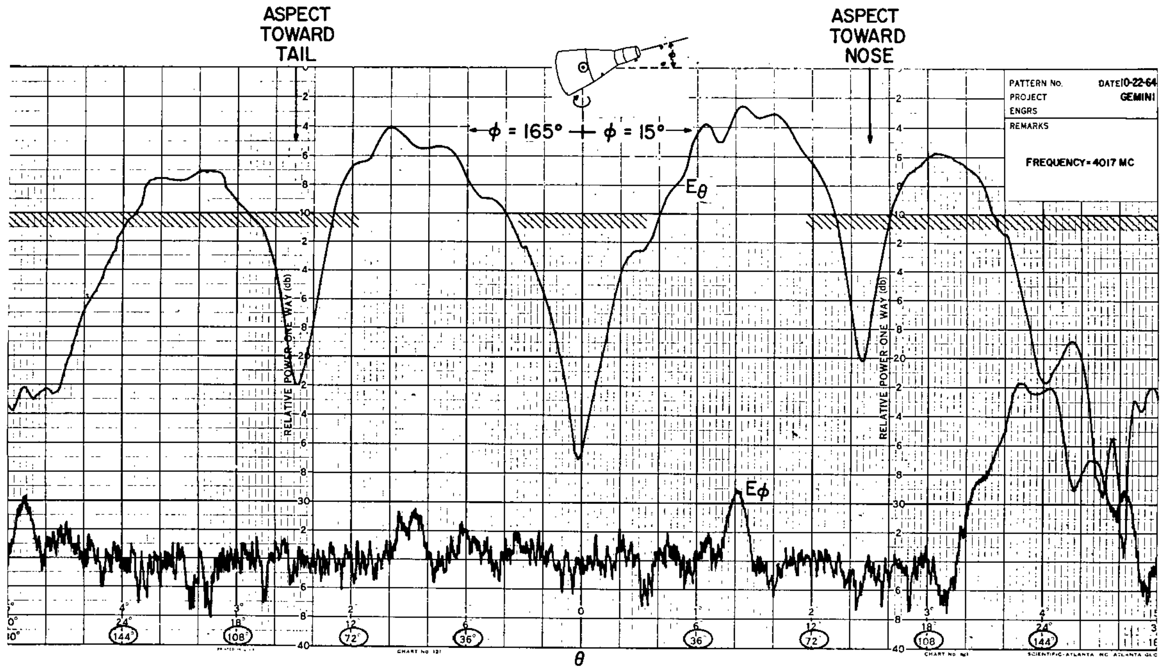


Fig. 14 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with ϕ = 15° and 165°

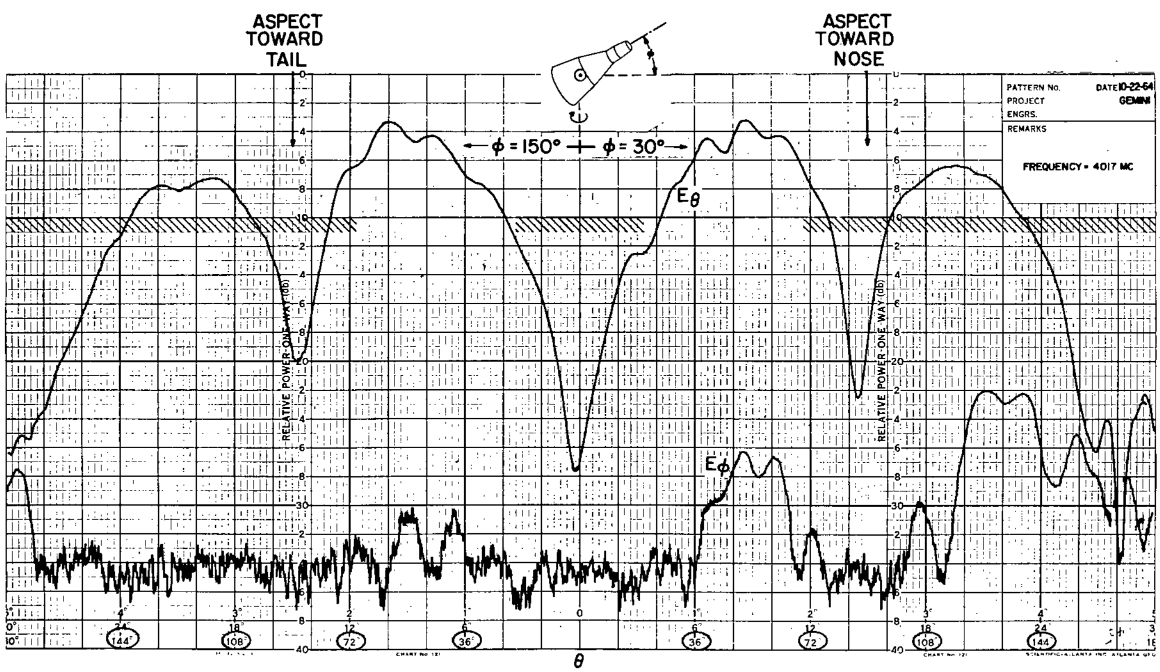


Fig. 15 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with ϕ = 30° and 150°

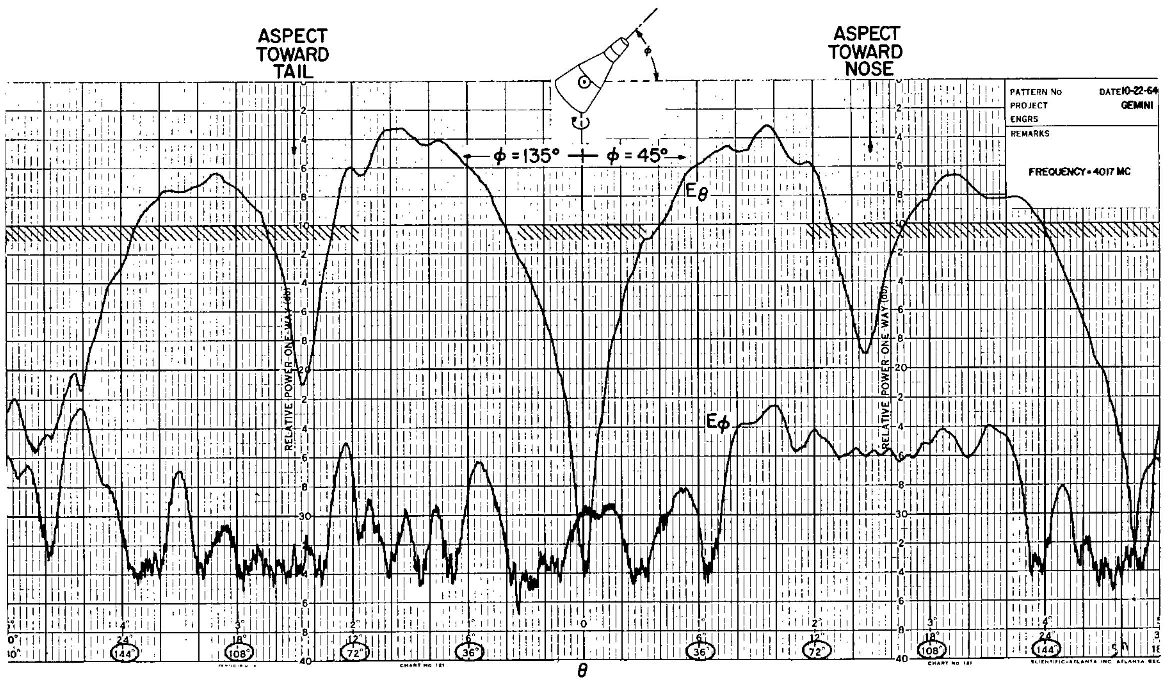


Fig. 16 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with $\phi = 45°$ and $135°$

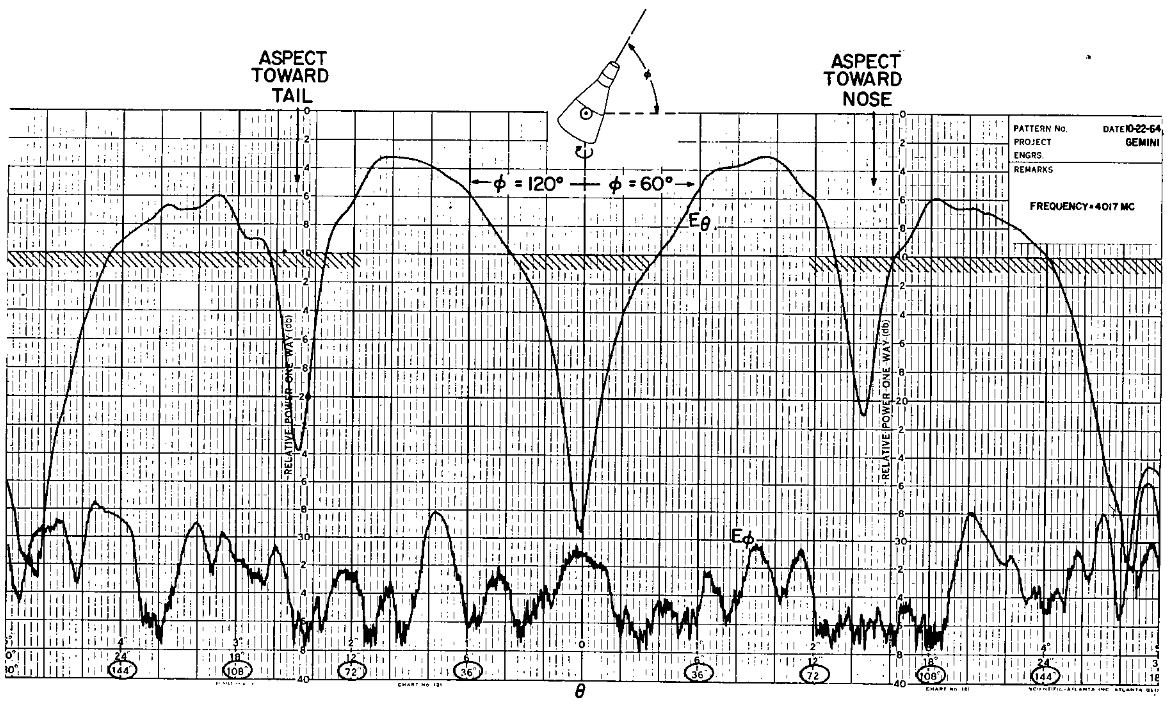


Fig. 17 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with $\phi = 60°$ and $120°$

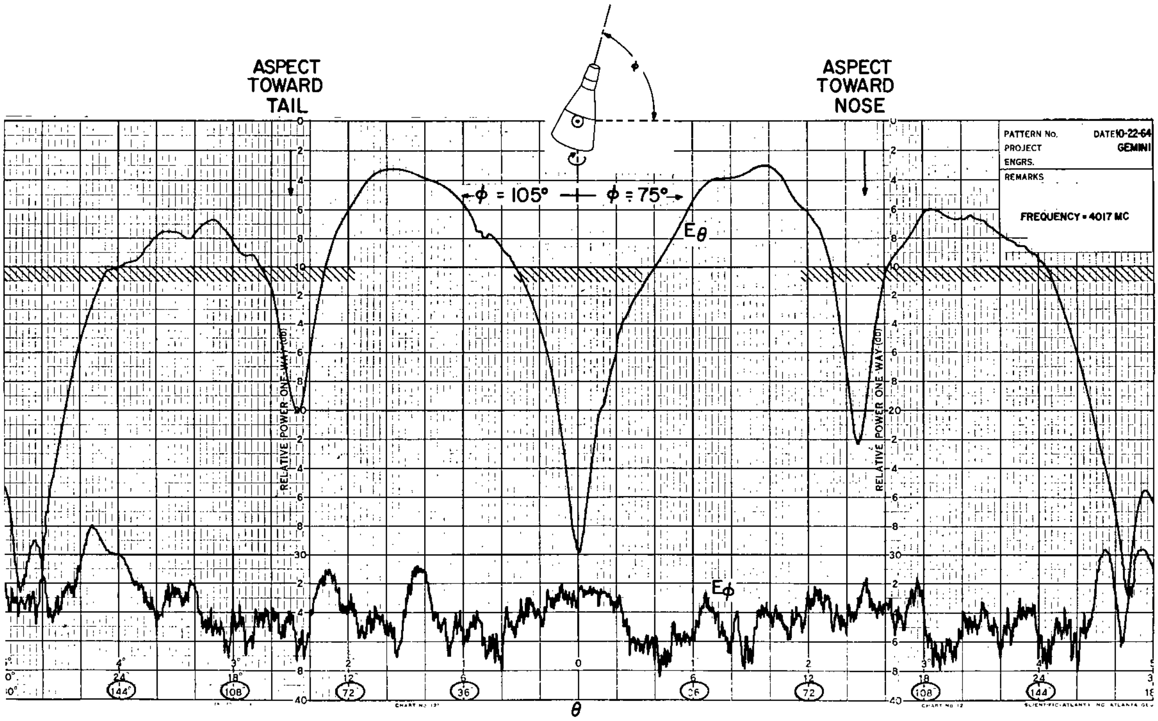


Fig. 18 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with ϕ = 75° and 105°

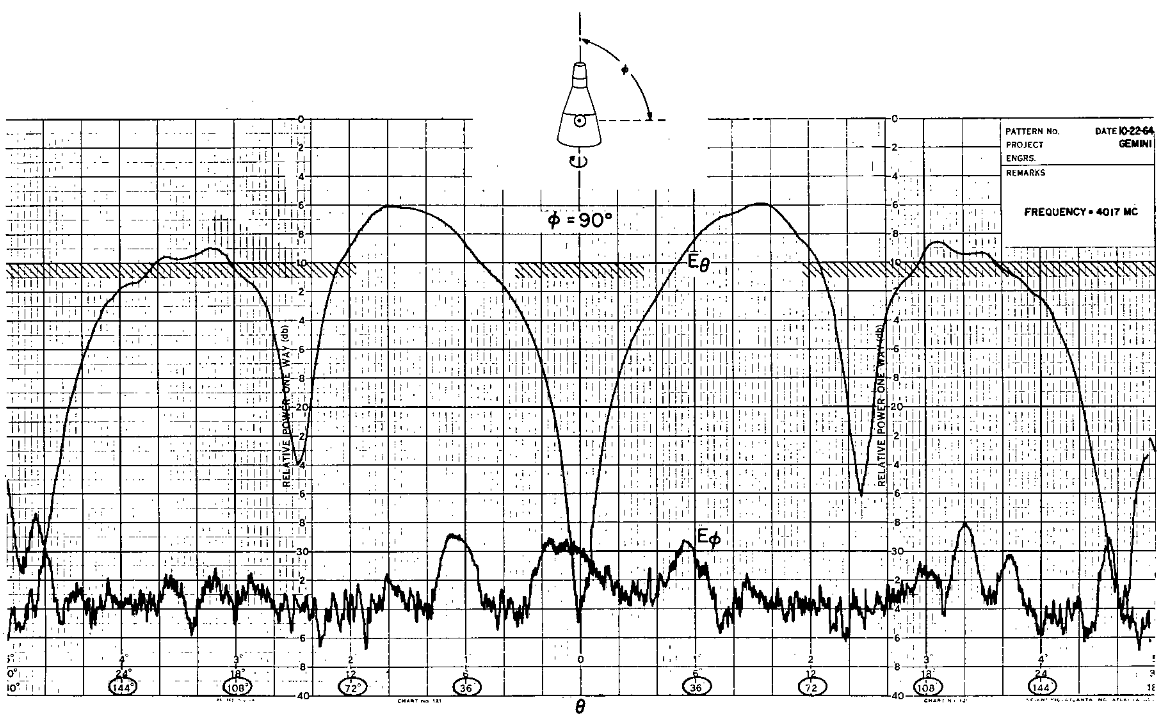


Fig. 19 - Direct- and cross-polarized patterns of the model antenna at 4017 Mc with ϕ = 90°

This is especially true when the patterns are considered from the viewpoint of an orbiting spacecraft and a ground-station observation point, as will be done later on in this report.

At 401.7 Mc (Figs. 13 through 19) the 1.5λ dipole presents a four-lobed E_θ pattern which is characteristic of this length radiator, with nulls off either end and also broadside to the antenna. This was judged to be acceptable, since for the application in the Gemini experiment the look angles from the ground station were expected to lie predominantly in the range of θ values from 20° to 70° (indicated by the open spaces between the horizontal shaded bars on each of the patterns), where the E_θ patterns show adequate coverage, and not near 0° and 90°, where the nulls occur.

At ϕ values of 0° and 90° at both frequencies the cross-polarized E_ϕ levels are acceptably low. However at intermediate values of ϕ, E_ϕ rises on the side of each pattern representing aspect angles which are oriented toward the nose of the spacecraft. This effect is most pronounced at 133.9 Mc (see Figs. 7 through 11). The rise of E_ϕ is caused by the shape of the antenna ground screen (the Gemini vehicle itself) which presents an asymetrical aspect in the θ plane except for the cases in which ϕ is 0°, 90°, and 180°. The practical significance of this fact was that in the performance of the Gemini D-14 experiment a sufficiently pure polarization, and therefore interpretable technical data, could be obtained only if the aspect angle of the vehicle as viewed from the ground station were restricted to orientations representing a general tail view.

It should be realized that D-14 was by no means a crucial experiment in the Gemini program. Like many other experiments aboard the various Gemini spacecrafts, this investigation was of secondary importance from the viewpoint of overall program objectives. Cooperation on the part of the Gemini crew had been planned to the extent of maneuvering the vehicle into position for the D-14 experiment. This was necessary because spacecraft limitations had required that the antenna be located on the top side of the vehicle. Thus, when within sight of the ground stations, it was necessary that the astronaut roll the spacecraft over to point the antenna toward the center of the earth for passes during which data were scheduled to be taken. However the restrictions dictated above by the pattern characteristics could perhaps have made further impositions on the astronauts' time and the spacecraft fuel cells that could not have been tolerated. Therefore some means was sought of controlling the station-to-vehicle aspect which would require a minimum of manuevering on the part of the spacecraft.

It is perhaps not readily evident how the antenna patterns of Figs. 6 through 19 are to be interpreted in regards to the station-to-vehicle aspects encountered in an actual experiment involving an orbiting spacecraft. It will be helpful to replot these data in a way which is more meaningful from the viewpoint of the ground-station observation point. The parameters selected for this purpose were the angles ϕ and ϵ. The angle ϕ is the same parameter used in recording the patterns and is the angle formed by the intersection of a vertical plane through the line of sight with a vertical plane through the spacecraft axis. This is illustrated in Fig. 5a and in the plan view of Fig. 20a. It can be seen that values of ϕ near 0° represent nose-oriented aspects of the spacecraft, while values near 180° represent tail-oriented aspects. The parameter ϵ is the elevation angle of the vehicle as viewed from the ground station. It is related to the parameter θ of the original patterns as shown in the elevation view of Fig. 20b. It can be seen in this view that the angle which the line of sight makes with the antenna axis is the angle θ. It follows, then, by the law of sines,

$$\frac{R}{\sin\theta} = \frac{R + h}{\sin(\epsilon + 90°)}$$

or

$$\frac{R}{\sin\theta} = \frac{R+h}{\cos\epsilon} .$$

So,

$$\epsilon = \cos^{-1}\left[\frac{R+h}{R}\sin\theta\right].$$

Using the parameters ϕ and ϵ, the antenna pattern data were replotted in Figs. 21 and 22 the form of E_θ/E_ϕ polarization contours for a Gemini spacecraft traveling in a circular orbit at a height h of 161 nautical miles. Only the data between $\theta = 0°$ and $\theta = 90°$ (refer to Figs. 6 through 19) were considered, since these would be the only portions of the radiation patterns observable from the surface of the earth. As was discussed earlier, no specific levels of E_θ/E_ϕ had been established beforehand. Therefore in the process of plotting these contours the pattern data were examined to determine the best compromise between a desirably high polarization ratio and a reasonably unrestricted operating region on the ϕ-ϵ plot. It was determined by examining various polarization levels that at 133.9 Mc E_θ/E_ϕ ratios of 25:1 (or 28 db) and greater would be accepted as most desirable, while ratios below 18:1 (or 25 db) would be undesirable. These ratios at vhf would correspond to angular errors in the polarization measurements of $\pm 2.3°$ (for 28 db) and $\pm 3.2°$ (for 25 db). In the vhf polarization contours of Fig. 21, therefore, region I represents E_θ/E_ϕ ratios 28 db and above, region II represents ratios between 27.9 and 25 db, and region III represents ratios below 25 db. This vhf signal of course provided the vernier measure of polarization, and of necessity had to be the more accurate of the two. The uhf signal on the other hand was to be used merely to resolve rotational ambiguities of $n\pi$ in the vhf signal; therefore the requirements for polarization purity of the uhf signal did not need to be as stringent. Thus the uhf contours in Fig. 22 represent E_θ/E_ϕ levels of 25 db and above (region I), 24.9 to 21.5 db (region II), and below 21.5 db (region II). This lower limit of 21.5 db represents an angular accuracy of $\pm 5°$ in the polarization measurement of the uhf signal and corresponds to an accuracy of $\pm 45°$, i.e. $(f_{uhf}/f_{vhf})^2 \times 5°$, in determining the position of the vector at 133.9 Mc. This is still adequate to resolve rotational ambiguities of $n\pi$ in the vhf signal.

It is apparent in considering Figs. 21 and 22 that flight-path restrictions due to the polarization requirements will be dictated by the vhf contours, since at uhf ample areas exist in which the polarization ratio is acceptable. The vhf contours of Fig. 21, on the other hand, show very restricted regions in which the polarization ratio is 28 db or greater. The region surrounding $\phi = 0°$ is quite narrow and would have necessitated very careful maneuvering of the vehicle during the pass to maintain the nose toward the station (to maintain an aspect angle ϕ equal to zero). The arc-shaped region in the upper left section of the diagram is larger and is useful for various aspect angles up to an elevation angle of about 45°. The spacecraft-control requirements in this region would have been less severe but still would have necessitated rather continuous maneuvering to keep the ϕ and ϵ coordinates of the spacecraft wholly within the preferred region. Therefore a compromise was sought which would reduce adjustments of the spacecraft orientation to a minimum while utilizing the preferred region to best advantage, even though this meant permitting portions of the passes to cross into less desirable regions of the E_θ/E_ϕ plot. Two such schemes considered for orienting the spacecraft were (a) maintaining the nose of the spacecraft at some fixed geographic or magnetic bearing and (b) maintaining the axis of the spacecraft perpendicular to the flight path with the nose oriented so that it would be pointing away from the ground station when the spacecraft made its closest approach.

From a preflight listing of projected paths of the Gemini flights over the two ground stations the ϕ and ϵ coordinates of sample passes were calculated to investigate their relationship with the polarization contours of Fig. 21. This investigation showed that

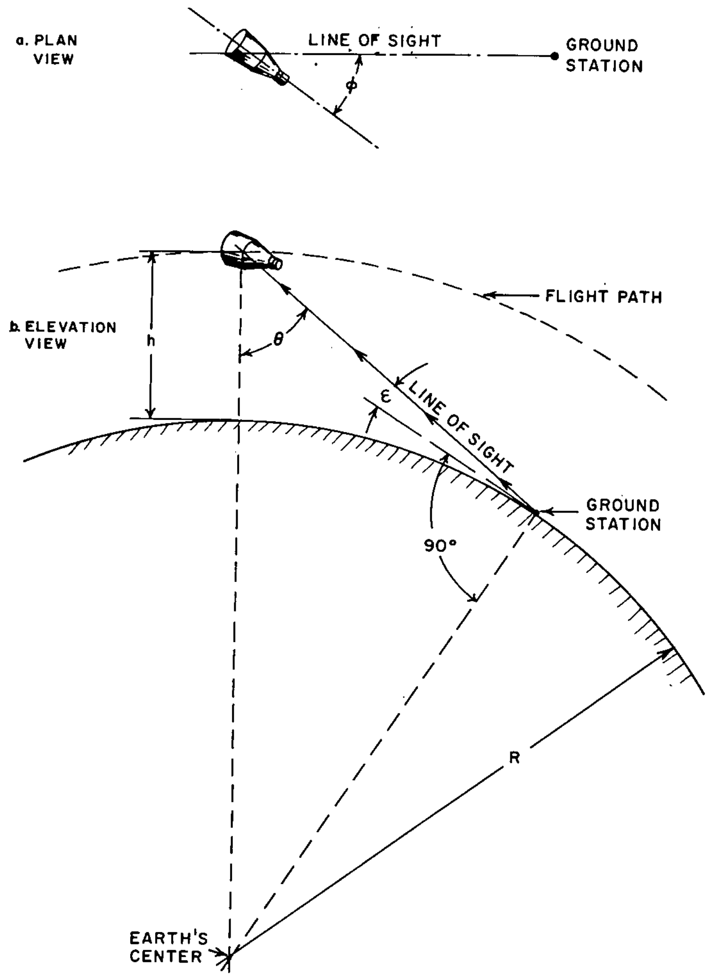


Fig. 20 - Parameters used to replot in Figs. 21 and 22 the antenna pattern data given in Figs. 6 through 19

approach (b) above gave a better utilization of the desirable regions. This approach, fortunately, was also preferred by the astronauts themselves, who considered it the simplest method of all those which had been considered for controlling spacecraft orientation.

For further elucidation of this scheme the paths of several sample passes are depicted in Fig. 23 on a polar plot of ranges and bearings from a tracking station. The arrows along each flight path indicate the constant orientation of the nose of the spacecraft during that pass. Thus, on a pass which would take the spacecraft north of the station at its closest approach (e.g., passes 1 and 2) the nose was oriented in a northerly direction, while if the spacecraft were to pass south of the station (e.g., passes 3 and 4) the nose was oriented in a southerly direction.

In Fig. 24 three sample passes have been plotted in the ϕ-ϵ coordinate system and superimposed on the vhf polarization contours. The reason for depicting these specific paths will be treated shortly; they are not, incidentally, identical with any of the passes shown in Fig. 23. In the ϕ-ϵ representation of Fig. 24 the paths are actually doubly traversed during a single pass; that is, as the spacecraft rises above the horizon (at $\epsilon = 0°$) the elevation angle rises along the curve to some maximum at the point of closest approach (where $\phi = 180°$) and then descends along the same curve back to $\epsilon = 0°$. The reason for

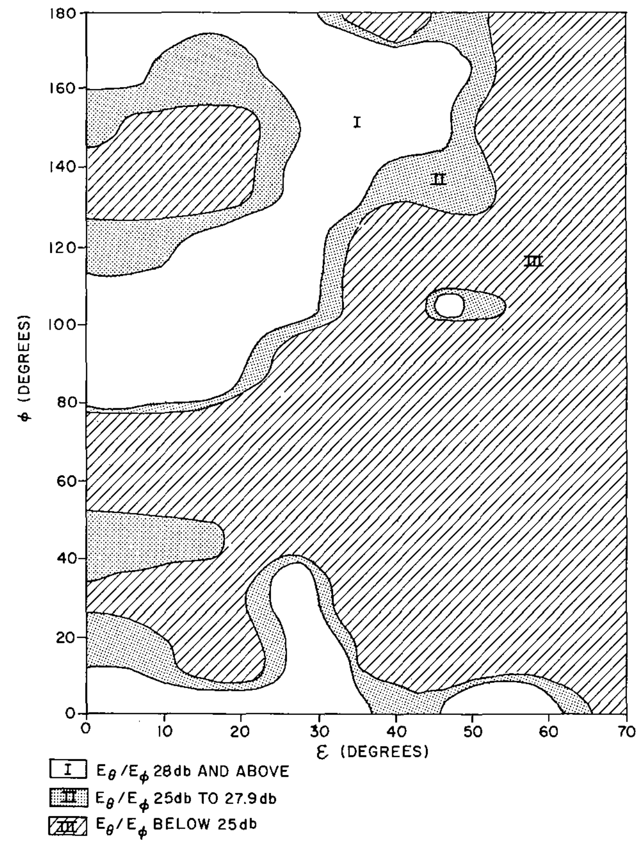


Fig. 21 - E_θ/E_ϕ contours for the Gemini vehicle antenna at 133.9 Mc (spacecraft altitude = 161 nautical miles)

this can be discerned by referring back to Fig. 23 in which it should be noted that both the elevation angle (ϵ) and the aspect angle (ϕ) of the spacecraft viewed from the ground station are symmetrically disposed about the point of closest approach.

Of the curves depicted in Fig. 24, path (b) is clearly the most desirable since it stays predominantly in region I. The question arose, however, as to what portion of the Gemini passes over the ground stations could reasonably be expected to follow paths such as (b). For an answer to this the preflight listing of anticipated flight paths was again examined. Referring to Fig. 23, it should be apparent that because the orientation of the spacecraft is perpendicular to the flight path, the ϕ and ϵ coordinates are the same for all passes which achieve the same maximum elevation angle, regardless of the angle which the path of the spacecraft makes on the polar diagram. Thus, because passes 2 and 3 in Fig. 23 reach their point of closest approach the same distance from the center of the polar diagram and therefore have the same maximum elevation angle, they will appear as identical curves when plotted in the ϕ-ϵ coordinate system of Fig. 24. This fact provided a simplified means of analyzing the anticipated flight paths to determine how well they would utilize the preferred regions of the polarization diagram. The maximum elevation angles of the passes over the two ground stations were tabulated and are depicted as circles above the contour plot of Fig. 24. These maximum angles can be conceived to fall into three general groups: those with low, medium, and high maximum elevation angles. Therefore, as representative of the three groups, complete spacecraft-path curves were drawn to the median of each of the groups. This is the significance of the curves labeled (a), (b), and (c).

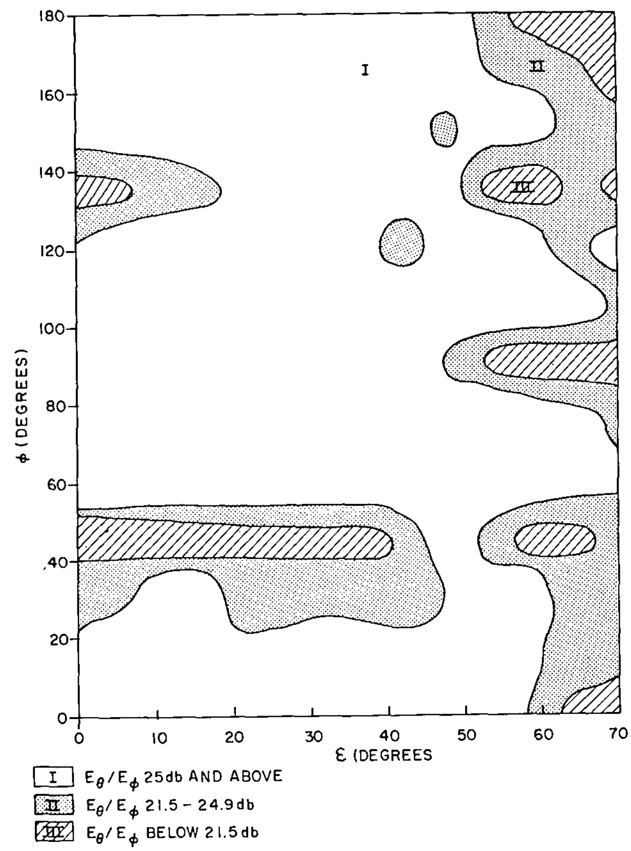


Fig. 22 - E_θ/E_ϕ contours for the Gemini vehicle antenna at 401.7 Mc (spacecraft altitude = 161 nautical miles)

It can be seen that most of the passes would be at low elevation angles corresponding to curve (a). However twelve of the passes would be at the intermediate elevation angles corresponding to the preferred path (b). In the early planning of the vhf-uhf polarization experiment it had been anticipated that fifteen to twenty data-taking passes for the two Gemini flights would be all that could reasonably be expected, considering the secondary status of the experiment. This number however was judged to be adequate to provide sufficient data for significant results. Therefore if eight or ten of the twelve passes indicated in the intermediate region of Fig. 24 were utilized on each flight, the experiment would quite successfully achieve its objectives. Even if, because of conflicts with other more critical Gemini objectives, it became necessary to accept others of the possible passes (i.e., some of those centered about curves (a) and (c)) the goals of the experiment might still be achieved, although with correspondingly reduced accuracy in the results.

Impedance Matching

As mentioned previously pattern considerations and physical size restrictions took precedence in determining the lengths of the dipole elements of the vehicle antenna. Therefore, once these parameters had been set, no adjustments were possible for matching the antenna to the 50-ohm feed line. The antenna had to be matched to the feed line at both frequencies in the restricted space available inside the rigid lower element/choke combination with a single coaxial line transformer. The original VSWR's of the antenna when fed directly from the 50-ohm line were in excess of 10:1 at both frequencies. Because of these large initial mismatches, several attempts were required to arrive at an acceptable transformer, each one providing a better starting point from which an improved

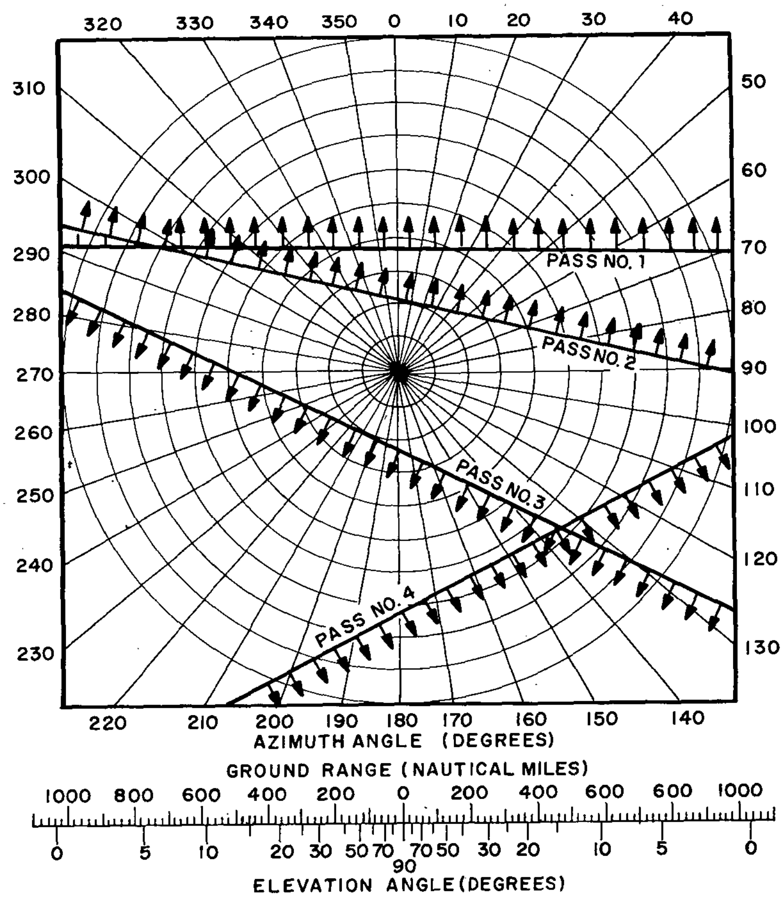


Fig. 23 - Gemini orbital paths as viewed from a tracking station. The scales at the bottom give the ground range and elevation angle ϵ when the spacecraft is at an altitude of 161 nautical miles. These parameters can be determined by measuring the radial distance from the center of the plot to a point on the orbit and laying this length off on the scales from zero ground range (or $\epsilon = 90°$).

transformer could be designed. The final transformer design is shown in Fig. 25. The residual mismatches with this transformer were 2.9:1 at 133.9 Mc and 1.5:1 at 401.7 Mc.

Final Models

The first final model of the Gemini D-14 vehicle antenna was constructed in the NRL shop in August 1964 and is shown in Fig. 26. The lower radiating element was a 2-inch-diameter aluminum tube coated with type C4 white radiator paint applied by McDonnell Aircraft Corporation to minimize thermal expansion gradients between the aluminum sleeve and the dielectric of the choke inside the sleeve. The dielectric-loaded choke was $\lambda/4$ at 133.9 Mc and $3\lambda/4$ at 401.7 Mc. The upper radiating element was a double-folded spring-loaded antenna of a type developed by the Satellite Techniques Branch at NRL and used many times as a telemetry antenna on numerous satellites.

The vehicle antenna in its folded configuration is shown in Fig. 27. While the unit was in its retracted position the upper element was restrained in this folded configuration by the housing in which the antenna nested in the Gemini spacecraft. During erection and once

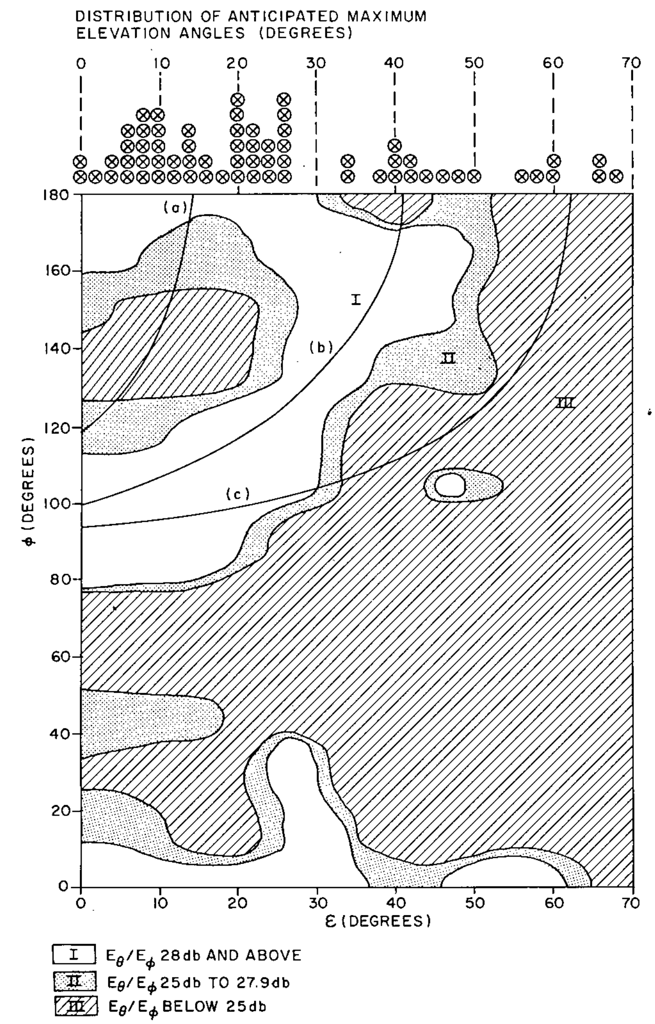


Fig. 24 - Gemini spacecraft paths superimposed on the 133.9-Mc polarization contours (spacecraft altitude = 161 nautical miles)

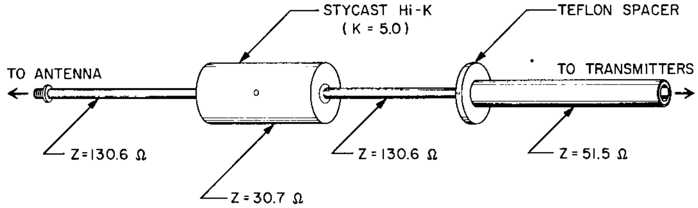


Fig. 25 - Impedance-matching transformer for the vehicle antenna

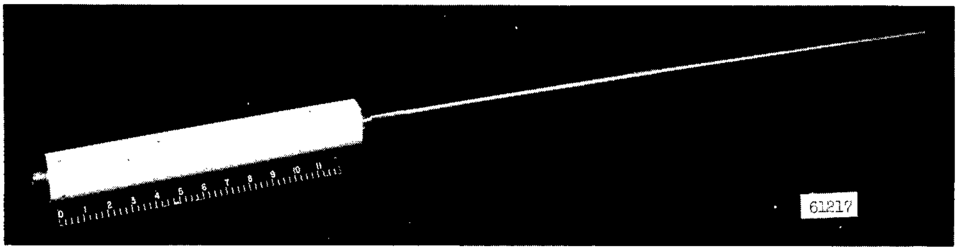


Fig. 26 - The Gemini vehicle antenna it its operating configuration

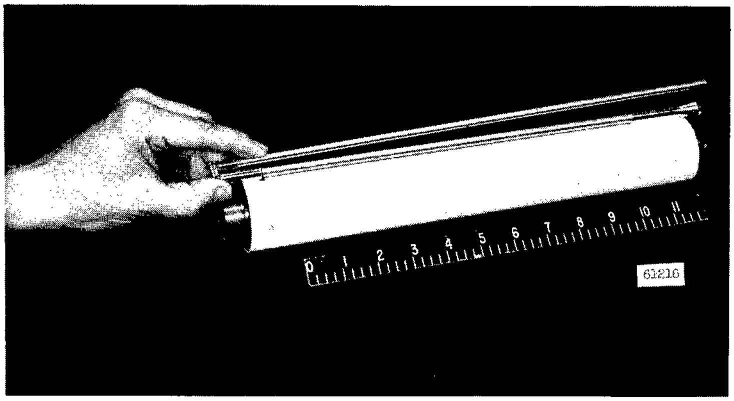


Fig. 27 - The Gemini vehicle antenna in its folded configuration

the antenna was clear of the housing, the upper element was snapped into its operating position by springs in the two joints of the antenna. Connection to the type RG-188/U feed line was made at the bottom of the lower element by means of a TNC coaxial connector.

Figure 28 shows the antenna attached to the boom along with the boom-operating mechanism. The overall weight of the antenna itself (exclusive of the boom and boom-operating mechanism) was slightly less than 2 pounds. The design of the vehicle antenna was such that it could not be fully retracted. The boom could be restowed automatically but the upper element could only be refolded manually. It was felt that this should present no real problem, since the retroadaptor section on which the antenna was located was to be separated from the cabin module prior to reentry. The folding technique would by then have served its purpose of keeping the antenna beneath the surface of the spacecraft during launch.

In all, five final models were built, one of which was subjected to the following environmental tests:

1. Shock and vibration
2. Heat soak (+160°F for 25.5 hours)
3. Cold soak (-60°F for 26 hours)
4. Hot-cold cycle (+160°F to -60°F in eight cycles of 2 hours each)
5. Humidity (95% relative humidity for 10 days)
6. Acoustical noise.

After each test the model was inspected visually for damage, and the VSWR's were measured at both frequencies and compared with the pretest values. After the humidity test

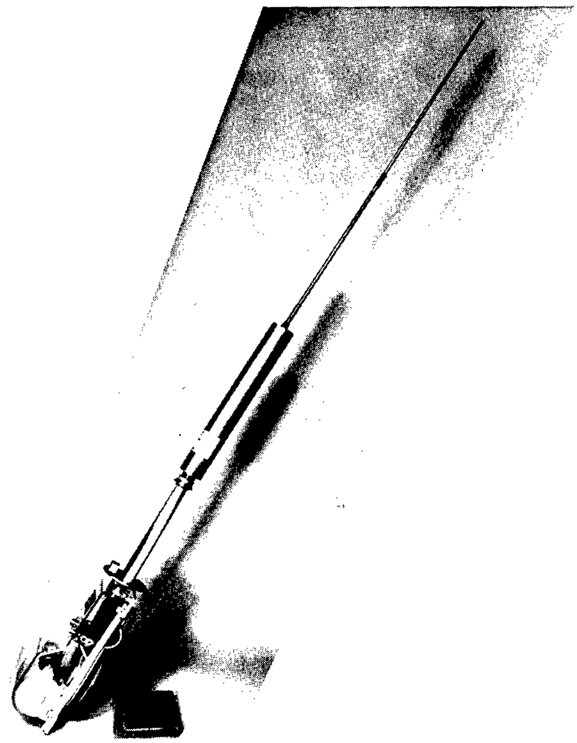


Fig. 28 - The antenna attached to the boom and boom-operating mechanism

small spots of corrosion were noticed under the coating of white radiator paint on the lower element. This was apparently occasioned by pinholes in the coating which had exposed the underlying aluminum to the highly humid environment. The problem was judged to be not serious enough, however, to justify remedial measures. Other than this minor problem, the antenna withstood the environmental tests without change in its physical or electrical characteristics.

GROUND-STATION ANTENNAS

Reflectors and Pedestals

The ground-station receiving antennas were located at Barking Sands on Kauai in the Hawaiian Islands and at the NASA tracking site on Antigua in the British West Indies (Figs. 29 and 30). Since tracking was passive, the antenna control systems were slaved to nearby active tracking radars.

The antenna reflectors were both D.S. Kennedy Model 350 28-foot paraboloids with a focal length of 12 feet. These antennas were acquired from surplus from the U.S. Army at Fort Monmouth, New Jersey. The screen mesh covering the surface could be used up to S-band and was therefore more than adequate for this application at vhf and uhf.

The pedestals and towers were purchased on contract and were required to be fitted to these antennas. The pedestals are capable of maximum tracking rates of 5°/sec in azimuth and 0.5°/sec in elevation. Maximum acceleration is 0.5°/sec^2 and pointing

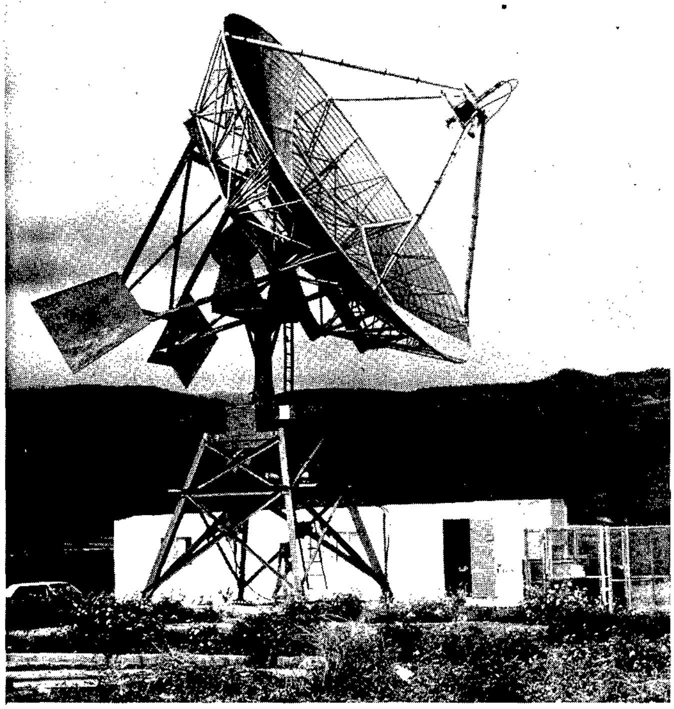


Fig. 29 - The tracking site on Kauai, Hawaii

Fig. 30 - The tracking site on Antigua, British West Indies

accuracy capability is 0.25° in both azimuth and elevation. These specifications were established on the basis of anticipated orbital parameters as viewed from the two tracking stations. (The pedestal at the Kauai site was built by Lear Siegler, Inc., of Deep River, Connecticut. The Antigua pedestal was manufactured by Antlab of Worthington, Ohio.)

The Feed System

A dual-frequency dual-polarized feed system was required for the ground-station antennas in order that all the necessary data be received for satisfactorily fulfilling the objectives of the D-14 experiment. All necessary data might have been received most simply by feeding the antenna with two sets of crossed dipoles arranged in tandem and situated in front of a flat reflector to achieve desirable primary beamwidths in both E and H planes. However this arrangement has the disadvantage that the vhf dipoles act as reflectors for the uhf dipoles, with the result that the phase centers of the two sets of radiators are different and the feed cannot be focused in the parabola for both frequencies. Therefore a feed was designed in which the radiators lay in the same plane at both frequencies. This feed is diagrammed in Fig. 31 which shows, in functional form, an element for one polarization. The finished feed comprised two of these elements mounted at right angles to provide for dual-polarized reception. The element (Fig. 31) is so constructed that at 401.7 Mc the antenna radiates predominantly along length A, while at 133.9 Mc the entire dipole (length B) is active. This is effected by the incorporation of choke sections, C. These polystyrene-loaded chokes, each of which is $\lambda/4$ long at 401.7 Mc, serve to isolate the antenna currents at that frequency from the outer sections of the dipole, thereby giving an effectively shorter, and closer to resonant, dipole. At 133.9 Mc the chokes are only $\lambda/6$ long and, although introducing some reactance, permit the entire element length to be active. Line D is a section of RG-9/U flexible coaxial cable which serves as a balun for the dipole. This balun is $\lambda/2$ long at 133.9 Mc and $3\lambda/2$ long at 401.7 Mc.

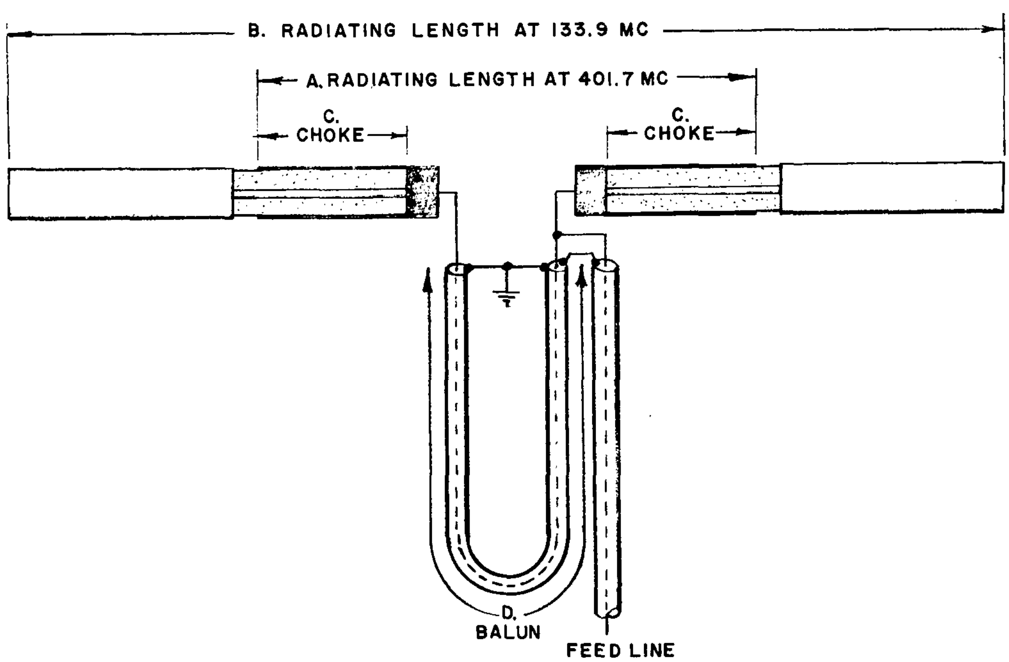


Fig. 31 - Functional diagram of a dual-frequency element for the feed of the 28-foot parabolic ground-station antennas

The original attempt in designing this dual-frequency dipole was directed toward obtaining an element which would be close to resonant at both of the design frequencies. This meant making the central segment and each of the outer segments of the radiator $\lambda/2$ long at 401.7 Mc, so that the overall length would be $\lambda/2$ long at 133.9 Mc. However it was found in making primary pattern measurements with this experimental model at 401.7 Mc that the E-plane pattern was too narrow for efficient illumination of the 28-foot reflector. It was apparent that coupling to the outer segments (which were resonant at 401.7 Mc) was increasing the effective size of the radiator with a consequent detrimental change in the beamwidth. Therefore these outer segments were shortened to the point at which they had a negligible effect on the pattern of the 401.7 Mc central element. Thus in the final model of the feed the uhf radiating length of each dipole arm was 7.38 inches (or 0.25λ) and the vhf radiating length was 18.16 inches (or 0.21λ).

The position of the cross-dipole feed in front of its ground screen was also determined experimentally. Since this spacing in terms of wavelengths was different for the two frequencies, it had a disproportionate effect on the two sets of patterns. Therefore the spacing was adjusted to give the best compromise of illumination tapers for the E- and H-plane patterns at the two frequencies. This resulted in a dipole-to-screen spacing of 11 inches.

The primary patterns of the feed are shown in Figs. 32 through 35, which also indicate the extent of the aperture being illuminated. Figure 36 is a photograph of the finished feed mounted on the ground-screen frame which also served as a structural support for the four booms supporting the feed. The RG-9/U cables seen wrapped around the 1-5/8-inch rigid coaxial feed lines in the picture are the half-wavelength baluns for the feed.

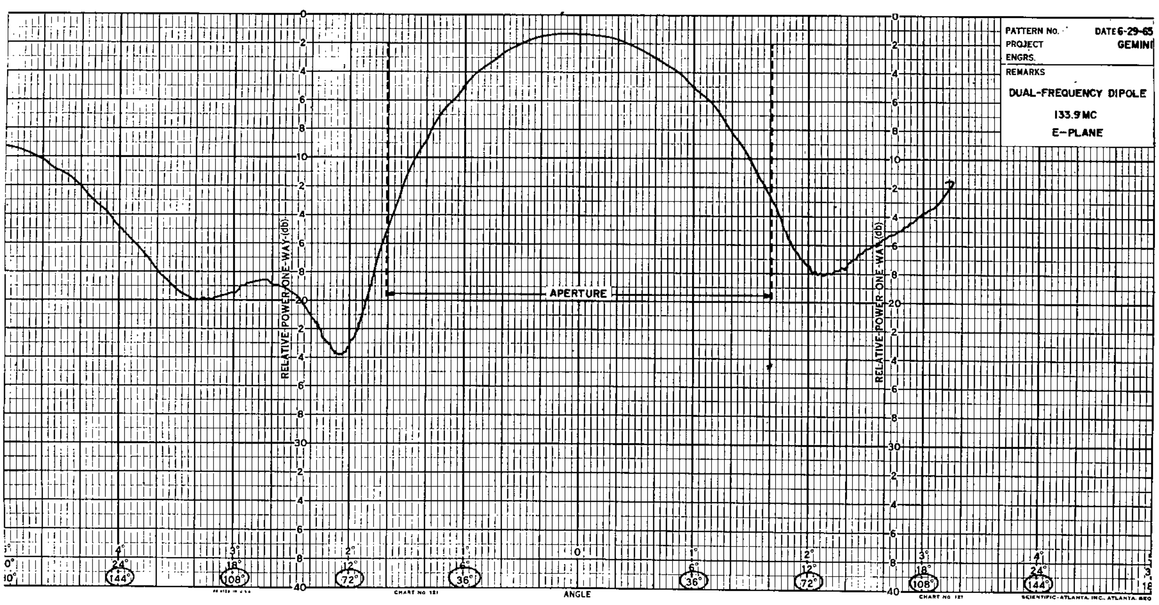


Fig. 32 - Primary E-plane pattern at 133.9 Mc of the dual-frequency dual-polarized ground-station-antenna feed

Secondary patterns were taken at NRL with the feed in place at the focal point of one of the 28-foot parabolic antennas (Figs. 37 through 40). It will be noted that at both frequencies side-lobe levels are lower in the E plane (Figs. 37 and 39) than in the H plane

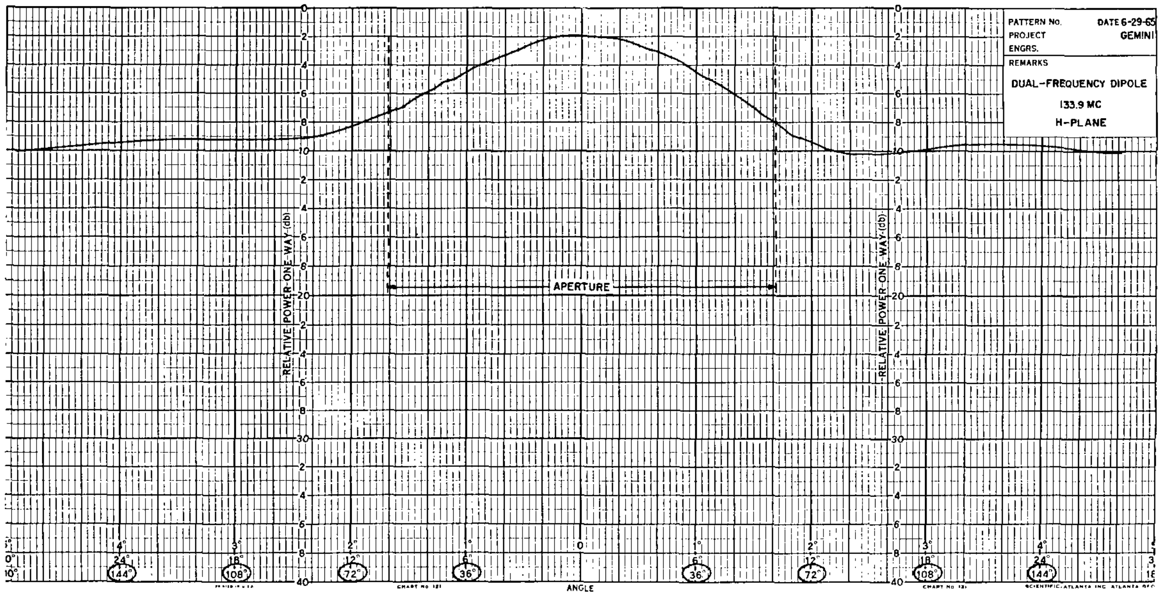


Fig. 33 - Primary *H*-plane pattern at 133.9 Mc of the dual-frequency dual-polarized ground-station-antenna feed

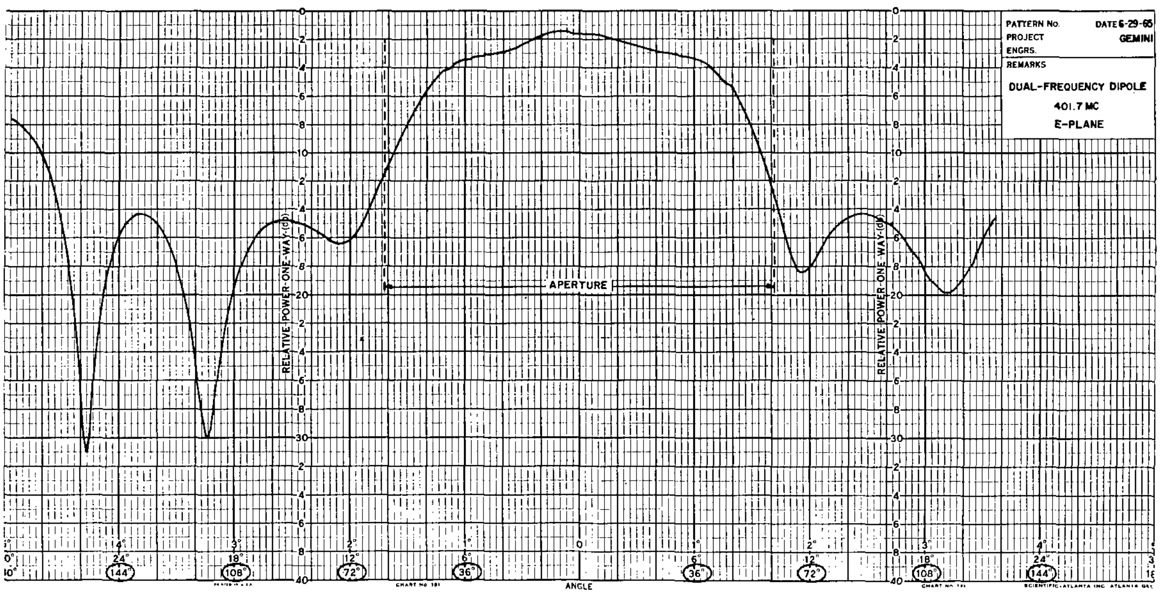


Fig. 34 - Primary *E*-plane pattern at 401.7 Mc of the dual-frequency dual-polarized ground-station-antenna feed

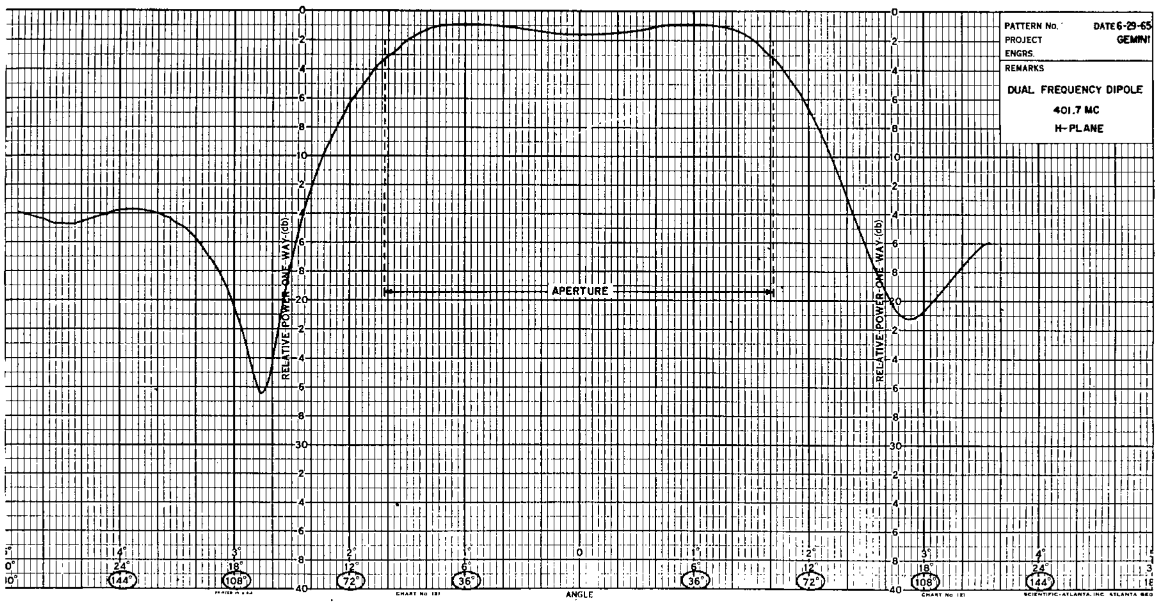


Fig. 35 - Primary H-plane pattern at 401.7 Mc of the dual-frequency dual-polarized ground-station-antenna feed

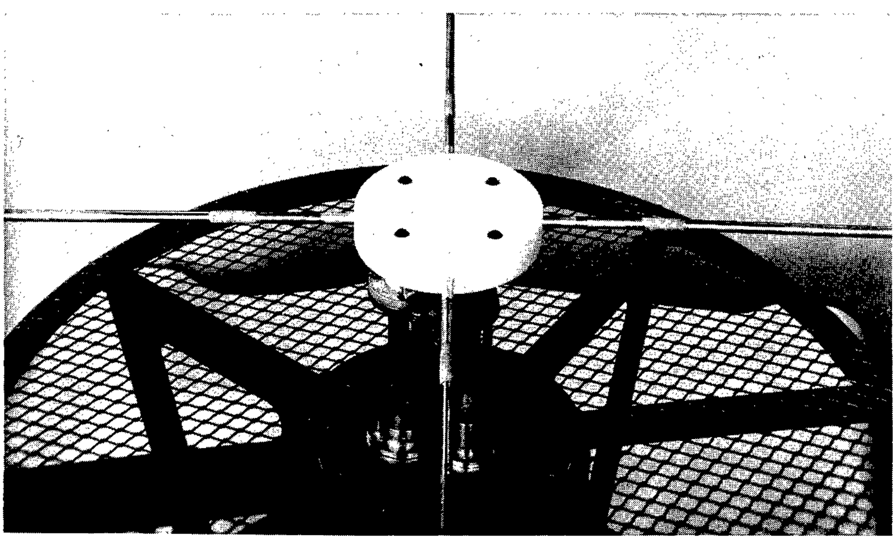


Fig. 36 - The dual-frequency dual-polarized feed for the 28-foot parabolic ground-station antenna

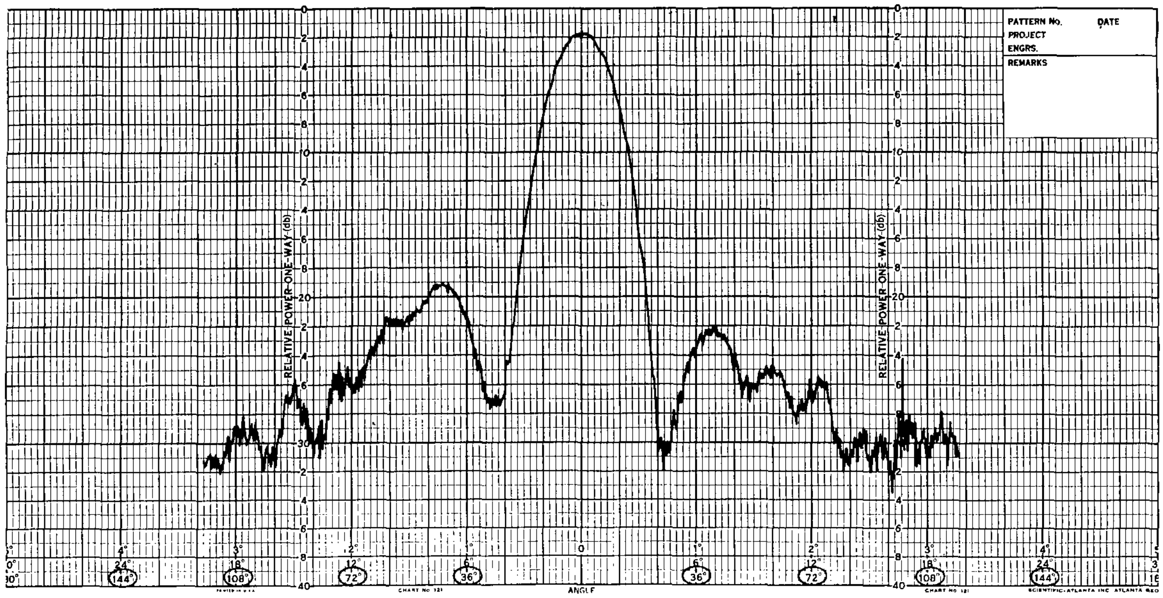


Fig. 37 - E-plane pattern (E_θ) at 133.9 Mc of the Gemini ground-station antenna

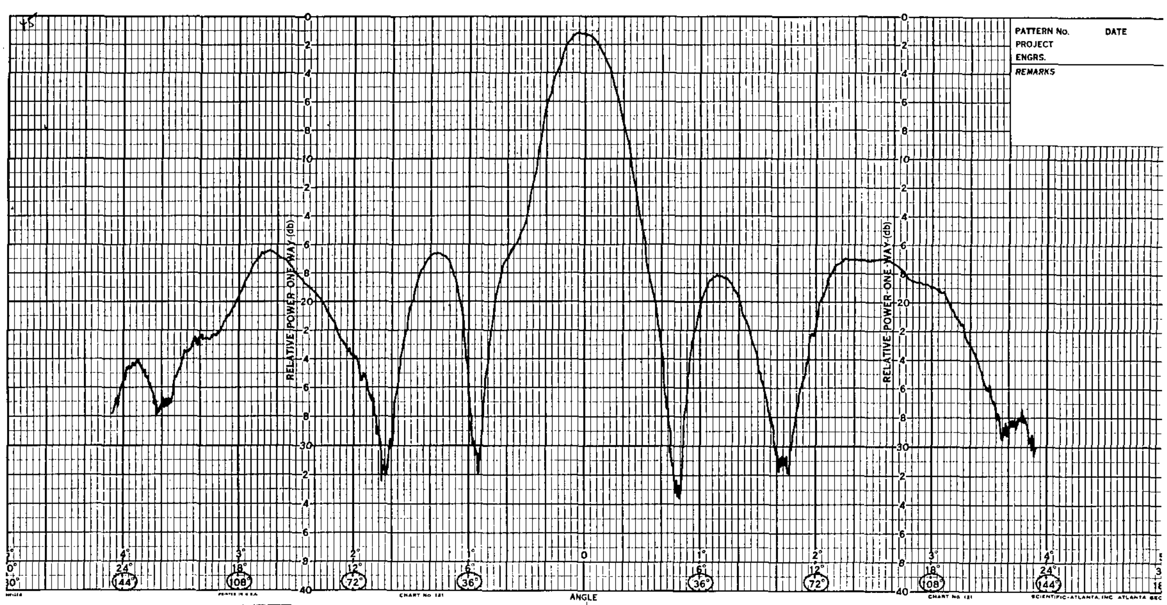


Fig. 38 - H-plane pattern (E_θ) at 133.9 Mc of the Gemini ground-station antenna

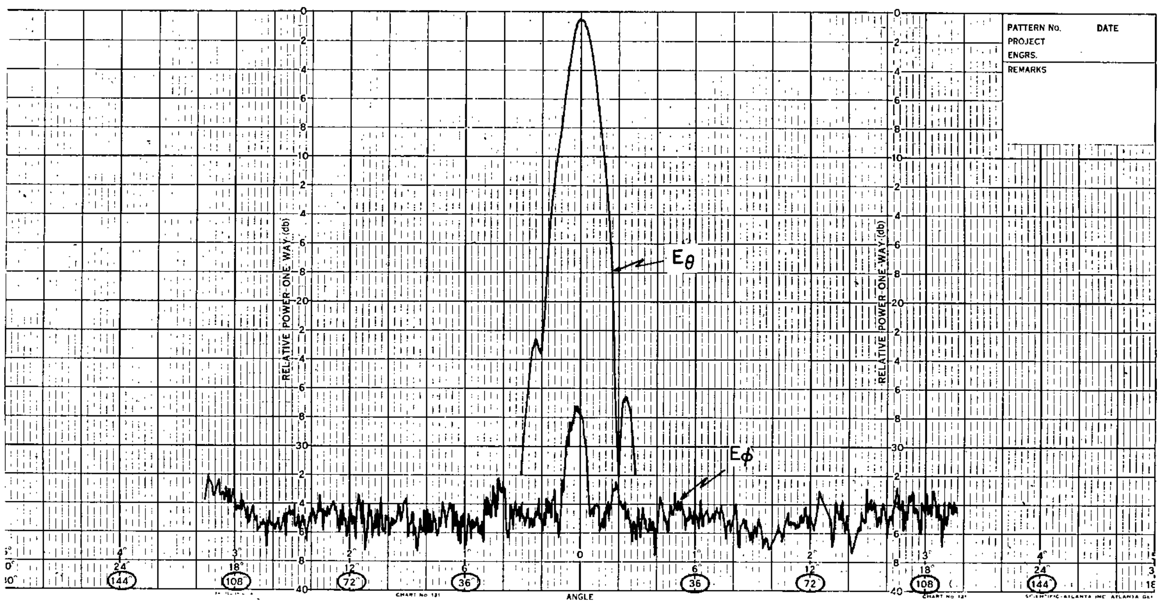


Fig. 39 - E-plane patterns (E_θ and E_ϕ) at 401.7 Mc of the Gemini ground-station antenna

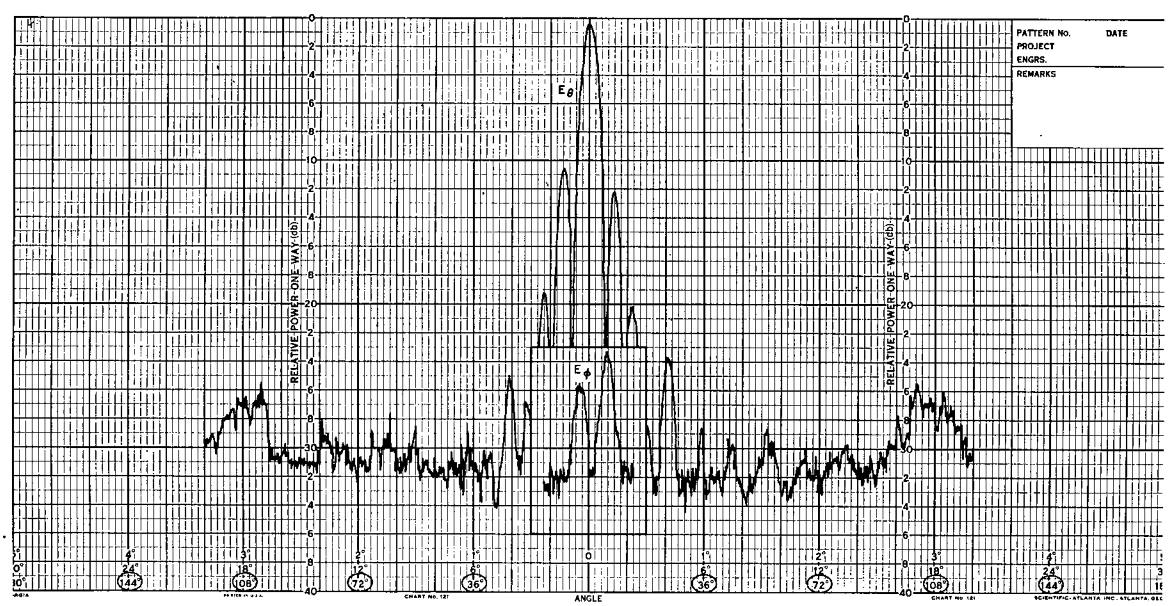


Fig. 40 - H-plane patterns (E_θ and E_ϕ) at 401.7 Mc of the Gemini ground-station antenna

(Figs. 38 and 40). This is of course a consequence of the more tapered illumination of the E-plane primary patterns (refer again to Figs. 32 through 35). This difference in illumination tapers also accounts for the narrower H-plane beamwidths, an effect which is more noticeable in the uhf patterns (Figs. 39 and 40).

Also shown in Figs. 39 and 40 are the E_ϕ (cross-polarized) patterns recorded at uhf. These E_ϕ patterns show peaks in the vicinity of the E_θ main beam. It was discovered in the course of the pattern investigations that these E_ϕ lobes varied in shape and level with respect to the E_θ patterns depending on such factors as a change in the type of illuminating antenna used, a change in the elevation angle on the test range, and a change in the separation between the two antennas on the range. This seemed a strong indication that these E_ϕ lobes were due primarily, if not entirely, to the effects of depolarized reflections caused by low grazing angles to the ground and surrounding objects on the antenna range. This hypothesis was tested by canting the illumination beam off the line of sight, first to one side and then to the other. This had the effect of differentially illuminating buildings and objects in the vicinity of the pattern range. This procedure resulted in considerable changes in the character of the E_ϕ patterns. As an example, in the H-plane pattern of Fig. 40 one of the pair of E_ϕ lobes could be made to disappear entirely below the noise level while the other increased several db, depending on the direction in which the beam was canted. It therefore seemed quite reasonable to assume that these cross-polarized lobes were due predominantly to reflections from the surroundings. At vhf the effects of depolarized reflections on the pattern range were so great and so unpredictable that no meaningful E_ϕ patterns could be made at that frequency. However if acceptably low E_ϕ levels could be obtained at uhf, the cross-polarized response at vhf must be at least as good.

Because the dipole elements had to be made shorter than resonant at vhf in order to obtain acceptable uhf patterns, the feed was poorly matched at 133.9 Mc. The resultant feeds had average VSWR's of 8.0:1 at 133.9 Mc and 1.3:1 at 401.7 Mc. A transformer was therefore designed to match the dipoles to the 50-ohm feed line. This consisted of a single coaxial line transformer for both frequencies and was located within the 1-5/8-inch coaxial line which supports the dipole. After these transformers were installed, the residual VSWR's of the feeds had average values of 1.3:1 at 133.9 Mc and 1.2:1 at 401.7 Mc.

POSTSCRIPT

Although the boom-mounted colinear-fed dipole designed for installation on the Gemini spacecraft did not provide the purity of polarization for all aspect angles which had originally been hoped for, it did provide a sufficient angular region in which useful data could be gathered. All that was required to utilize this region was a minimum of vehicular aspect control during the data-taking passes.

The equipment was installed on Gemini-8 and Gemini-9. Unfortunately Gemini-8 was aborted at an early stage before the polarization experiment was scheduled to commence. The D-14 polarization experiment was carried out with Gemini-9, although the six data-taking passes eventually allotted to the experiment were fewer than had been hoped for. The polarization data gathered at the two ground stations are now being processed and will be presented in a future NRL Report by other authors.

UNCLASSIFIED

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13. ABSTRACT

An experiment was conducted to measure the spatial and temporal distribution of free electrons in the lower layers of the ionosphere. This study used a Gemini spacecraft as a platform from which signals at 133.9 Mc and 401.7 Mc were transmitted.

A single antenna (a boom-mounted colinear-fed dipole) was used to transmit linearly polarized signals at both of the desired frequencies. The effort in designing this antenna was centered chiefly on attempts to achieve polarization purity in the transmitted signal. The proximity of the Gemini spacecraft acting as a reflector introduced an undesirable component of cross-polarization to the signal. By careful design and orientation of the antenna-spacecraft configuration, this cross-polarized component was minimized.

The spacecraft-launched signals were received on 28-foot parabolic antennas at two separate ground stations. The reflectors and pedestals were commercially-manufactured. Dual-frequency crossed-dipole feeds were designed and built for these reflectors.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Antennas						
Design						
Antenna radiation patterns						
Measurement						
Very high frequency						
Ultrahigh frequency						
Electromagnetic waves						
Polarization						
Ionospheric propagation						
Ionosphere						
Electron density						
Satellites (artificial)						
Manned spacecraft						
Gemini spacecraft						