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ABSTRACT

Work on the design, fabrication and testing of three broadband antennas is described. The antenna types are: 1) fore-shortened planar log-periodic, 2) loaded conical helix, and 3) omnidirectional.

Under Task 1 a number of crucial experiments were made to evaluate some of the fundamental changes necessary to produce a fore-shortened planar log-periodic dipole antenna. In this report studies showing the possibilities of shortening the boom as well as shortening the individual elements are presented.

Certain significant results have been achieved in shortening the boom structure of a log-periodic dipole. The shortening of individual electric dipole elements in the low frequency range appears possible to the extent of reducing length by a factor 0.5. This reduction in electric dipole lengths can be achieved by either right angle bends at the ends of the dipoles or by a zig-zag wire construction of the dipoles.

Under Task 2, preliminary work had been done on discrete capacitor loading of a helix antenna, including dielectric loading between the turns which indicates the probable success of this technique. Unexpected patterns were obtained when a helix was wound with a coiled wire, although approximately a 2:1 reduction was evident. Suppressing higher modes with multifilar windings is promising and possibly can be used to reduce size by 4:1 . Initial experiments using a resonant turn in back of a conical helix to suppress higher modes indicate that the turn must be at least 0.1λ in back of the antenna.

Under Task 3 (development of a broadband omnidirectional antenna), an extensive study of the capacitively loaded Hallén antenna has been conducted. In addition a preliminary investigation of an inductively loaded antenna has been initiated. From the capacitive antenna study it has been shown that an antenna having a VSWR under 3:1 and over an 8.5:1 frequency band can be fabricated. However, the pattern characteristics for this antenna need further attention as preliminary data is not too satisfactory.

FOREWORD

This report was prepared by the University of Michigan Radiation Laboratory of the Department of Electrical Engineering. The work was performed under United States Army Electronics Command Contract No. DA 28-043 AMC-01263(E). The contract was initiated under United States Army Project No. 5A6-79191-D902-02-11, "Broadband Antenna Techniques Study". Work was administered under the direction of the Electronics Warfare Laboratory, Supporting Developments Technical Area at Fort Monmouth, New Jersey. Mr. Anthony DiGiacomo is the Project Manager and Mr. George Haber is the Contract Monitor.

The material reported herein represents the results of the investigation into techniques applicable to the design and development of broadband antennas.

The authors wish to acknowledge the contributions of Prof. C.T. Tai and Mr. D.R. Marble for their work on the omnidirectional antenna; and Mr. U.E. Gilreath and R.J. Carducci in obtaining some of the measurements on the log-periodic and conical helix antennas, and Dr. J.B. Rao and Mr. P.W. Eng for their work on the omnidirectional antenna.

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I

INTRODUCTION

Task 1 of this project has been pursued primarily upon a design and an experimental basis. The purpose of the experiments has been to ascertain the extent to which the usual design parameters of log-periodic dipole structures can be changed in order to achieve an antenna with very much reduced dimensions. In this way it is hoped to thoroughly explore the possibilities of shortening the boom of the antenna, shortening the individual electric dipole elements, and using fewer electric dipole elements by incorporating broadband dipole elements instead of the usual narrow band electric dipole elements. The first two of these approaches are already underway and are described in the appropriate sections of this report. It is encouraging to note that some success has been achieved in shortening the boom. However it must be realized that shortening the boom may result in some reduction of gain. The reduction of gain although mentioned in this report has not been fully studied as of this date.

In the study of shortening of the individual elements substantial success has been achieved by two methods; each of these two methods is described in this report. One of these methods is the use of a zig-zag wire structure in making the electric dipoles. Although it has not been possible to completely assess the merits of this structure due to measurement difficulties, the data presented in the last Quarterly Report (ECOM- 01263-5, 7260-4-Q) indicated considerable promise. It should be emphasized at this point however, that the antenna range at the frequency of measurement has some defects which may have obscured confirmation of this assessment.

Coverage is included in this report on an array utilizing a shortening procedure involving bends at the ends of the dipole elements in the lower frequency ranges. Some success has been made in shortening in this way permitting lower frequency operation. The reduction of length factor applicable to such right angle bends at the ends of each dipole is of the order of 0.55. This multiplicative factor indicates the possible reduction of length in a preliminary way.

In Task 2 preliminary work has been started on the case of discrete capacitor loading in a conical helix antenna. Dielectric material was placed in between the turns of a helical antenna. These results tend to confirm our belief that replacing the dielectric with capacitors would indeed produce a size reduction.

During this report period work was completed on testing a helix wound with a helical slow wave structure. A size reduction was achieved; however, the reduction was not as great as would be expected by design of the slow wave structure. In addition very high back lobes were observed and very unusual radiation was observed just below the normal backfire radiation zone.

Additional consideration was given to using multifilar windings to suppress higher modes. Another promising feature of multifilar windings appears to be that a reduction in size can be obtained when the number of windings is on the order of eight. Another higher order mode suppression technique investigated in this period employed a resonant turn in back of a conical helix antenna. Initial experimental results indicate that the turn must be placed at least one tenth of a wavelength in back of the antenna at the desired frequency of operation.

In Task 3 the objective of this study is to design a broadband omnidirectional antenna for the monopole or dipole configuration. A discussion of the requirements of the antenna are presented along with some typical data for a capacitively loaded Hallèn antenna.

II

FORE-SHORTENED PLANAR LOG-PERIODIC ANTENNA

Under Task 1, a number of variations of log-periodic dipole antennas were designed, fabricated and tested. The individual types are described and the results are given.

2.1 Boom Spacing Studies

An attempt was made to establish the feasibility of using smaller than normal design spacings of the elements along the beam. For this purpose, an antenna design, LPDA-1, was made. This design was described in the preceding quarterly report with a misprint in the statement of size. The corrected dimensions appear in Fig. 2-1. Since that time, this design has been modified through the use of a new feed structure consisting of two hollow copper tubes, through one of which, a coaxial cable is used as an infinite balun. The feed is at the front end and the center conductor of the coaxial feed is attached to the opposite hollow tube in a symmetrical fashion. Considerable attention was given to making the feed at the front as symmetrical as possible. This design has also been built using a simple transmission line of two wires crossing in the horizontal plane. This configuration uses a feed at the front end which is connected on a balanced basis using an Anzac hybrid in the feed line from the coaxial cable. The experimental results achieved are almost exactly the same for either type of feed structure. In future work, it is very likely that the open wire type structure using a balun will be more useful in experimental procedures, since inductance and capacitance in either lumped or continuous distributions can be more readily inserted in such a line ; in this way, delay from the feed point of one element to the feed point of another element can be accomplished. The studies on boom length spacing have not yet utilized the possibility varying the delay occasioned by the transmission line from one element to the next element.

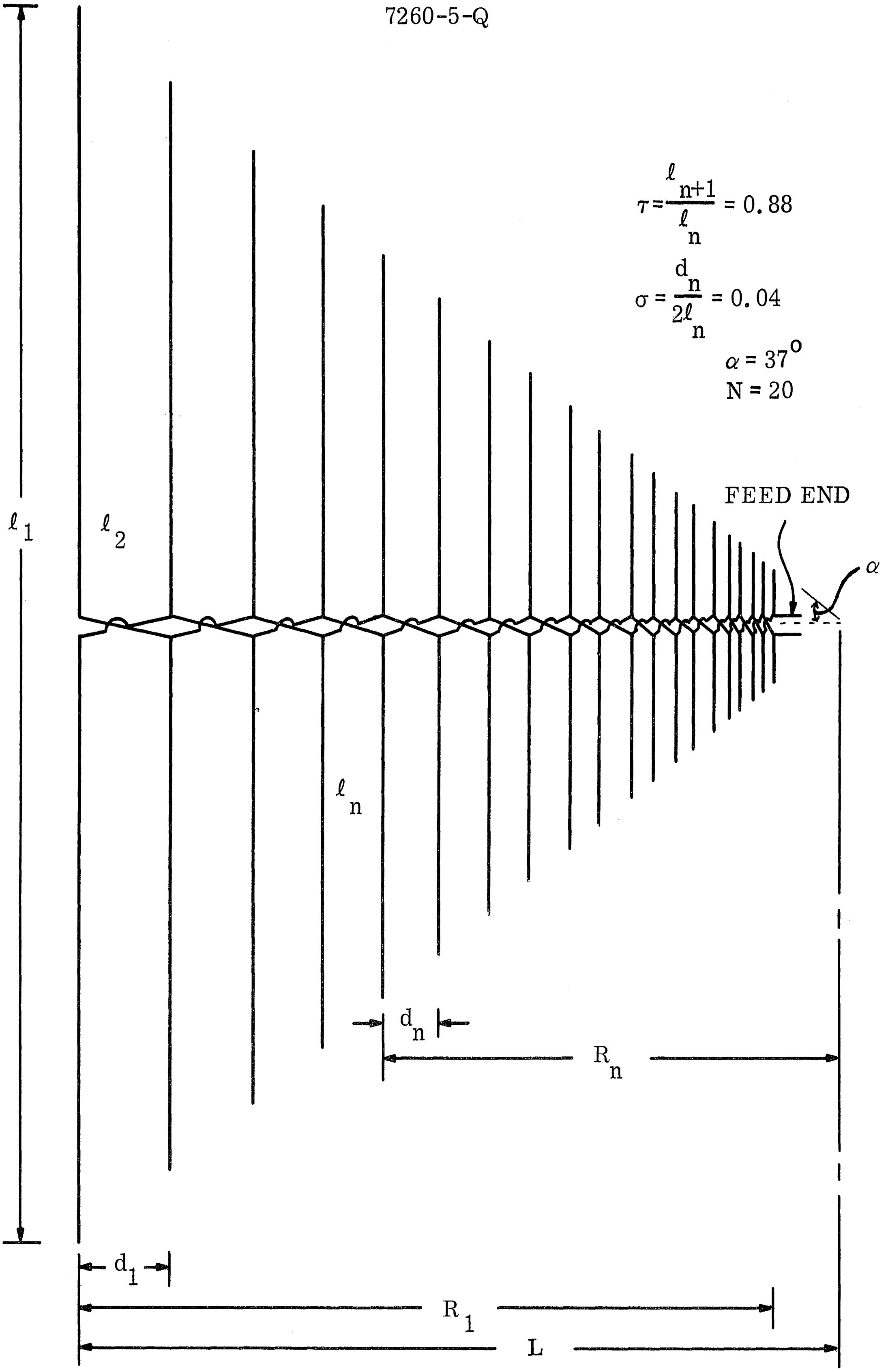


FIG. 2-1: ANTENNA LPDA-1. LONGEST DIPOLE 100 cm (λ/2 at 150 MHz)
SHORTEST DIPOLE 8.8 cm (λ/2 at 1700 MHz)
SIZE: 103 cm x 66 cm

The design of antenna LPDA-1 uses a tapering factor, τ, with a value 0.88. This is a usual design value. A spacing factor, σ, of 0.04λ (free-space wavelength) was utilized; this value of the σ factor is approximately half the value normally used under ordinary design procedures. On the basis of the two design factors mentioned, then half the angle subtended by the apex of the antenna corresponds to 37°; 20 dipole elements were used in this design. The length of the dipole elements correspond, of course, to the τ factor already indicated. The factor τ is defined as the ratio of the length of the (N+1)st element to the length of the Nth element, counting along the boom, divided by the spacing of the Nth element along the boom, also corresponds to the the τ factor. The experimental design had final overall dimensions of 9.5 cm across the smallest tip of the antenna; 103 cm across the bottom corresponding to the length of the longest dipole element; 66 cm corresponding to the overall length of the boom. A series of E-plane radiation patterns were obtained over a frequency range 100 - 1500 MHz. The radiation patterns are shown in Figs. 2-2a and 2-2b. In testing the antenna over the frequency range specified, it was observed that the standing wave ratio was below 2.0, as measured at the end of a coaxial feed with equipment located approximately 1.5 meters from the feed point at the apex of the antenna. These VSWR measurements were with the design version having the hybrid in the feed. The cable used in all arrangements for feeding the antenna was RG58/U.

An examination of the radiation patterns indicate that the E-plane half power beamwidth at any frequency has not been changed very much from a corresponding antenna having the usual boom spacing (σ) of approximately twice the value as used for these experimental antennas. It now appears that decreasing the boom length and thus decreasing the spacing of elements as shown in these experiments will result in some decrease in gain. An accurate evaluation of the gain or more specifically of the loss of gain will be made.

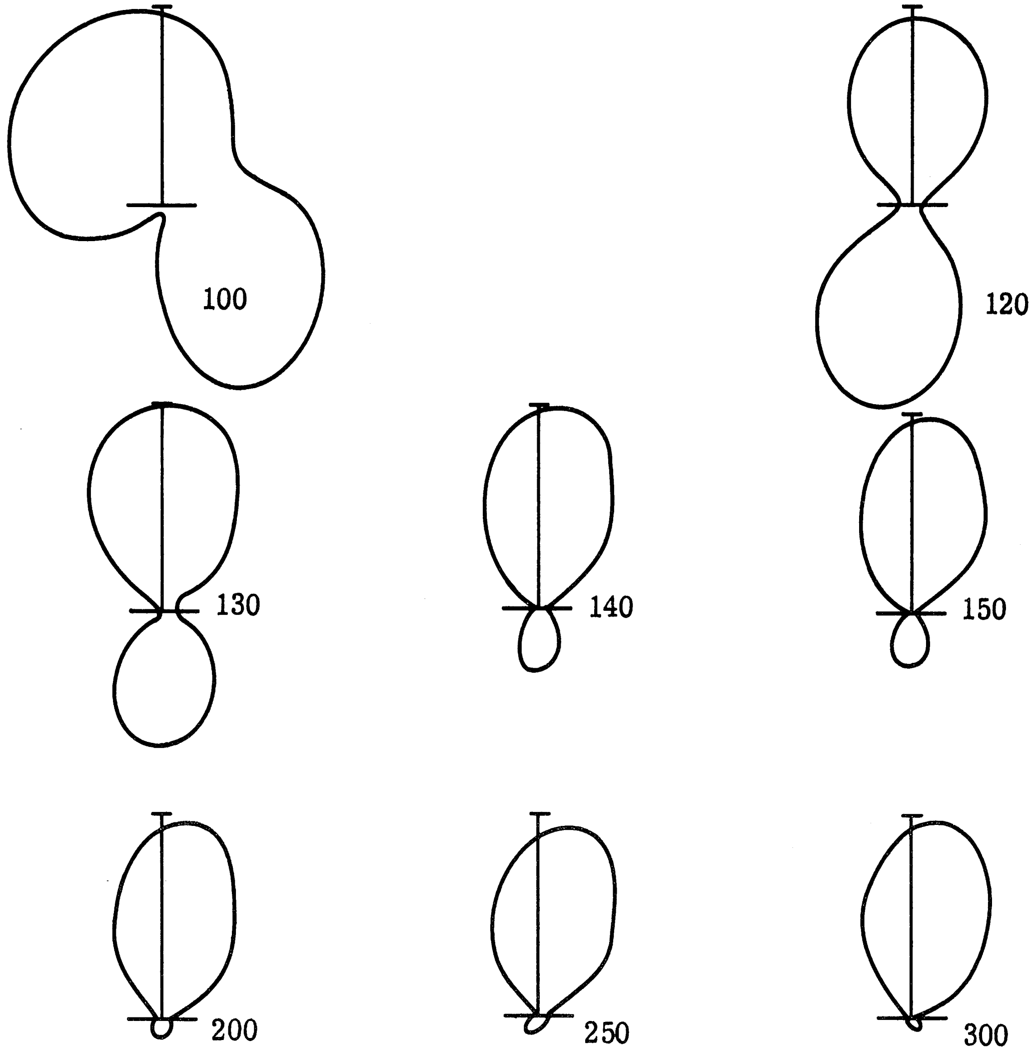


FIG. 2-2a: LPDA-1 100-300 MHz
E-PLANE LINEAR POWER PATTERNS

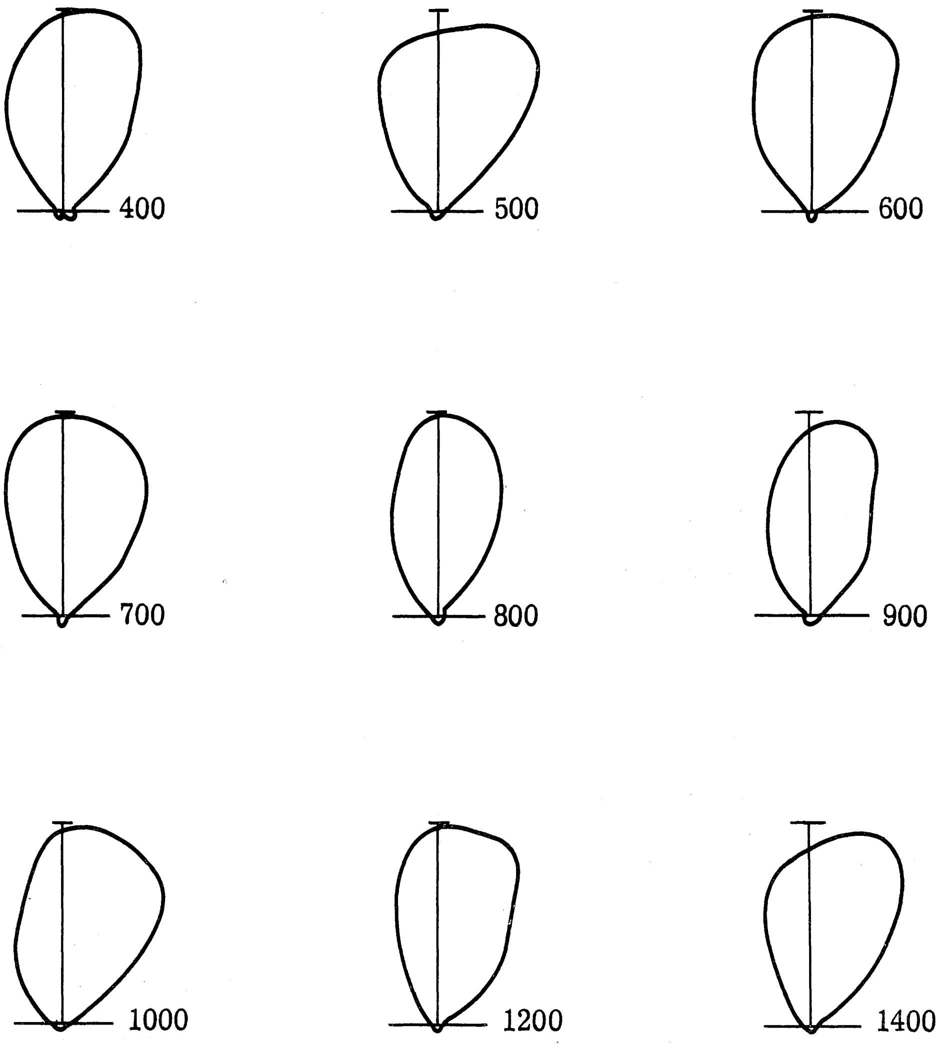


FIG. 2-2b: LPDA-1 400-1400 MHz
E-PLANE LINEAR POWER PATTERNS.

2.2 Shortening of Individual Elements by Folds

In this study an attempt was made to evaluate the effectiveness of right angle bends or folds on each of the electric dipole elements in the lower frequency range. This antenna with the bends shortening the individual elements is designated LPDA-2. The design was illustrated in the quarterly report 7260-4-Q with a misprint in the statement of size. The corrected dimensions appear in Fig. 2-3. This design utilized the reduced spacing of the elements along the boom as indicated in the previous section where σ is equal to 0.04λ (free space wavelength). Other design parameters used were similar to antenna LPDA-1. The final overall physical size of this antenna is; 9.5 cm across the apex end; 55 cm across the bottom corresponding to the longest element; 75 cm measured from the apex or smallest element to the back or the longest element. E-plane patterns were obtained for the frequency range 130 MHz to 1500 MHz. There are indications from design considerations that this antenna would operate well above 1500 MHz, perhaps up to 1700 MHz. However, the antenna was not tested as high as this in frequency due to the lack of a suitable signal generator at the time of test.

An examination of the patterns shown in Fig. 2-4 indicates that suitable radiation patterns have been obtained down to 150 MHz. This indicates there has been achieved a good radiation pattern for an element that is 55 cm long through the use of the folds at each end of this element. If the 55 cm length represented a simple straight electric dipole, then this would be halfwave resonant at a frequency of about 280 MHz. This indicates that the double bend at each end of the electric dipole giving a 55 cm length has resulted in a reduction in the lowest frequency of operation from approximately 280 to 150 MHz.

A modification was made on the design of LPDA-2 whereby the element at the lowest frequency end was bent in the opposite direction. This meant that right angle bends at the two ends of this dipole had the bent portion now pointing forward over several of the adjoining elements instead of pointing away from these

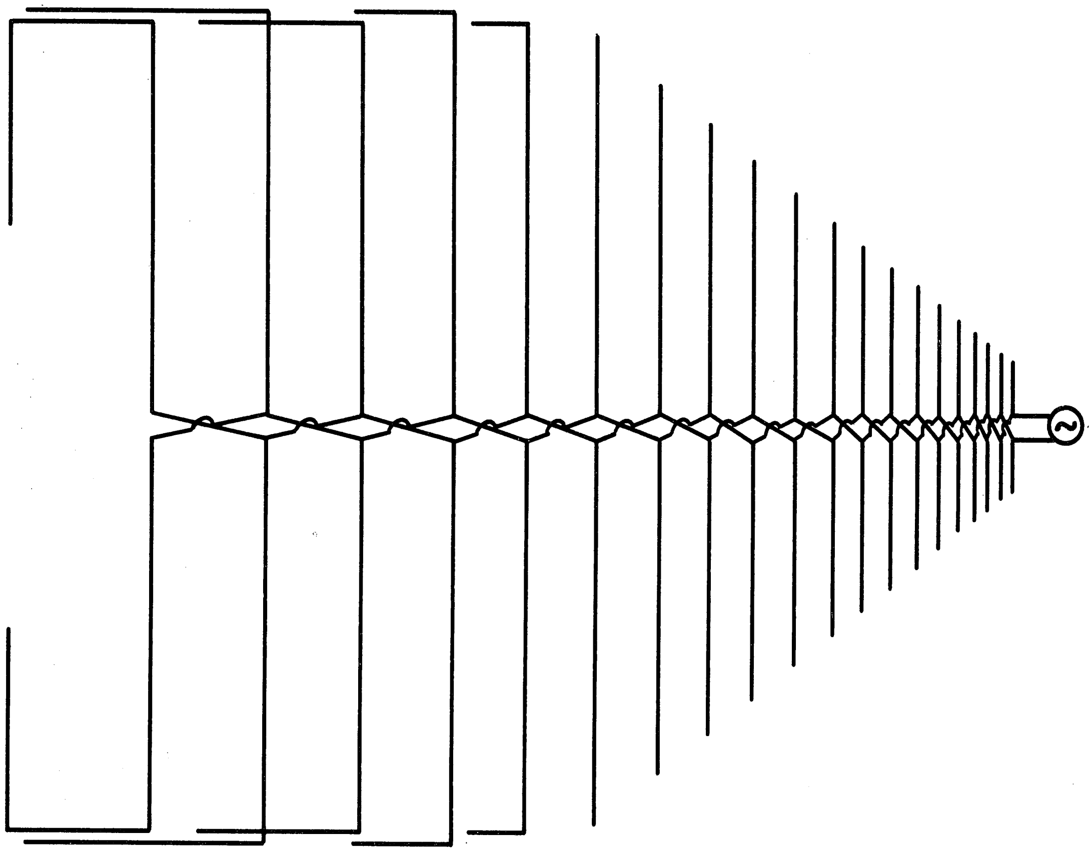


FIG. 2-3: ANTENNA LPDA-2: LONGEST DIPOLE 100 cm ($\lambda/2$ at 150 MHz)
SHORTEST DIPOLE 8.8 cm ($\lambda/2$ at 1700 MHz)
SIZE: 55 cm x 75 cm

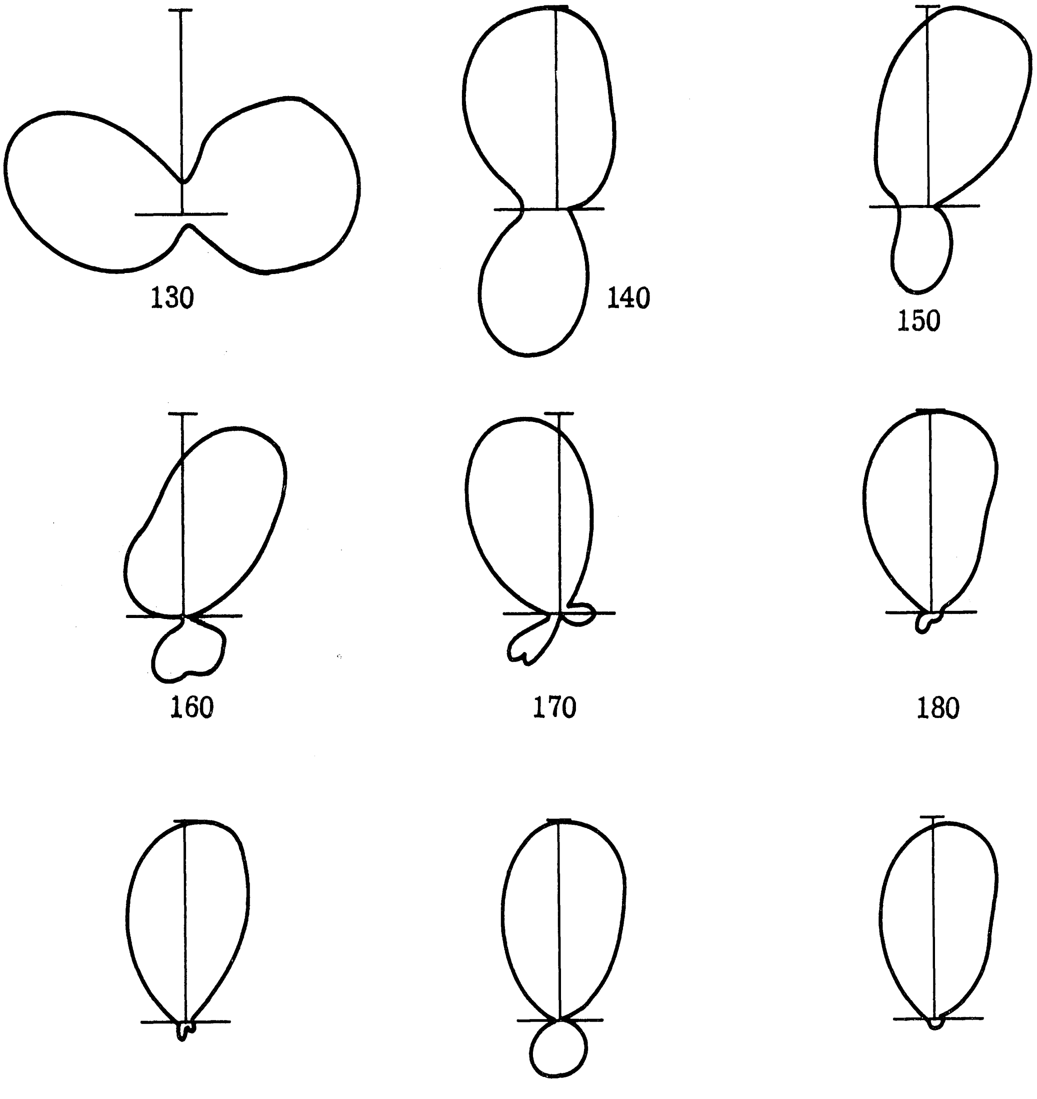


FIG. 2-4: LPDA-2 130-300 MHz
E-PLANE LINEAR POWER PATTERNS.

Note: Patterns above 300 MHz are nearly identical to those of LPDA-1 (Fig. 2-2b).

elements. This type of modification indicated a rather serious shortcoming when the radiation patterns were examined. An undesirable backlobe developed at frequencies of 180 MHz and lower. In view of these results this manner of bending the lowest frequency electric dipole does not seem appropriate because of the serious deterioration of the pattern; no further experiments with this bending in the direction toward the apex will be used.

Still another possibility offering a slight improvement in the reduction of boom length is shown using a slight bend on the last low frequency dipole commencing right at the feed and having the extreme ends of the dipole again bent towards the apex. Figure 2-5 shows the arrangement used for this antenna designated as LPDA-6. It is interesting to observe the radiation patterns shown in Fig. 2-6. These patterns are reasonably good and should be compared with the patterns in Fig. 2-4 obtained for the antenna LPDA-2. This further reduction in boom length of 5 cm has been achieved with substantially the same radiation patterns resulting.

2.3 Study of Mixed Array With Zig-Zag Elements

An antenna was designed using a zig-zag configuration for the entire length of each electric dipole in the low frequency range up to a frequency of approximately 350 MHz. At still higher frequencies straight electric dipoles were used. Below is a description of this antenna:

Antenna No: LPDA-7

Description: Zig-zag elements in low frequency section;
Straight elements in high frequency section

$\tau = 0.86$

$\sigma = 0.096$

$\alpha = 20^{o}$ (half of the apex angle)

Size: Width of tip 7.0 cm;($\lambda/2$ at 140 MHz)
Width across bottom 93 cm
Length along boom 110 cm.

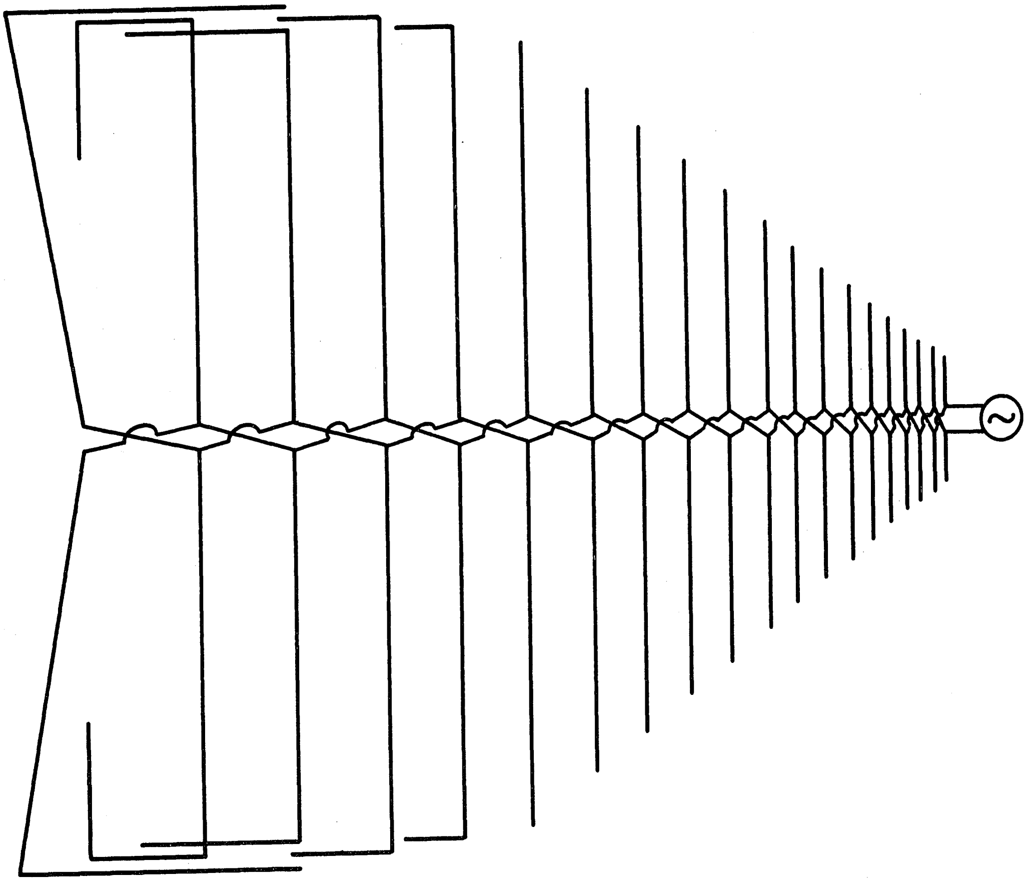


FIG. 2-5: ANTENNA LPDA-6: LONGEST DIPOLE 100 cm (λ/2 at 150 MHz)
SHORTEST DIPOLE 8.8 cm (λ/2 at 1700 MHz)
SIZE: 56 cm x 70 cm.

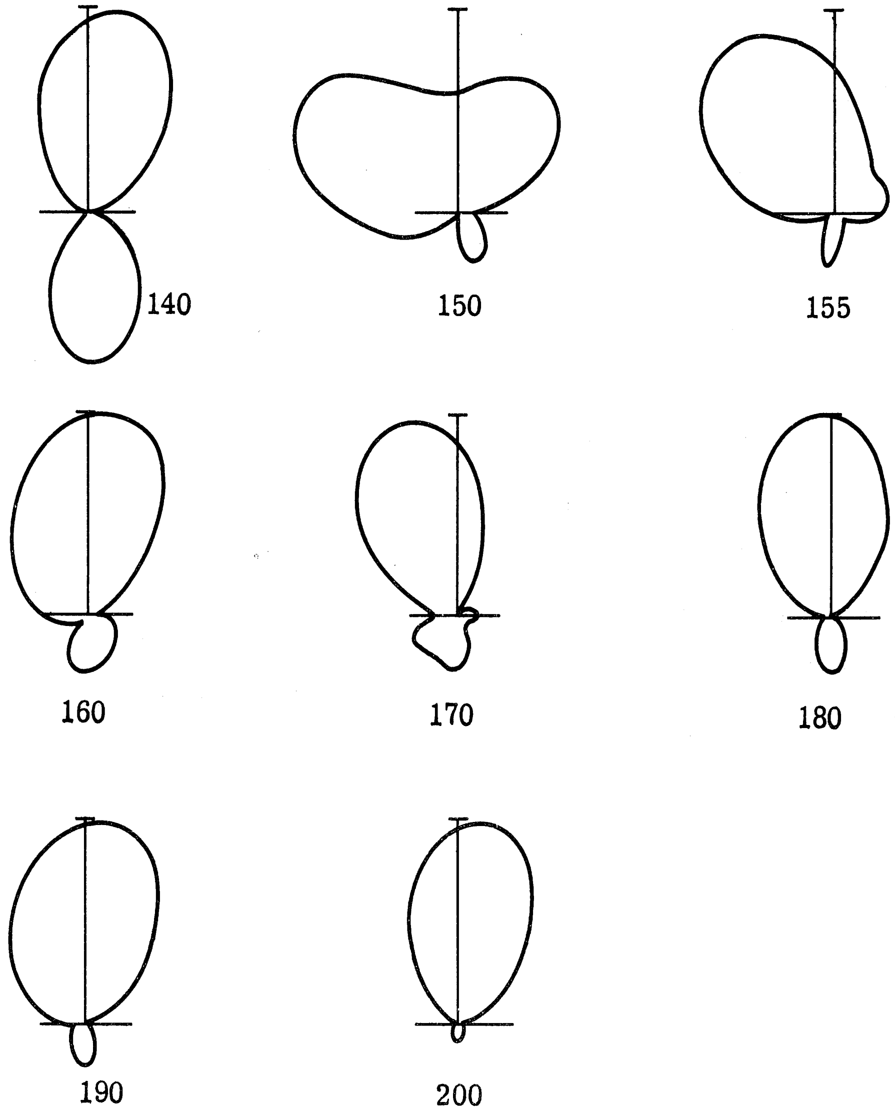
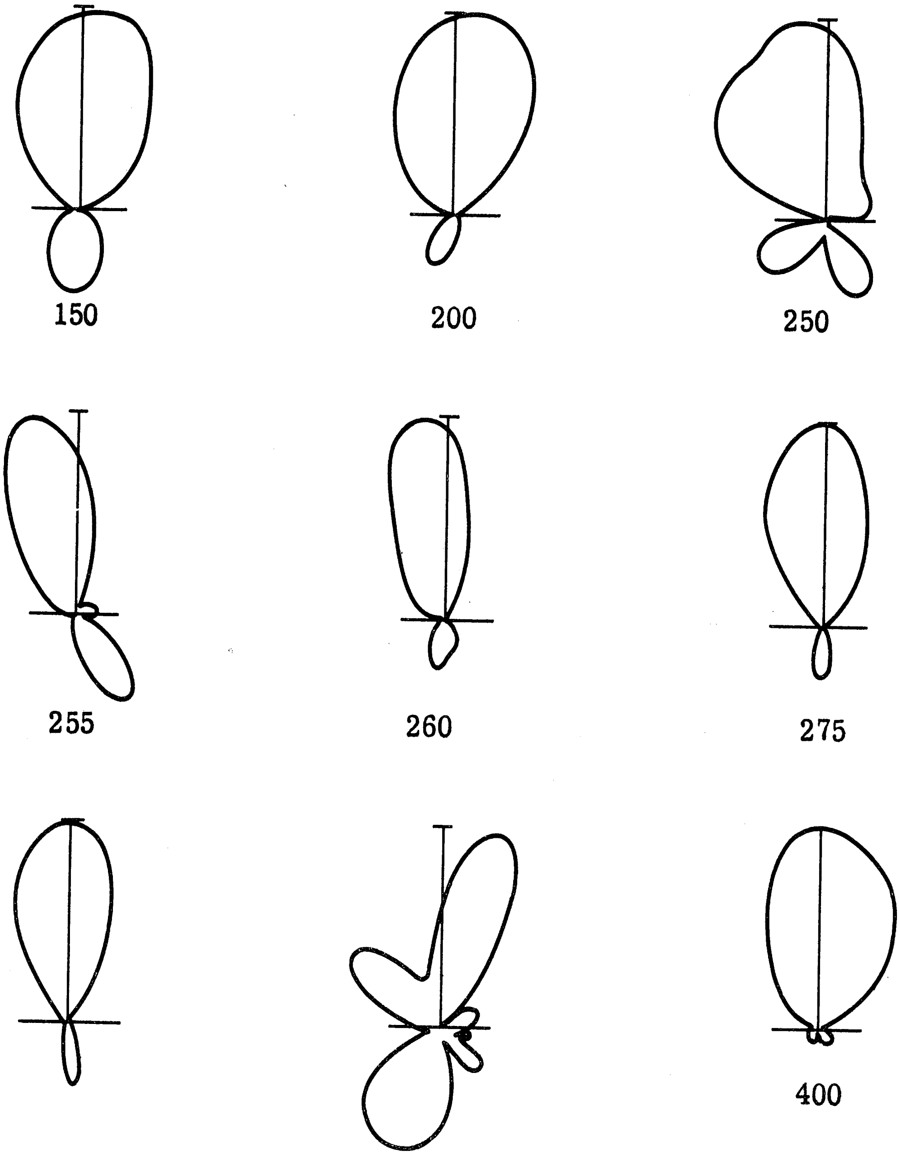


FIG. 2-6: LPDA-6 140-200 MHz
E-PLANE LINEAR POWER PATTERNS:

In Fig. 2-7 will be found the E-plane radiation patterns for this antenna. It is to be observed that there are some irregularities in the pattern at frequencies of 250 MHz, 255 MHz and 350 MHz. These irregularities are observable especially after a comparison of patterns taken for the high frequency end of this antenna alone and the low frequency end of this antenna alone. The patterns for the individual two parts of the antenna are not included in this report. However, they have been used in studying the behavior of the patterns for the entire frequency range. It is expected that some modifications will be made in this antenna in order to improve the pattern at the frequencies noted. It should be mentioned that a broken element was observed which may be at least a partial explanation for the difficulties encountered from 250 to 255 MHz. Moreover, due to measurement difficulties, patterns were not taken below 150 MHz. Based on the data presented for the zig-zag monopole in the last quarterly report (7260-4-Q), one would expect to find acceptable operation below 150 MHz. Some satisfactory radiation patterns were observed at frequencies below 150 MHz for a low frequency section of the array consisting only of zig-zag elements.



150 200 250

255 260 275

300 350 400

FIG. 2-7: LPDA-7 150-400 MHz
E-PLANE LINEAR POWER PATTERNS

Note: Patterns above 400 MHz are well behaved and similar to those of LPDA-1 (Fig. 2-2b).

III

LOADED CONICAL HELIX ANTENNA STUDY

The purpose of study under Task 2 is to develop a conical helix antenna covering a 50 MHz to 1100 MHz frequency range that is lightweight and yet one fourth the linear dimensions of conventional conical helix antennas. The antenna is to have a hemispherical pattern shape, 0 db gain with respect to an isotropic source, circular polarization, a VSWR of less than 2.5 to 1 with respect to a 50 ohm source, and a capability of handling 150 watts average power input.

During the report period, study was made on discrete capacitor loading, slow wave structure windings, and higher mode suppression. During this period, a helix antenna was loaded with a dielectric material in between the windings to test the effect of capacitance in this area of the antenna for reducing the size. The results were very favorable.

In another experiment, a coiled conductor was used as a winding on another helix. A size reduction of about 2 to 1 was observed, although there were higher back and sidelobe levels. Strong forward fire radiation was also observed in a narrow frequency range below the backward fire mode.

In an effort to suppress the high backlobe that sometimes occurs with reduced size antennas, a resonant turn reflector was mounted in back of a conical helix. No significant improvement was noticed at the small spacing used for the reflector. The study on this technique is continuing.

3.1 Discrete Capacitor Loading

If a conical helix antenna is thought of as a transmission line wound on a cone, then radiation occurs when the circumference is about a free space wavelength. It would therefore seem that to reduce the size of the antenna the phase velocity of the transmission line must be reduced. This is the rationale for using capacitors or slow wave structures in the windings of conical helix antennas. This explanation may seem to be an over-simplification which is, at best, useful only for grasping a qualitative appreciation for what is happening. However, many experimental results are readily explained by the theory and a mathematical analysis of the problem (Rassweiler, 1966) also tends to confirm the transmission line point of view as a very good approximation.

In the interim report (Ferris et al, 1966) the results of tying the leads of a conical helix together at the base with a resistor are discussed. It is pointed out that an optimum resistance can be found that reduces the reflection of unradiated energy off the base. These reflections were responsible for high backlobes in the loaded antenna.

Using the substitution method with carbon composition resistors, the characteristic impedance of the transmission line was found to be 2200 ohms . The Allen-Bradley Company later confirmed in a private communication that at the frequencies involved, the true resistance would be closer to 150 or 200 ohms (Fitzpatrick, 1966). These are values commonly accepted for the characteristic impedance of a helix or conical helix.

At the request of the sponsor, a further experimental check was performed in the report period. Antenna 217, a bifilar helix with an infinite balun feed wound on a thin epoxy-fiberglass tube, was covered on the outside to a thickness of 1/4" with Emerson and Cuming K-10 powdered dielectric. The dielectric was held in place with a 1/16" thick NEMA Grade XXX (Mil-P-3115-PBE) laminate tubing as indicated in Fig. 3-1. The experiment was not conducted as a further test of dielectric loading, but solely as an additional confirmation of the advantages of cpacitor loading. It was felt by those desiring the experiment that high dielectric material concentrated between the windings may reduce the phase velocity along the windings and therefore result in some size reduction. Since high dielectric material is necessarily heavy and capacitors and inductors are comparatively light weight, they considered it worthwhile to give some consideration to the possibility of using discrete lumped constants in order to control the phase velocity along the windings.

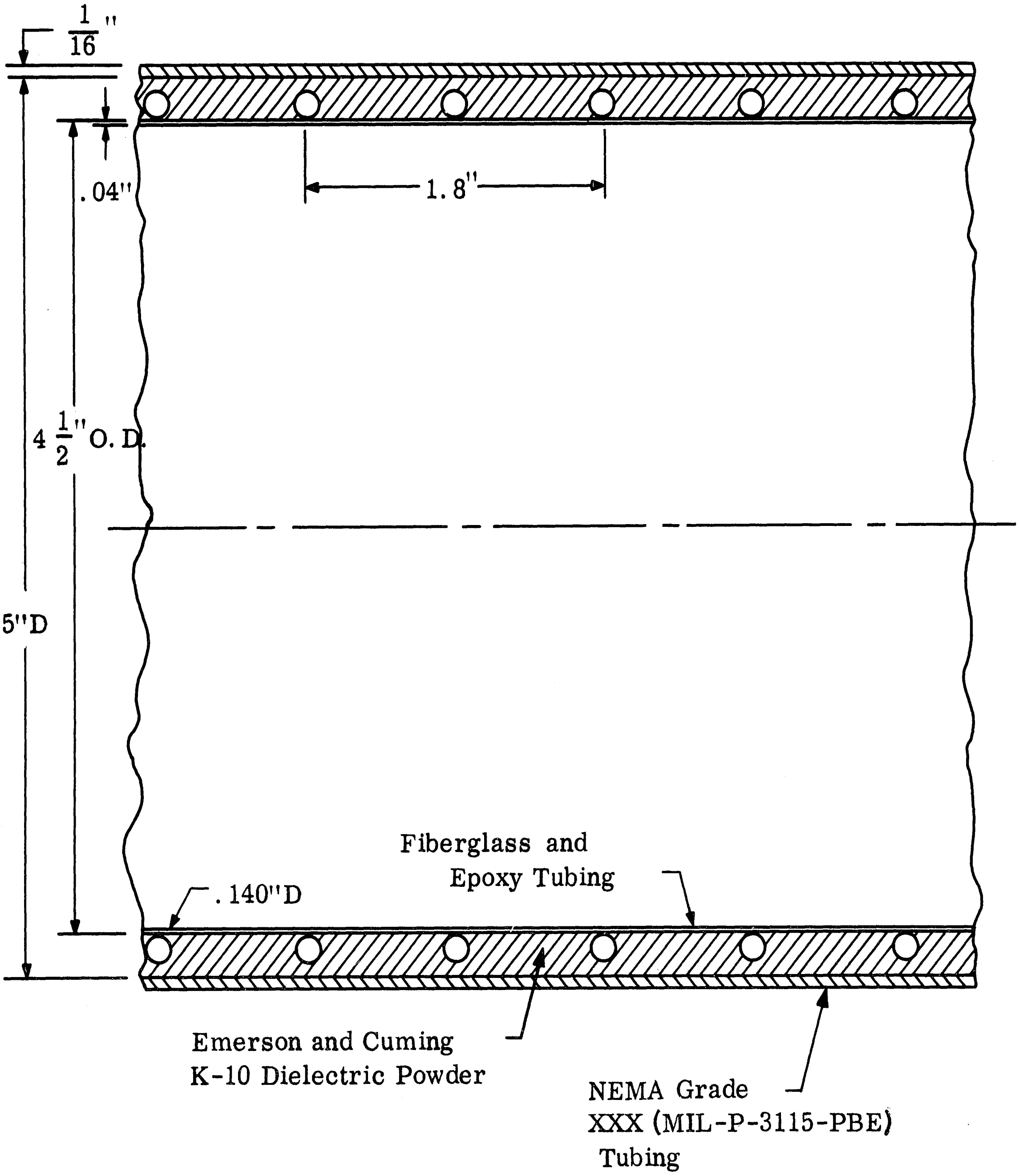


FIG. 3-1: LOADING OF BIFILAR HELIX 217 WITH EMERSON CUMING K-10 POWDERED DIELECTRIC.

The far field patterns are given in Fig. 3-2 along with the far field patterns of the unloaded antenna. Note that the unloaded patterns break up around 900 MHz on the high end and around 400 MHz on the low end. The arithmetic mean center frequency calculated on this basis is 650 MHz, whereas the near field probing of the antenna indicates it to be 750 MHz. For the loaded antenna, the upper and lower frequencies are about 800 and 300 MHz, respectively. This gives an arithmetic mean frequency of about 500 MHz. Thus, there appears to be a reduction factor of about .85.

With these results in mind, calculations were made to determine how much capacitance had to be added to achieve a desired reduction in phase velocity and hence a reduction in size. Starting with the transmission line formulas for characteristic impedance and phase velocity in terms of capacitance and inductance per unit length, it can be shown that the capacitance per unit length, C, is equal to $1/(Z_0 v_p)$, where Z_0 is the characteristic impedance and v_p is the phase velocity. If R is the ratio of the desired phase velocity to that of the light, it follows that R is also the reduction factor of the antenna. If C' is the capacitance per unit length needed to give the reduction factor R, then C' equals C/R^2. Since the characteristic impedance is usually about 150 ohms and the reduction factor is specified as 0.25, then C is 22.2 pf/m and C' is 355 pf/m. Thus 333 pf must be added per meter of winding.

Since helical antennas are much easier to build than conical helices and reduction phenomena are easier to observe with them, a bifilar, 14^o pitch angle, 9.8 cm diameter, 35 cm long helix has been constructed to test capacitor loading. The capacitance will be added in the form of 12 pf ceramic capacitors spaced every eighth of a turn. The antenna is being tested as this report is written. The results will be published in the next quarterly report.

3.2 Slow Wave Structure Windings

Work was started on a helical antenna wound with a helix slow wave structure

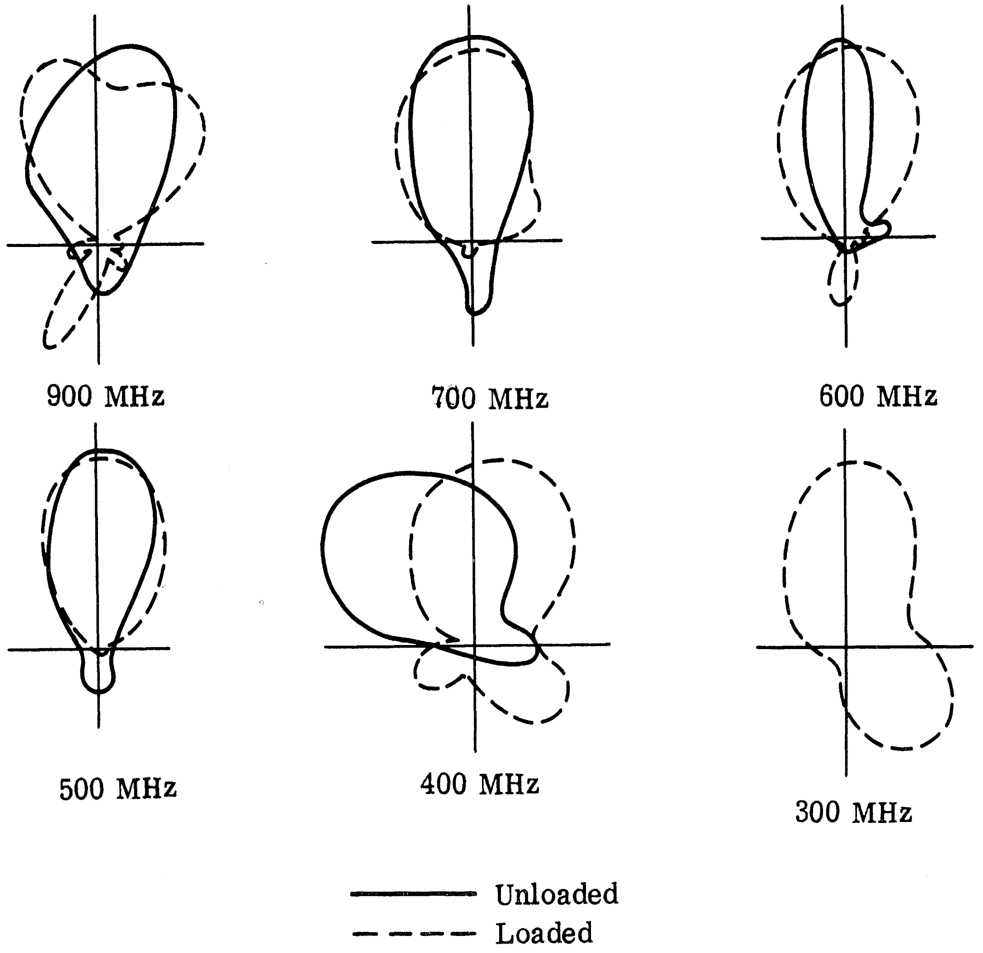


FIG. 3-2: ANTENNA 217, BIFILAR HELIX WITH AN INFINITE BALUN FEED, WITH A COVERING OF K-10 DIELECTRIC 1/4" THICK ON THE OUTSIDE.

(coiled wire). Figure 3-3 shows a picture of the test antenna. The antenna is bifilar wound and fed at the tip with a hybrid. The antenna is wound on a 3"I.D., 1/16" thick piece of NEMA grade XXX (Mil-P-3115-PBE) paper phenolic laminate tubing 29" long. The pitch is 4" and there are seven turns per winding. Each winding is a monofilar helix wound on a 3/4"O.D., 3/32" thick piece of Tygon vinyl tubing. The winding consists of No. 20 enameled wire and has a pitch of 1/3".

This design was a compromise. Most helix antenna theory is based on windings that are thin in the radial direction. However, to get a helix to operate as a slow wave structure, the pitch angle must be small and the circumference must be a fairly large fraction of a wavelength. Thus a trade off must be made between a diameter large enough to operate as a slow wave structure, yet small enough to approximate a wire winding.

If the antenna were wound with wire (not coiled) on a tube equal to the mean diameter of Antenna 228, it would have a center frequency of about 800 MHz. Figure 3-4 shows the far field patterns taken on Antenna 228. Notice that there is almost a 2:1 reduction in frequency of operation, but not a 4:1 reduction as would be predicted by the phase velocity of the slow wave structure (Okubo, 1965).

At 400 and 500 MHz, the patterns have a well-defined main lobe, although there are sizable back and sidelobes. If the slow wave winding were wound on a conical helix instead of a helix, the backlobes would be much smaller due to the reflector effect of the windings in back of the active region. The pattern at 300 MHz is completely unexplainable. The large backlobe appears only over about a 50 MHz bandwidth around 300 MHz. At 200 MHz the antenna appears to be moving into the region where broadside radiation occurs.

In an effort to better understand how the antenna operates, near field probing of the antenna was done at 0.1λ between antenna and probe (Fig. 3-5). The patterns are very unusual and not at all like those of a regular helix antenna, which usually show a strong amplitude at the tip and very rapid decay towards the base. Indeed, near field probing patterns at 800 MHz are very similar to the near field patterns of regular helix antennas, except for the humps in the middle of the antenna.

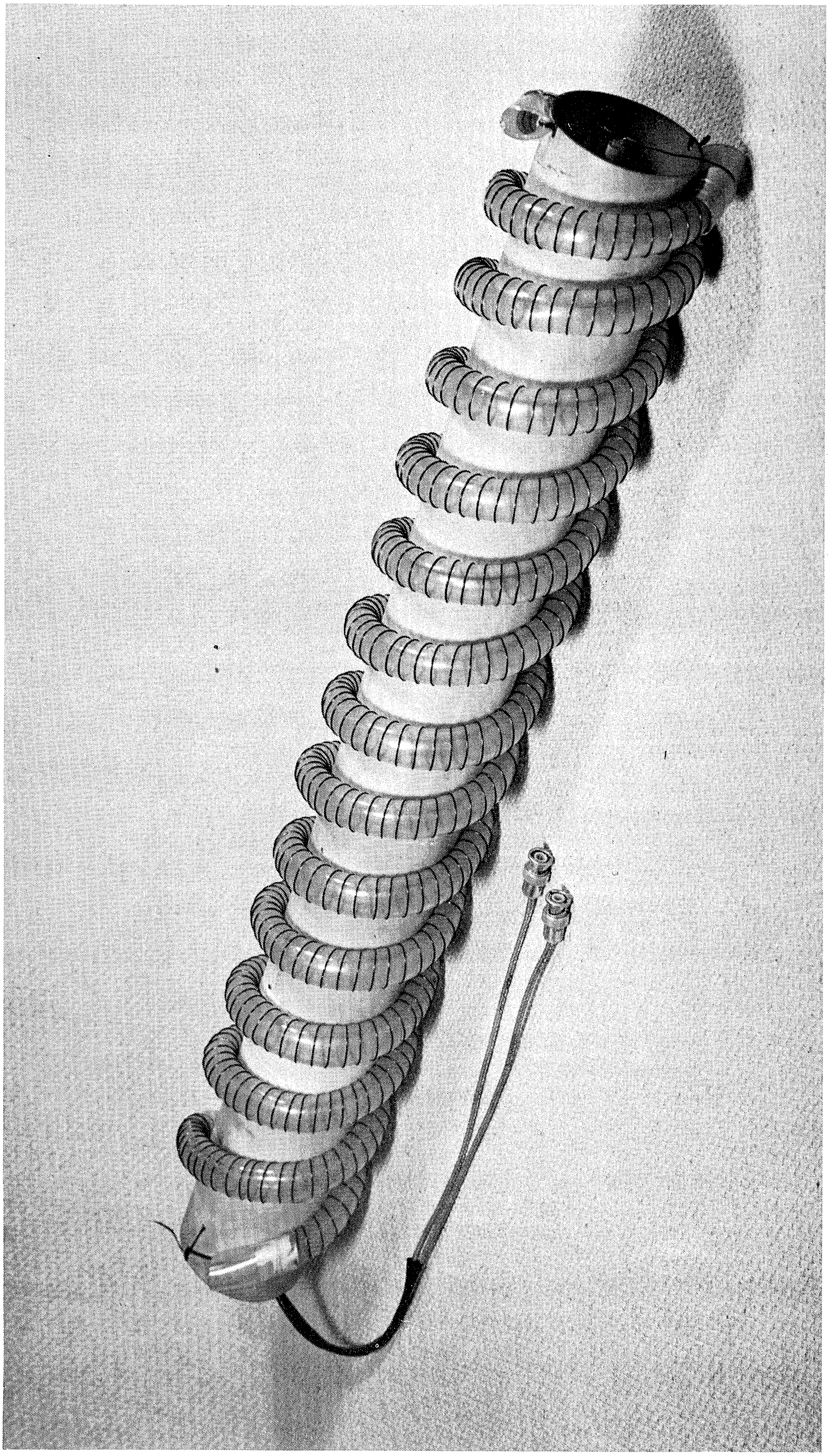


FIG. 3-3: ANTENNA 228, BIFILAR HELIX WITH A HELICAL WINDING.

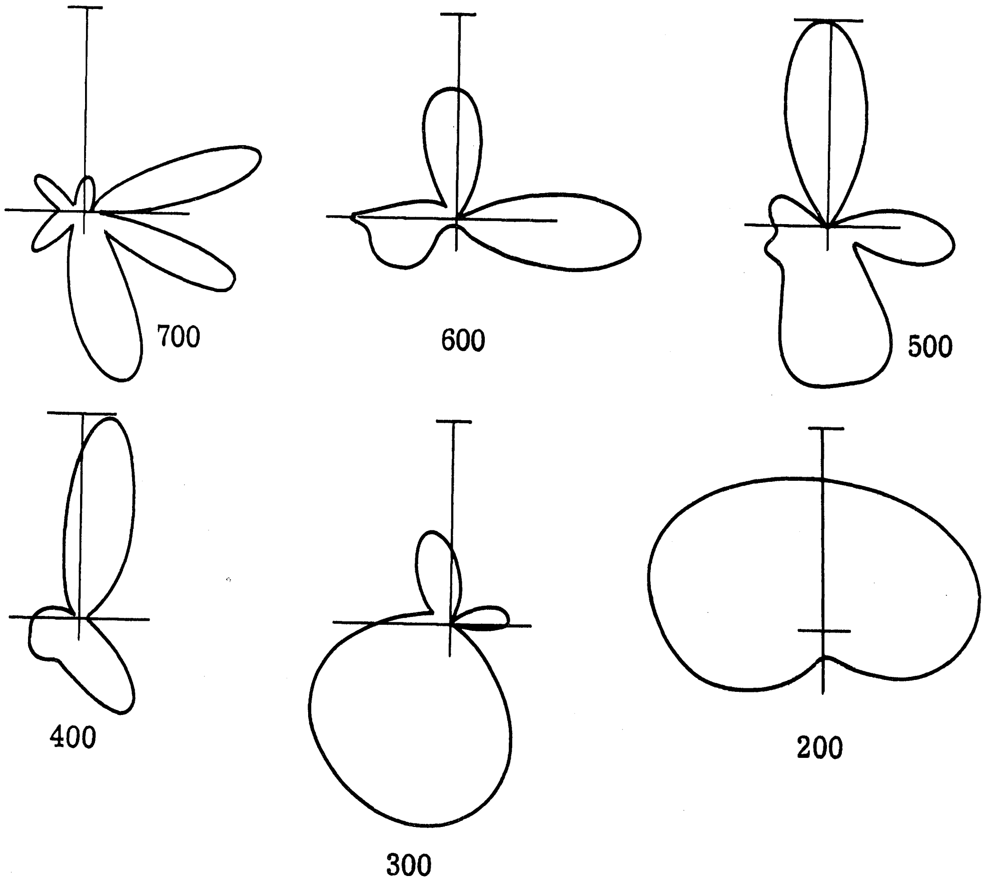


FIG. 3-4: ANTENNA 228, BIFILAR HELIX WITH A HELIX WINDING.

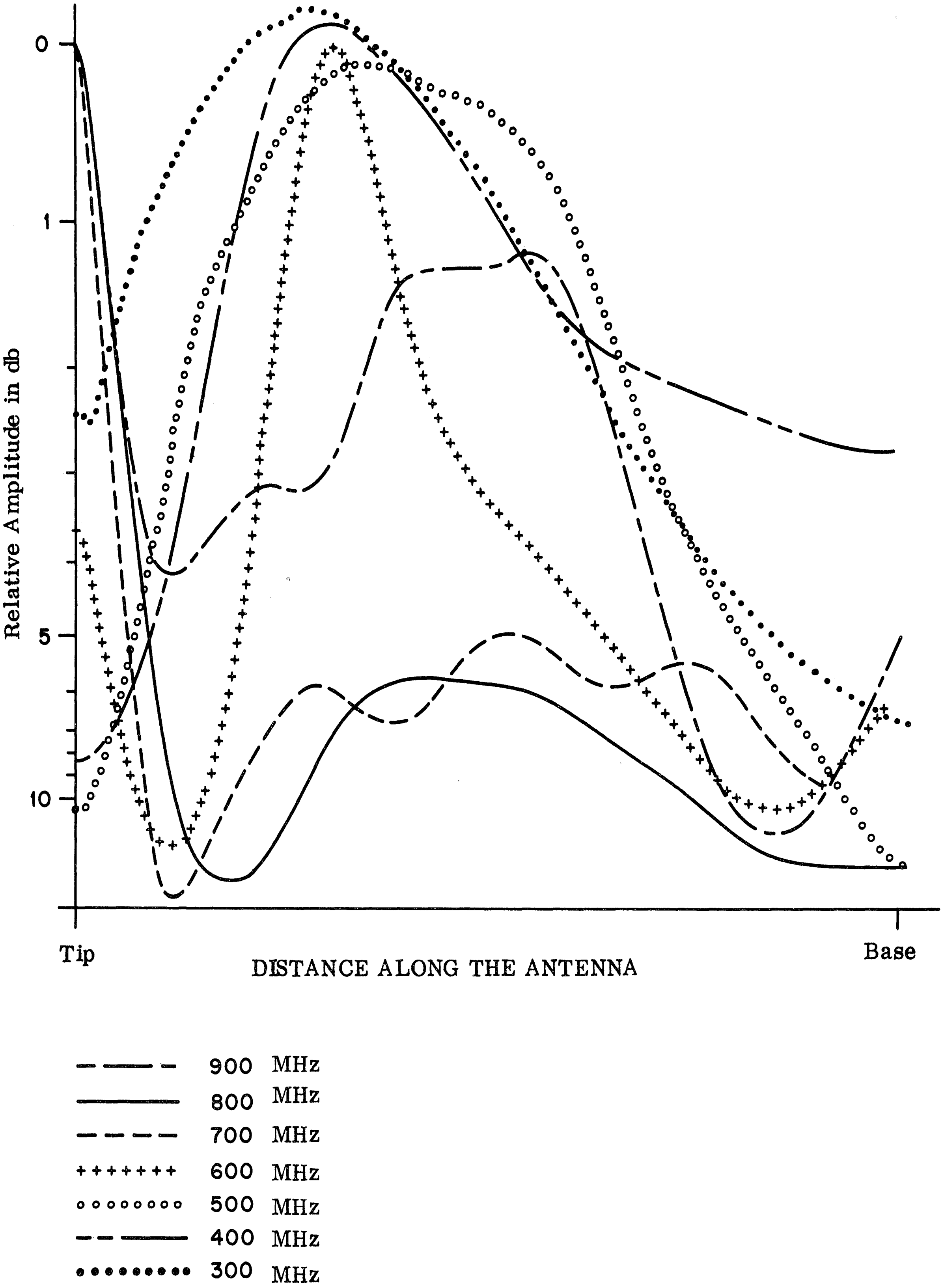


FIG. 3-5: NEAR FIELD PATTERNS OF ANTENNA 228, BIFILAR HELICAL WINDING HELIX AT 0.1λ .

As a further aid to understanding the operation of Antenna 228, a plot was made of phase velocity along the slow wave structure normalized to the speed of light and versus frequency (Fig. 3-6). The data were obtained from Sensiper (1951, p. 66). Observe that Fig. 3-6 is for a pitch angle of 10^o, whereas the pitch angle of the slow wave structure of Antenna 228 is closer to 8^o. However, the difference is not very critical. Curves for both the sheath model of a helix and the tape model with a tape width-to-pitch ratio (x) of 0.1 were replotted.

Note that even though the phase velocity is increasing somewhat as the frequency is decreasing, this does not explain the large backlobe at 300 MHz. It does not appear to be from the normal forward fire mode which occurs higher in frequency than the backfire mode. More than likely, the extraneous effects are from the large winding, or additional mutual coupling.

In an attempt to reduce the side and backlobes, the antenna will be rewound with the slow wave structure windings parallel to the axis, instead of perpendicular to it as is the case for the patterns of Fig. 3-4.

However, before that is done, the slow wave structure will be filled with powdered dielectric. This could have two effects: 1) slow down the phase velocity even more, and 2) decrease the size of the winding diameter. With a small pitch angle and a high permittivity it may be possible to build a small slow wave structure with a 4:1 reduction in phase velocity that is still relatively lightweight.

3.3 Higher Mode Suppression

One of the problems encountered in reducing the size of conical helices has been the excitation of higher modes. With some loadings, these modes propagate along the structure and radiate, causing high backlobes or sidelobes. The interim report covers several techniques (Ferris et al, 1966). Two additional techniques have been given consideration in this report period.

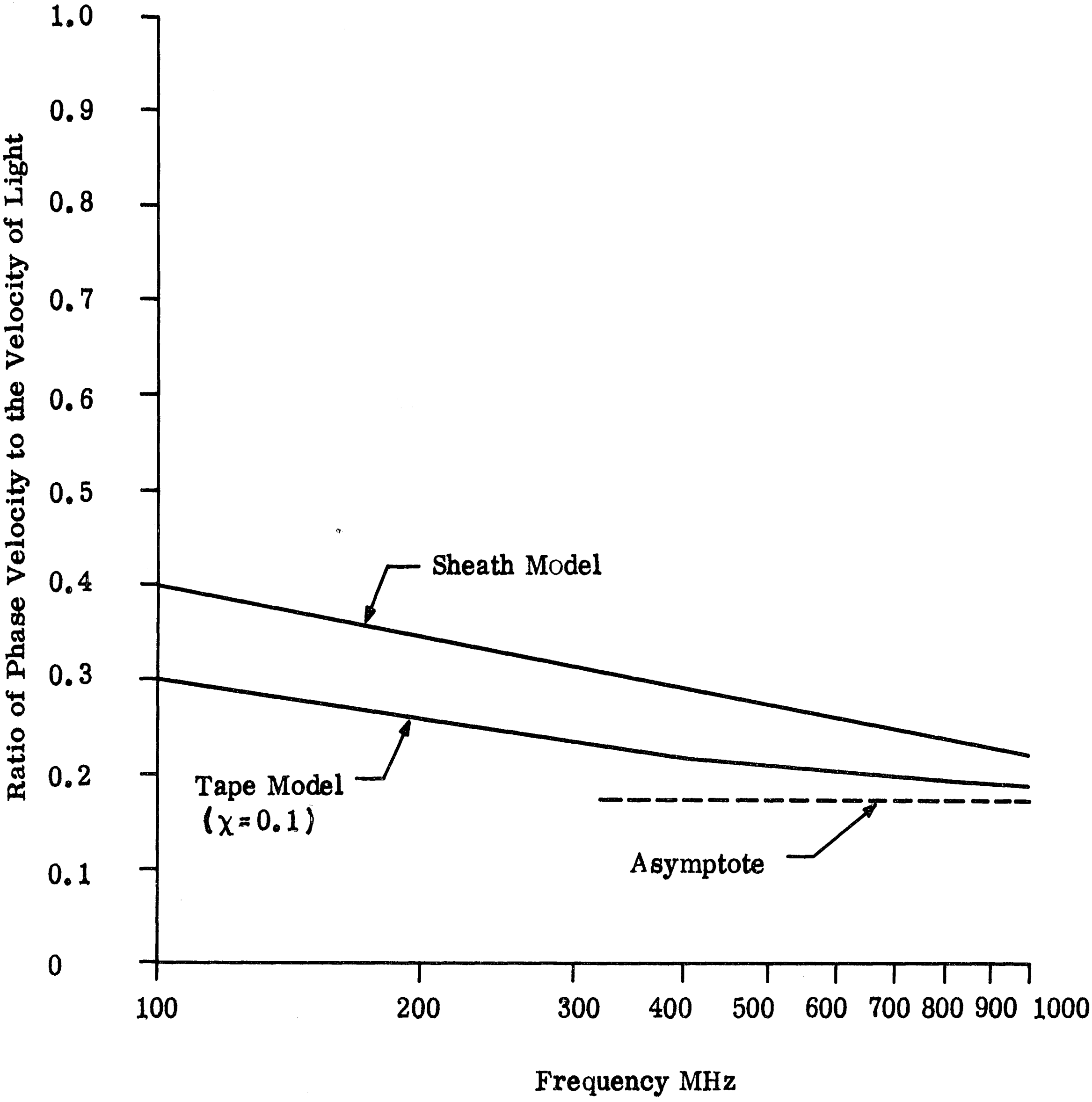


FIG. 3-6: PHASE VELOCITY FOR A 3/4" DIAMETER 10° HELIX.

The first is the use of multifilar windings to suppress higher modes. Multifilar helices have been used successfully as antennas (Gerst and Worden, 1966). The reason is that a helix with n windings cannot support either the first n modes or their harmonics. Thus, power is not lost in exciting these modes since they cannot exist. Hence, the efficiency is high.

One drawback to this construction is that each winding must be fed so that the phase difference between successive windings is $2\pi/n$ radians, where n is the number of windings. Since high power versions of equipment for producing the required phase shifts over a 22 to 1 bandwidth are both expensive and difficult to make, this technique does have its drawbacks. However, the mechanical construction of such an antenna is relatively easy.

An interesting feature of the Gerst and Worden paper is the size reduction and high bandwidth obtained with a multifilar helix. Unfortunately, their techniques applies only to the forward fire mode of operation. This is the type of helix operation originally discovered by Kraus (1950). The backward fire mode of Patton (Walter, 1964), which is almost always used to excite a conical helix, is not amenable to size reduction by this technique.

However, it may be possible to build a reduced size antenna incorporating the multifilar helix in the following way; a conical helix could be placed inside of a multifilar helix and the base of the conical helix could be connected to that of the multifilar helix. The conical helix could be either a bifilar antenna connected to the multifilar helix through power dividers and phase shifters, or a multifilar antenna connected directly to the multifilar helix. Assuming that the conical helix operates in the backfire mode, the multifilar helix would then be operating in the forward fire mode, so that the major lobe of both antennas would be in the same direction. However, the antenna patterns would not be strictly frequency independent. When the multifilar helix section of the antenna was radiating, the beamwidth would be much broader at lower frequencies than at higher frequencies.

The other higher mode suppression technique considered in this quarter was the use of a resonant turn placed back of the conical helix to act as a director. For many years, radio amateurs have been using such a technique in an antenna they call the Cubical Quad (Orr, 1959). The cubical quad antenna, consists of equal sized loop antennas cut to resonate at a particular frequency. One is fed at the midpoint of a side, while the other has an open circuited transmission line connected at the corresponding midpoint. The second loop is tuned by adjusting the length of the shorted transmission line until the loop acts as a director. Design parameters are given by Orr for both two element and three element antennas.

Antenna 223 L-2, which is a scale model of the prototype delivered last spring under Task 3, was modified to test the application of the tuned loop reflector to a conical helix. It may be recalled that in the dielectric loaded region of this antenna, higher modes were excited that produced a high backlobe. The modification consisted of adding a polyfoam core which protruded out the back, making an extension of the winding planes of the antenna. A turn was wound on this extension at one-tenth wavelength (at 250 MHz) from the plane of the base of the antenna. The one-tenth wavelength spacing is about the minimum feasible distance indicated by Orr's data. The 300 ohm twin lead transmission line tuning stub was adjusted to different lengths while taking patterns at 250 MHz . Some effect on the backlobe was noted, but the maximum effect was no more than about 1 or 2 db. In the next quarterly, additional tests with arrangement modifications will be made.

IV

BROADBAND OMNIDIRECTIONAL ANTENNA

4.1 Introduction

Hallén has proposed a broadband antenna concept and has discussed it in terms of a reflection-free antenna. One of these proposals utilizes an antenna with increasing impedance per unit length. Such an antenna would impose a gradual amplitude taper toward the end eliminating major reflections so that the periodicity of conductance and susceptance is eliminated. However, in the discussion of such an antenna, the term broadband is carefully applied only to the impedance properties. An antenna with this type of current distribution would be a special form of a traveling wave antenna described by Kraus (1950). Kraus defines a traveling wave antenna as having a uniform current distribution, with a linear phase distribution along the antenna. Assuming an antenna could be built that has a decreasing current distribution (from the feed to the free end) independent of frequency, we can calculate the far field pattern by integration of a traveling wave. For convenience, assume this current distribution is triangular, i.e.,

$$I_z = I_o \left(1 - \frac{z'}{\ell}\right) \sin\omega \left(t - \frac{r}{c} - \frac{z'}{v}\right)$$

The triangular current distribution gives a far field pattern

$$H_\xi = \frac{I_o}{4\pi r} \frac{\sin\gamma}{\cos\gamma - \frac{1}{p}} \sqrt{(2A\sin\alpha + \cos\alpha)^2 + \sin^2\alpha} \qquad (4.1)$$

where

$p = \frac{v}{c}$ = relative phase velocity $\qquad A = \frac{1}{2\alpha}$

$\alpha = \frac{\omega b}{2pc}(1 - p\cos\gamma)$

γ = angle between the antenna and observer

The effect of assuming a triangular current form is to produce a radical term instead of the $\sin\omega u_2 - \sin\omega u_1$ term obtained by Kraus. It is important to observe that the resulting pattern for H_ξ is still tilted in the direction of the traveling wave. An exponential current of the form

$$I = I_o \, e^{-\alpha z'} \sin\omega \left(t - \frac{r}{c} - \frac{z'}{v}\right)$$

produces a far field pattern that is also tilted in the direction of the traveling wave. The far field of the exponential current distribution is given by

$$H_\xi = \frac{I_o}{4\pi r} \frac{\sin\gamma}{\sqrt{D}} \sqrt{1 + e^{-2b\alpha} - 2\cos 2\beta e^{-b\alpha}} \qquad (4.2)$$

$$D = \left(\frac{\alpha\lambda}{2\pi}\right)^2 + \left(\cos\gamma - \frac{1}{p}\right)^2$$

$$\beta = \frac{\omega b}{2pc}(1 - p\cos\gamma) \quad .$$

If $b\alpha$ is such that the current is allowed to flow to the antenna tip, a tilted waveform will result when the antenna becomes electrically long. The tilted pattern resulting from currents flowing on a long antenna will limit the use of Hallén's proposed antennas to applications where horizon coverage is not a critical requirement. However, if by some means, it is possible to control the current attenuation (α) as a function of frequency such that the current is limited to the lower $\lambda/2$ of the antenna at any frequency, then the traveling wave antenna will exhibit both desirable impedance and pattern characteristics. In Eq. (4.2), we see that for higher frequencies if $\alpha b >> 1$ then the equation reduces to one giving a broadside type of pattern.

The above discussion assumed a relative phase velocity of 1.0. The equation is sufficiently general that we may have any value of p we wish. A fast wave traveling wave antenna radiates off axis and typically at high elevation angles. As the phase velocity increases the beam tilts toward the horizon.

With this as a background, it is possible to make several generalizations about the type of antenna needed to fulfill the impedance and pattern requirements for this contract. A traveling wave antenna would be acceptable if a constant electrical length of less than $\lambda/2$ could be maintained over the entire frequency band. With a traveling wave no reflections would be present so that a constant input impedance would result. Desirable impedance and pattern characteristics could also be obtained by a resonant quarter wavelength standing wave antenna. To obtain this type of antenna over a broad frequency band, the trap concept again appears desirable along with antennas whose impedance increases as a function of antenna length and frequency. In the following sections several antenna types under consideration are discussed.

4.2 Traveling Wave Structures

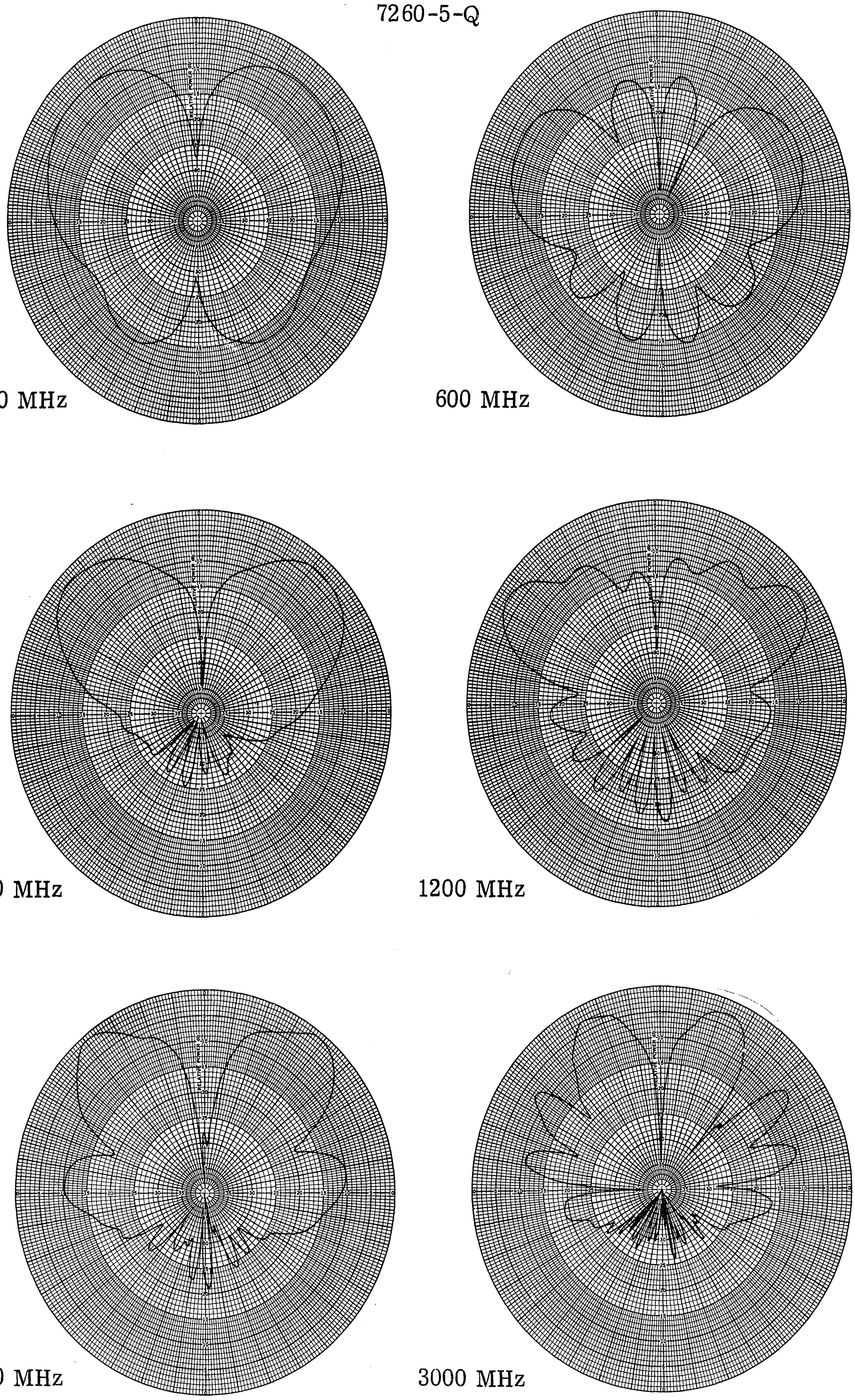
During this reporting period, major emphasis has been on the Hallén capacitive type antenna. Hallén's original version displayed a 3:1 impedance bandwidth. By trying various cylinder lengths and separation distance the bandwidth for a 3:1 VSWR has been extended to 8.5:1. Surface current measurements show the antenna to be a fast wave structure at the lower frequencies where the capacitive reactance is large. As the frequency increases the capacitive reactance decreases, and standing waves begin to appear. At that time the phase velocity approaches that of the free space. By the time the antenna behaves as a standing wave antenna, it is electrically long and electrically long antennas characteristically display good impedance properties.

Hallén increases the spacing between the cylinders as a function of antenna length in an attempt to have an increasing impedance toward the tip of the antenna. The increased spacing does give an increasing capacitive reactance but this reactance decreases with frequency which is exactly opposite to the desired effect. For this reason standing waves start to appear on the antenna at the higher frequencies (in the neighborhood of the second harmonic). These standing waves do not detrimentally effect the impedance but they do affect the antenna patterns as shown in Fig. 4-1a,b,c,d,e,f. While these patterns do not eliminate the antenna from the study, it is presently felt that other antenna configurations are more applicable to the project requirements. If the capacitive reactance is increased to prevent standing waves at the higher frequencies, this increased reactance limits the current to the lower region of the antenna at the lower frequencies giving a high VSWR as illustrated in Fig. 4-2.

One of the more promising antennas is an inductively loaded antenna similar to the type described by Hallén (1962). An inductively loaded antenna is a traveling wave antenna with a phase velocity which is expected to be less than 1. As a result there may be some beam tilt above the horizon. With this type of antenna the increasing inductive reactance per unit length also increases as a function of the frequency. It is theoretically possible to design a rate of increase of inductive reactance to limit the currents to less than $\lambda/2$ as a function of the frequency, thereby eliminating any serious beam tilt due to a slow wave structure.

One of the major problems with this type of antenna is the lack of a suitable technique for fabricating a pure inductance at microwave frequencies. Several types of "inductive" antennas have been tested. These can be placed in three basic groups: 1) coil inductances, Fig. 4-3; 2) inductance utilizing current constriction, Fig. 4-4; and 3) inductance of shorted coaxial sections, Fig. 4-5.

Surface current measurements show the coil type antennas to be limiting the currents to a small region near the input terminal. It is believed this is due to the coil inductance being too large thus preventing the establishment of current over a proper length of the antenna. A new coil antenna is in the process of being designed which employs inductances that vary from a small inductor at the feed to a large inductor at the free end. The purpose of this study is to determine the proper impedance taper required to establish the desired current waveform as a function of frequency. A question arises as to whether it is possible to obtain the required inductance at these frequencies (100 - 1000 MHz) since coils of wire at microwave frequencies



300 MHz

600 MHz

900 MHz

1200 MHz

1500 MHz

3000 MHz

FIG. 4-1: CAPACITIVELY LOADED REACTIVE ANTENNA.

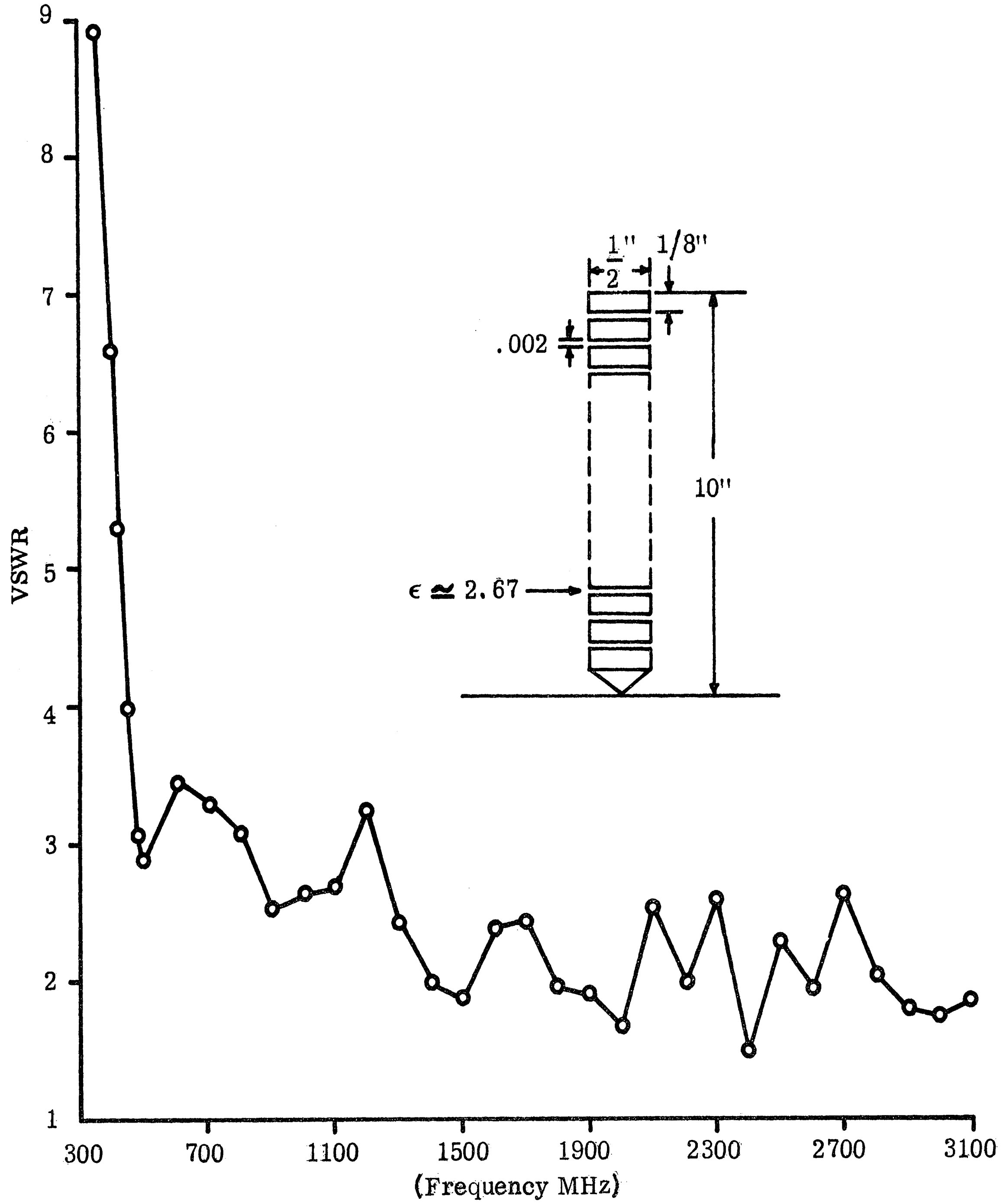


FIG. 4-2: VSWR CHARACTERISTICS OF A CAPACITIVELY LOADED MONOPOLE.

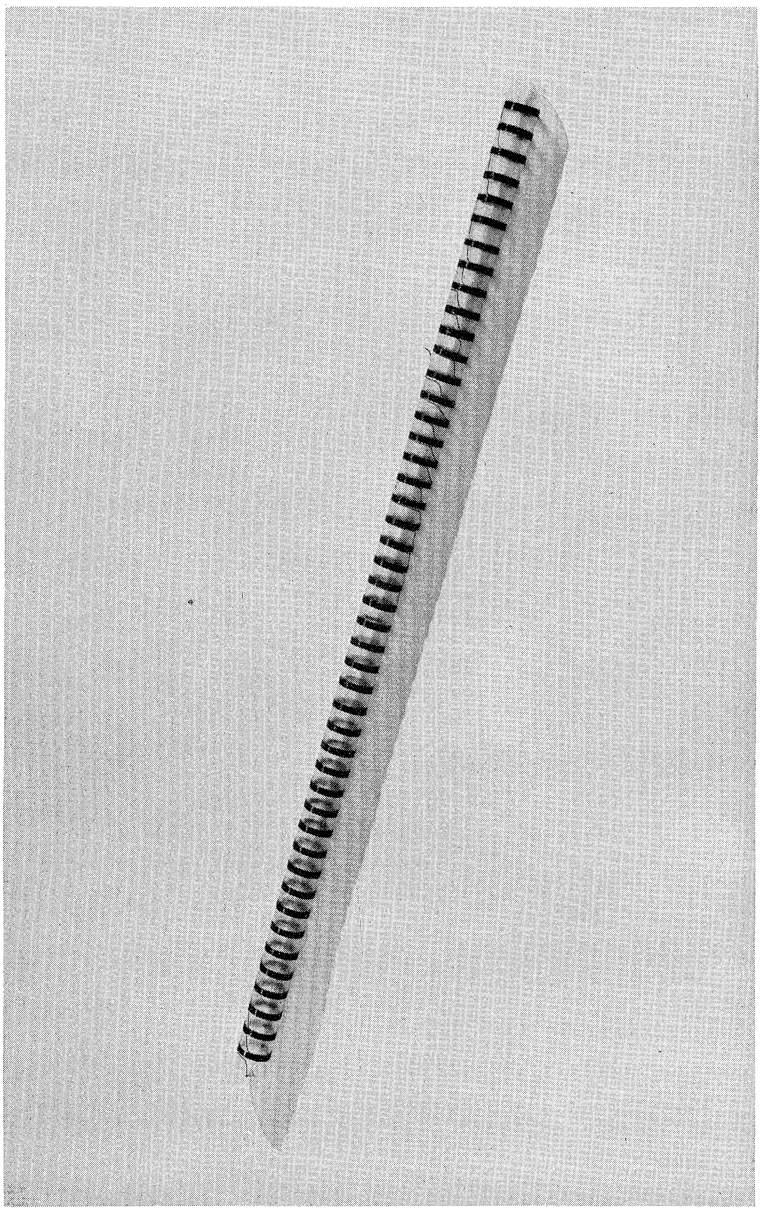


FIG. 4-3: INDUCTIVELY LOADED REACTIVE ANTENNA No. 1.
(Coil Configuration)

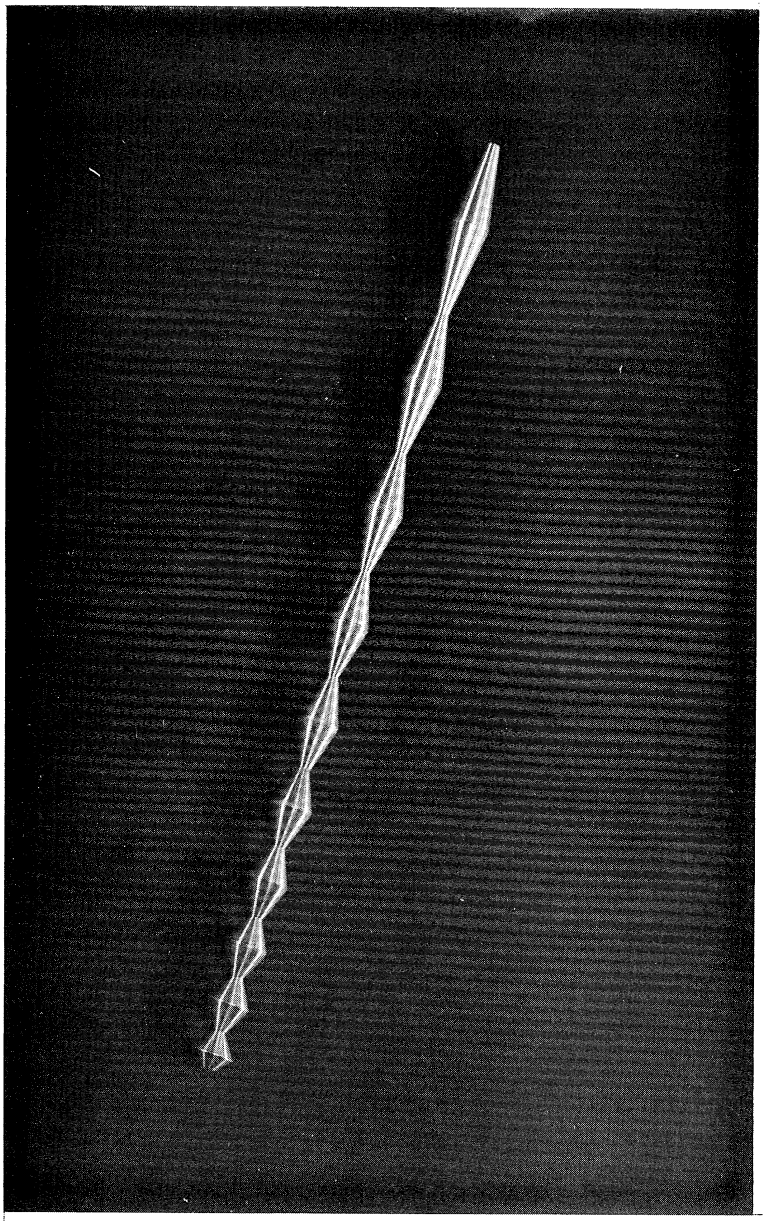


FIG. 4-4: INDUCTIVELY LOADED REACTIVE ANTENNA No. 2.
(Current Constriction Configuration)

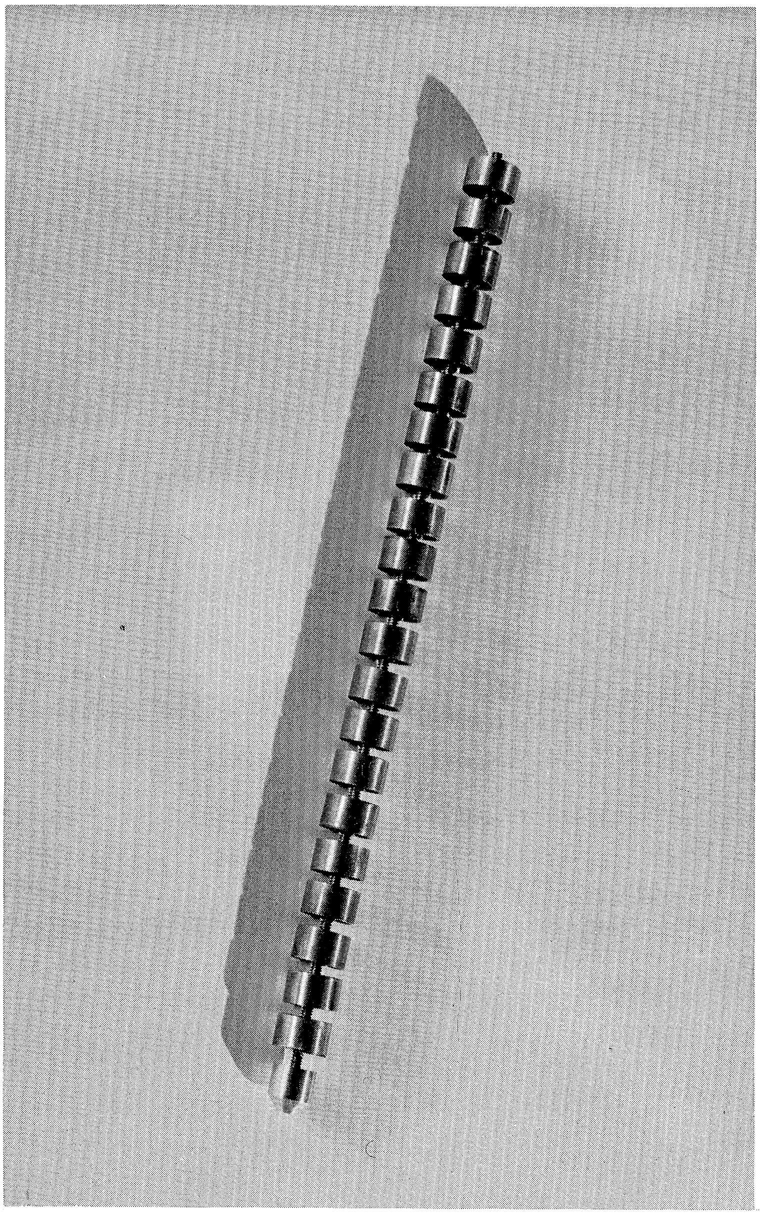


FIG. 4-5: INDUCTIVELY LOADED REACTIVE ANTENNA No. 3.
(Shorted Coax Configuration)

have capacitance between the windings. How severe a problem is posed by this parallel inductance and capacitance is not known at present.

To overcome the coil geometry consider the infinitely long single filament of wire. The formula for the self inductance per unit length of this wire is:

$$\frac{L}{\ell} = \frac{\mu_0}{2\pi}\left[\frac{\mu}{4} + \log\left(\frac{1}{a}\right)\right]^{*} . \tag{4.3}$$

From this simple formula it is evident that a wire of smaller diameter has a greater inductance. The inductive geometry antenna of Fig. 4-4 utilizes this concept of changing conductor diameter and thereby changing the inductance by increasing the current density. Since there are several parameters of this antenna to be varied, it is too early to draw any definite conclusions. However, preliminary data for this antenna indicates that with the outer diameter limited to two inches the practical ratios of the conductor diameters may limit the inductances to values below those needed to limit the current at the odd harmonics of the fundamental frequency.

The antenna in Fig. 4-4 has a maximum radius of 0.5 inches. This diameter was chosen for the 300-3000 Mc scale antenna since the aluminum stock was readily available and when scaled to 100-1000 Mc range this would closely approximate the design goal of 2 inches. It is desirable to have the smaller diameter to be as small as possible to achieve the maximum change in the self-inductance of the wire. Since it was necessary to machine the antenna in sections it was decided to support the structure by drilling and taping each section and attaching them to a long threaded rod. For convenience a 6-32 thread was used. Therefore the smaller diameter was limited to 3/16 inch. Since an abrupt change of diameter may produce reflections and increased capacitance tapered sections were used to minimize these effects. For the Hallén capacitive antenna, it was found desirable to have eight capacitive sections per wavelength at the highest frequency of operation. This criteria results in 1/2 inch spacing between constrictions at the feed point. Spacing between current constriction areas was logarithmically increased toward the tip of the antenna.

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* Hallén (1962)

The third inductive antenna consisted of short cylinders with shorted ends. The short cylinder design had two basic requirements: 1) the shorted sleeves were to be less than $\lambda/4$ long at the highest frequency of operation, and 2) there should be a sufficient number of these cylinders per $\lambda/2$ at the highest frequency of operation to control the currents. Both of these requirements were filled by using 8 elements per $\lambda/2$ at the highest frequency of operation. Variable spacing between short cylinders was achieved by using a 6-32 rod and threading the shorted end of the shorted cylinders. Preliminary data indicates that the short cylinders are not effective in controlling the currents. However, it is felt that the shorted cylinder configuration will require further consideration before it can be discarded.

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Work on the design, fabrication and testing of 3 broadband antennas is described. The antenna types are: 1)fore-shortened planar log-periodic, 2)loaded conical helix, and 3) omnidirectional.

Under Task 1 a number of crucial experiments were made to evaluate some of the fundamental changes necessary to produce a fore-shortened planar logperiodic dipole antenna. In this report studies showing the possibilities of shortening the boom as well as the individual elements are presented.

Certain significant results have been achieved in shortening the boom structure of a log-periodic dipole. The shortening of individual electric dipole elements in the low frequency range appears possible to the extent of reducing length by a factor 0.5. This reduction in electric dipole lengths can be achieved by either right angle bends at the ends of the dipoles or by a zig-zag wire construction of the dipoles.

Under Task 2, preliminary work had been done on discrete capacitor loading of a helix antenna, including dielectric loading between the turns which indicates the probable success of this technique. Unexpected patterns were obtained when a helix was wound with a coiled wire, although approximately a 2:1 reduction was evident. Suppressing higher modes with multifilar windings is promising and possibly can be used to reduce size by 4:1. Initial experiments using a resonant turn in back of a conical helix to suppress higher modes indicate that the turn must be at least 0.1λ in back of the antenna.

Under Task 3, an extensive study of the capacitively loaded Hallén antenna has been conducted. In addition a preliminary investigation of an inductively loaded antenna has been initiated. From the capacitive antenna study it has been shown that an antenna having a VSWR under 3:1 and over an 8.5:1 frequency band can be fabricated. However, the pattern characteristics for this antenna need further attention as preliminary data is not too satisfactory.

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