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RESEARCH ON
LOG-PERIODIC ARRAYS OF SLOTS

by
J. W. GREISER

January 1964

Technical Report No. 3

Contract No. NOBSR 85243
Index Number SS024001

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DEPARTMENT OF THE NAVY
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1. INTRODUCTION

Probably the last remaining application of log-periodic antenna principles that has not been really satisfactorily developed consists of slot arrays. There is a need for an efficient, frequency-independent, flush-mounted design to be used in aircraft, missiles, and hardened-site situations. A few designs have been reported in the literature[1,2] but they suffer from either excessive size, or a rather narrow bandwidth. Research on a promising design is being carried out at the present time and may, in the end, provide one solution to the problem.[3] The philosophies with which these investigators have approached the problem are somewhat varied. Schomer and Isbell begin by considering the strict electromagnetic dual of a LP dipole array but are forced to deviate when faced with the problem of constructing a satisfactory dual of the dipole array's twisted feed line. Mittra and Wahl begin with a uniformly-periodic corrugated surface antenna----then attempt to taper it into a log-periodic device. Mikenas and Mayes start out with a log-periodic array of slots with individual cavity backings and study the problem of coupling to the cavity fields in a frequency-independent manner. None of these designs has been able to reach the standards of performance achieved by the free-space LP dipole array over large bandwidths.

Nor do the designs to be discussed in this report reach that standard of performance in a cavity-backed form. However, a symmetrical slot design (i.e., one that radiates on both sides of the ground plane) has shown excellent wide band pattern performance for a range of physical parameters. In addition, this new slot design has an exact electromagnetic dual in free space; and further, the free space dual has image symmetry along its axis, thus allowing one half of the structure to be operated over ground as a LP monopole array. No other known frequency-independent design possesses this high degree of symmetry and the resulting wide versatility. All three forms of the new design have demonstrated similar wide band pattern and impedance characteristics.

2. MISCELLANEOUS AND PRELIMINARY DESIGNS

Many a designer of log-periodic antennas has expressed the wish for a catalogue of unsuccessful devices since it is virtually impossible for the engineer to predict with certainty whether a given new design will be a success or a failure. And because authors seldom list their failures in technical papers, some of these are apt to be repeated several times. Therefore, a few marginal designs and failures will be reported here.

One of the major ideas which has guided the present work on slot arrays is the viewpoint that the fewer the variables or parameters in a problem, the easier the solution will be. For this reason all initial work was done on bilaterally symmetric slot arrays. It was felt that if these devices were successful, the addition of a cavity backing would be a second, less difficult step. Another guiding principle, was the belief that approximately the same physical parameters satisfactory for existing LP designs would also be suitable for the slot arrays. This latter principle has been found true for the new slot arrays and their related duals. The designs discussed below are not taken up in chronological order; although it might be mentioned that the earliest of them was conceived in December 1961.

2.1 Log-Periodic Zigzag Slot Antennas

The zigzag slot angenna shown in Figure 1a was inspired by the successful free-space LP zigzag.[4] The new device did provide good backfire patterns over most of its design band; however, it had two major defects: 1. Serious pattern breakup occurred over narrow bands of frequency at one or two points in the design band; 2. Beam wagging was a persistent problem.[5] The shorting straps, whose endpoints are indicated by dots in the drawing, were found necessary for back-fire operation. They essentially are short lengths of conductor which break the zigzag slot into segments while forcing the opposite sides of the ground plane to the same potential. In spite of the design's marginal performance, an open sloping cavity was added to one of the models. The distance from each slot to the bottom of the cavity was adjusted to $\lambda/4$ at the slot resonances. Unfortunately, the open cavity (i.e., no interior partitions) almost completely destroyed the backfire characteristic of the zigzag slot element.

A second form of the zigzag slot antenna, which was suggested by P. E. Mayes, used a small loop to couple to the magnetic field of the slot as shown in Figure 1b. These devices exhibited very similar patterns to the models just discussed while not suffering as much from the occasional pattern breakup. Beam wagging still remained even on the best models, and a cavity backing again obliterated the backfire effect.

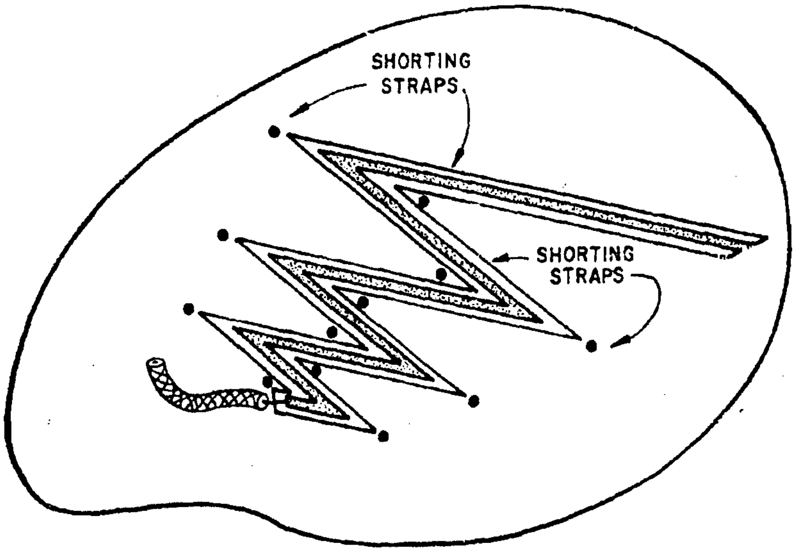


Figure 1a. Log-periodic zigzag slot antenna

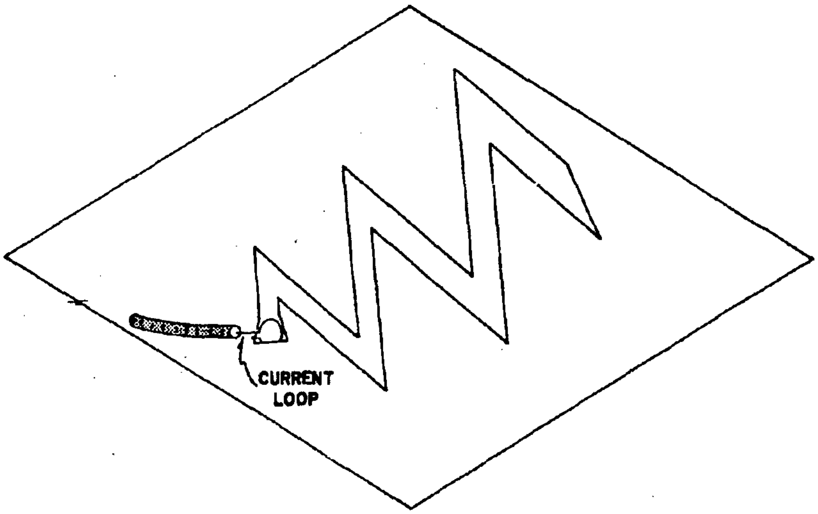


Figure 1b. Zigzag slot with loop coupling

2.2 Log-Periodic Simple Slot Arrays

It is possible to simulate the twisted feed line of the log-periodic dipole arrays by coupling to the magnetic fields of the slots with properly oriented loops. Figure 2a illustrates one such design using alternately wound square loops. Round loops have also been tried, but for loops of small area the difference is probably slight. Rather good backfire patterns were measured over parts of the design bandwidth, but, serious break-up appeared in other portions. Although the results were encouraging, study of these loop-coupled arrays was discontinued in favor of more promising designs.

The only other log-periodic array of simple slots that will be discussed here is the capacitively coupled array of Figure 2b. It is analogous to the monopole arrays of Wickersham.[6] Basically it was hoped that sufficient voltage differences would be developed across the gaps in the log-periodically segmented outer conductor of the coaxial feed line to excite the slots. The line was moved off the axis of the slot array for impedance matching. All models of this type showed persistent bidirectional patterns, indicating insufficient coupling of energy from the feed line to the slot fields. In addition the unsymmetrical feed system caused beam squint at numerous frequencies.

2.3 Preliminary Log-Periodic Folded Slot Arrays

Past experience in log-periodic antenna design indicates that the impedance of the radiating elements and the impedance of the feed system should not deviate too widely if good coupling and subsequent low VSWR are to be achieved. This criterion is difficult, at best, to satisfy when arrays of simple slots are used because their resonant impedance is above 400 Ω without a cavity backing and 800 Ω with a resonant cavity backing. It is well-known that the impedance, Z_s, of a two-dimensional slot and Z_d of its free space dual bear the following relation

$$Z_s Z_d = \frac{(377)^2}{4}$$

Thus, if the free space dipole has an impedance of $Z_d = 72\ \Omega$, the dual slot impedance will be $Z_s = 493\ \Omega$. On the other hand, if the electromagnetic dual of a folded dipole or a folded tripole is taken, impedances of 125 Ω and 55 Ω should result. These values have been experimentally verified in the laboratory. A pair of dual folded slot and folded dipole antennas are depicted in Figure 5d, wherein the dots indicate their feed terminals.

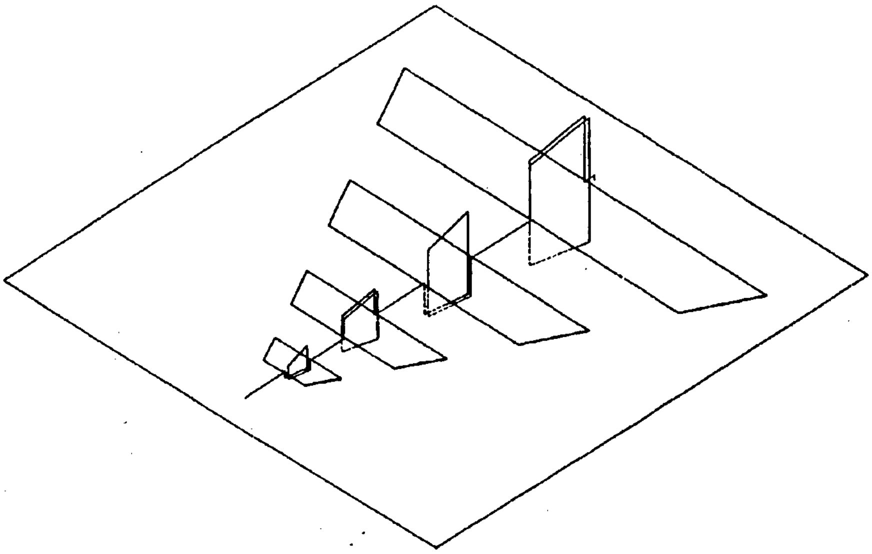


Figure 2a. Log-periodic array of slots with loop coupling

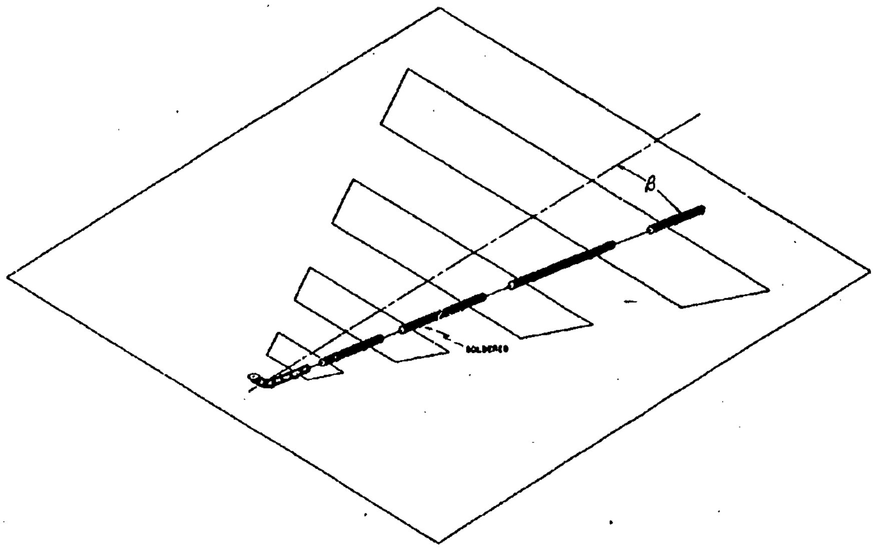


Figure 2b. Capacitively coupled log-periodic slot antenna

Initial attempts with models incorporating the folded elements were encouraging. One of the early models is sketched in Figure 3a. Note that the segmented coaxial feed line is grounded along the central axis of the array, and that its center conductor is periodically connected to the center conductors of the slots. Here another advantage of the folded slot elements over ordinary slot elements appear; it is possible to attach a whole series of elements with varying resonant frequencies to a single feed line with no danger of shorting out the low frequency energy in the high frequency portion of the antenna.

Radiation patterns of several models like the one of Figure 3a were in general good -- in fact the best so far obtained--except for persistent inexplicable anomalies, such as were found in the zigzag slot antennas. The models were also rather insensitive, making pattern measurement difficult suggesting that impedance problems may have still remained.

3. LOG-PERIODIC FOLDED SLOT ARRAYS AND THEIR RELATIONS

3.1 Coaxial Cable Phasing Lines

The turning point in the log-periodic slot array research came with the testing of an antenna of the type shown in Figure 3b. Two points of difference from the array of Figure 3a should be noted: 1. The segmented outer conductor of the feed line is not grounded, 2. The individual segments have been lengthened in a log-periodic fashion to provide a controlled amount of extra phase shift per period. The effects of this extra phase shift on the radiation patterns were much the same as those previously experienced with bent log-periodic zigzag antennas. In any case, the anomalies in the patterns disappeared and and an average of 20 db more signal was available when measurements were carried out.

As the patterns of Figure 4 show, something is still to be desired in the operation of this type of folded slot array. In the actual models, sections of microdot coax provided the required phasing between slots, and inaccuracies in these cables may have been part of the problem. Their lengths generally averaged 2-5 times the distance between slots.

3.2 Printed Circuit Log-Periodic Folded Slot Arrays

A considerable improvement in accuracy and simplification of construction was made possible by adopting completely printed antenna construction. This improvement was also reflected in the radiation patterns. The method of reducing the

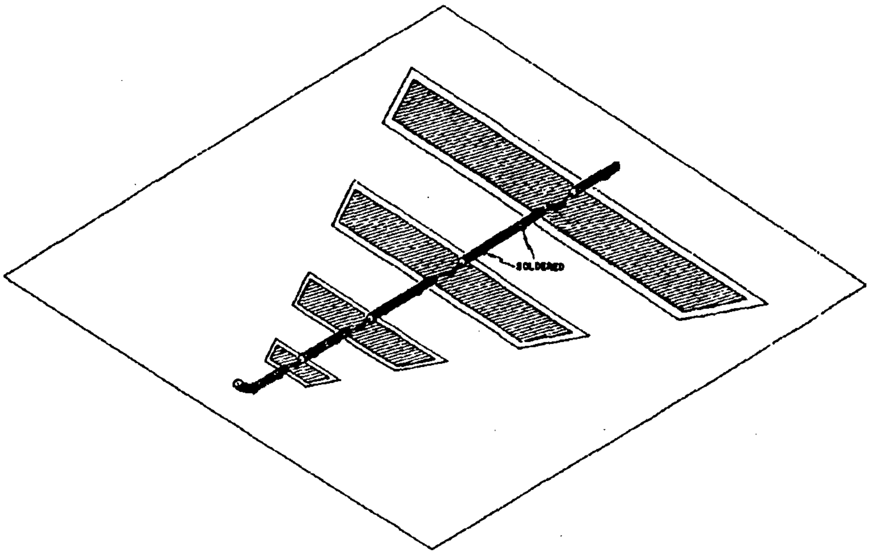


Figure 3a. An early log-periodic folded-slot array

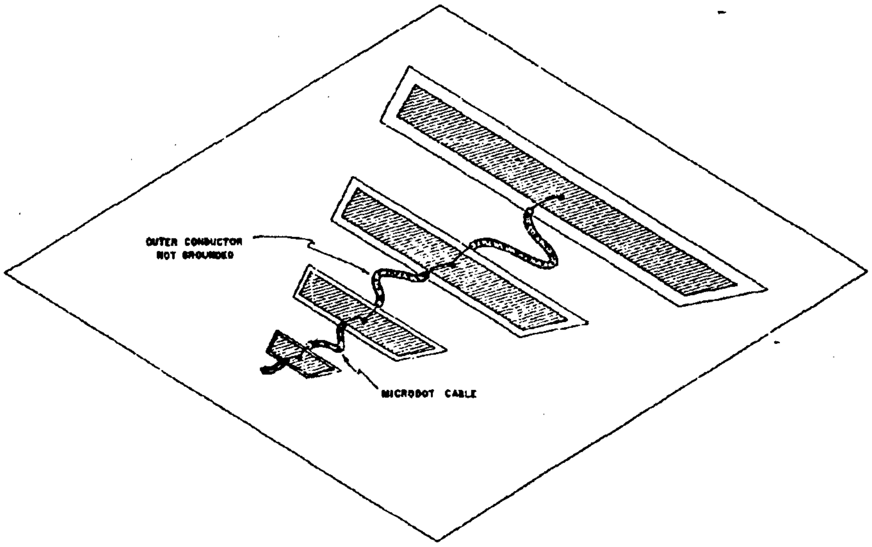


Figure 3b. Log-periodic folded slot antenna with phasing lines

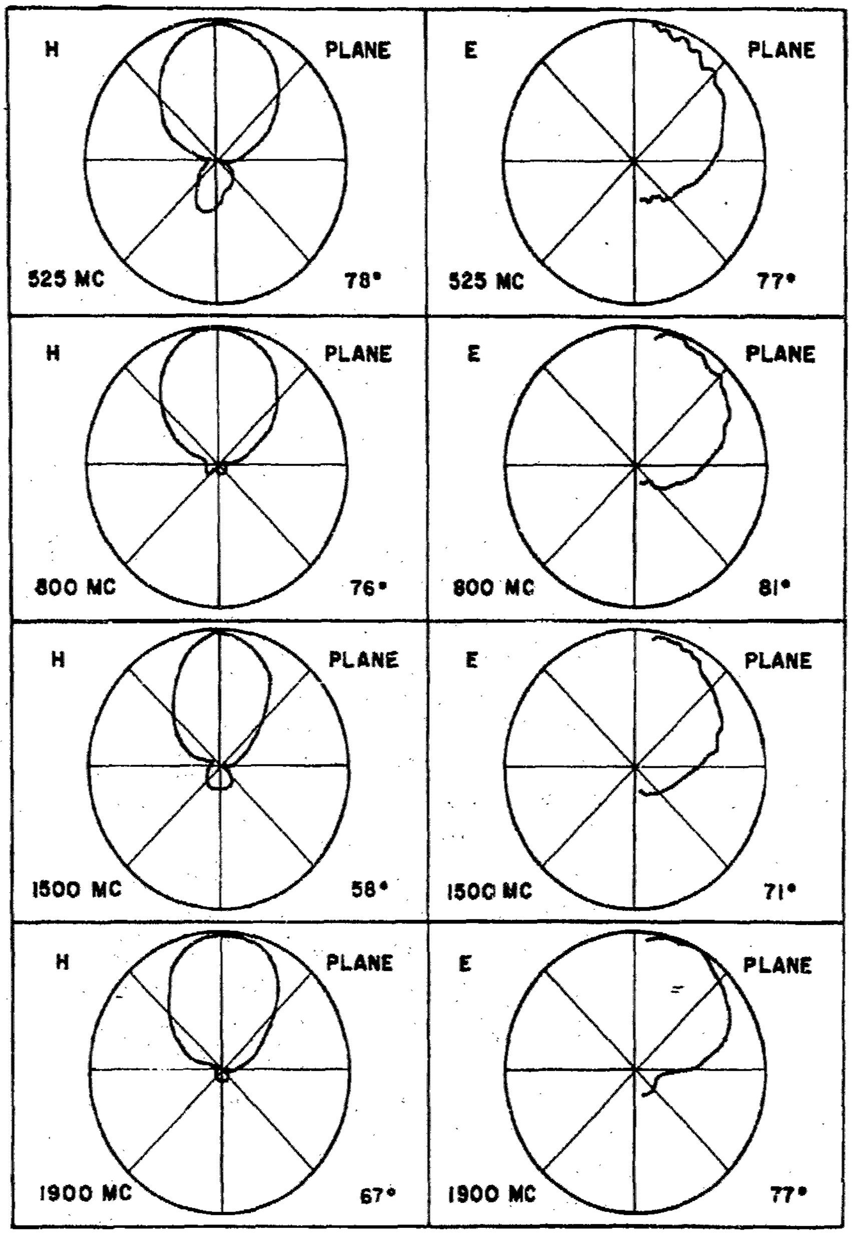
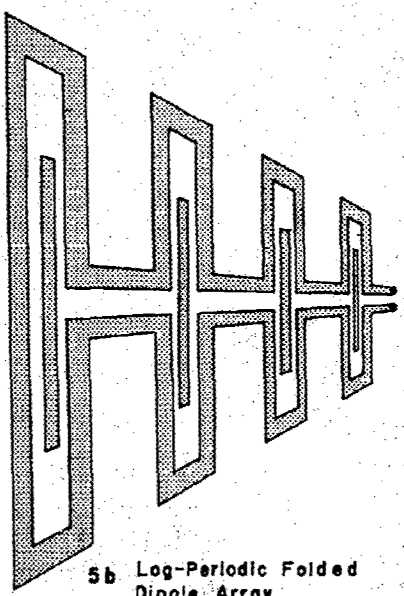


Figure 4. Radiation patterns of SA-2B, $\tau = .81$, $\alpha_E = 22.5^\circ$

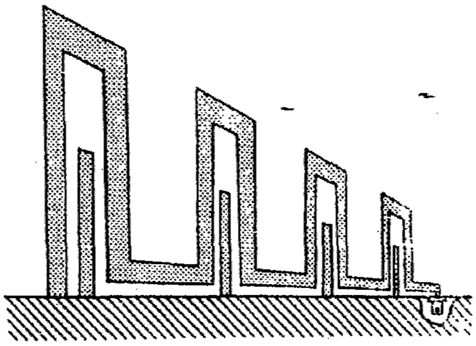
phasing cable sections to a two-dimensional structure is illustrated in Figure 5a. Antenna currents flowing on the ground plane on the array axis are parallel to a line bisecting the elements (i.e., the axis of the array). Thus, the ground plane can be cut along the array axis and sections of printed circuit transmission line inserted therein. An adjustable phasing mechanism is provided by the smaller slots which are symmetrically cut into the center conductors of the outer slots. It has been determined experimentally that the optimum length for these phasing slots is in the neighborhood of one half the length of the outer slots. Appreciable deviations from the optimum length are accompanied by pattern and impedance disturbances.

The unique symmetry properties of the printed circuit version of the LP slot array were not recognized immediately since attention was principally directed towards flush mounted designs. However, a fortuitous mistake in the specification of the type of negative to be made from a folded slot drawing drew attention to the unusual symmetry of the new design. To this writer's knowledge there is no other single log-periodic antenna design that will operate in all three basic modes: 1. As a slot array, mounted flush with a ground plane and producing vertically polarized radiation; 2. As a linearly polarized free space antenna; and 3. As a vertically polarized monopole array over ground. Figures 5a, b, and c illustrate how the various forms of the design are related. A family of folded element antenna arrays which were all made from the same original drawing is shown in Figure 6. Since this report is primarily concerned with flush-mounted antennas, nothing more will be said of the folded dipole and folded monopole arrays except to state that they have excellent impedance and pattern characteristics which are implied by duality and symmetry considerations.

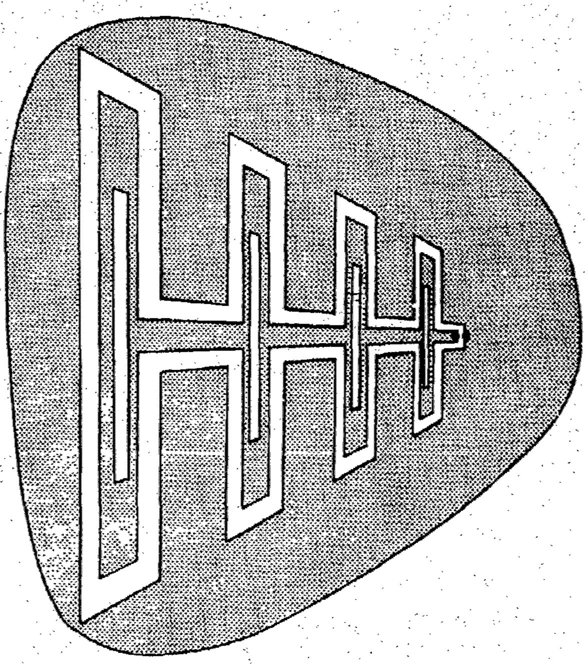
A series of patterns measured on the first printed circuit folded slot array, FSA-1, is shown in Figures 7 and 8. This design had an average directivity of 7.5 db/ isotropic with average beamwidths of 58.8° and 58.5° for the E and H plane respectively. Kraus's relation was used to calculate the directivity value.[8] When specifying the low frequency cutoff of a log-periodic antenna, care must be taken to first choose a reasonable criterion and second, to properly relate this critical wavelength to the physical size of the antenna structure. In the present work, the frequency at which the front-to-back ratio reached 10 db was chosen as the low frequency criterion. This wavelength corresponding to the low frequency was then compared to the largest



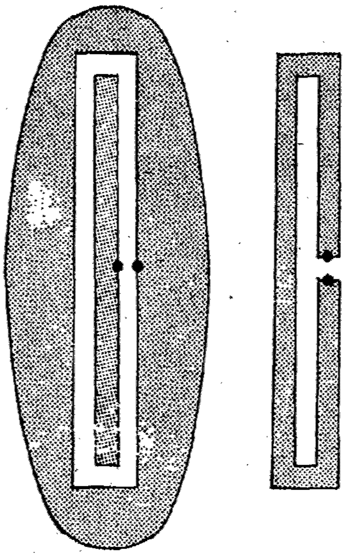
5b Log-Periodic Folded Dipole Array



5c Log-Periodic Folded Monopole Array



5a Log-Periodic Folded Slot Array



5d Dual Folded Slot and Folded Dipole

Figure 5. Log-periodic folded element arrays

Figure 6. A family of log-periodic folded element arrays

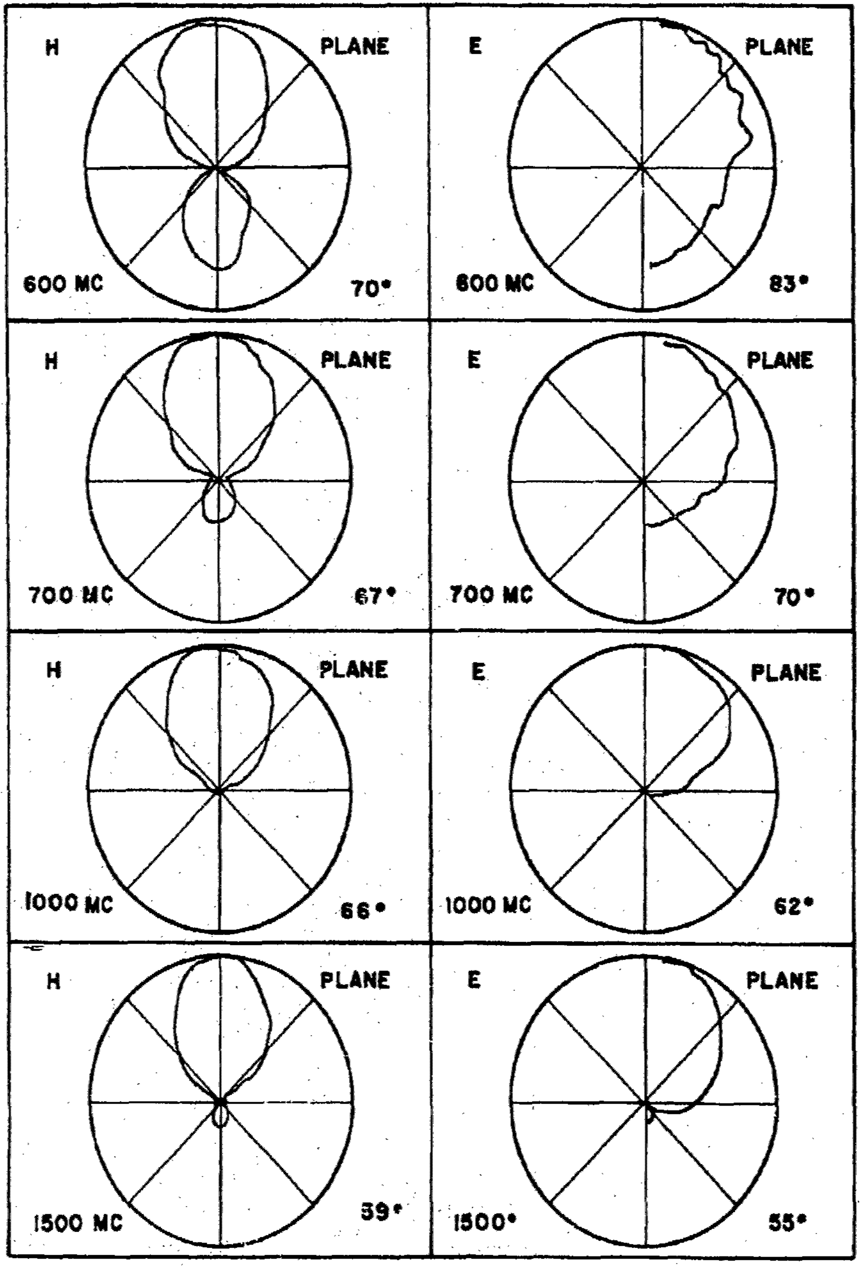


Figure 7. Radiation patterns of FSA-1, τ = .78, $\alpha_E = 25^\circ$, $\alpha_S = 12.5^\circ$

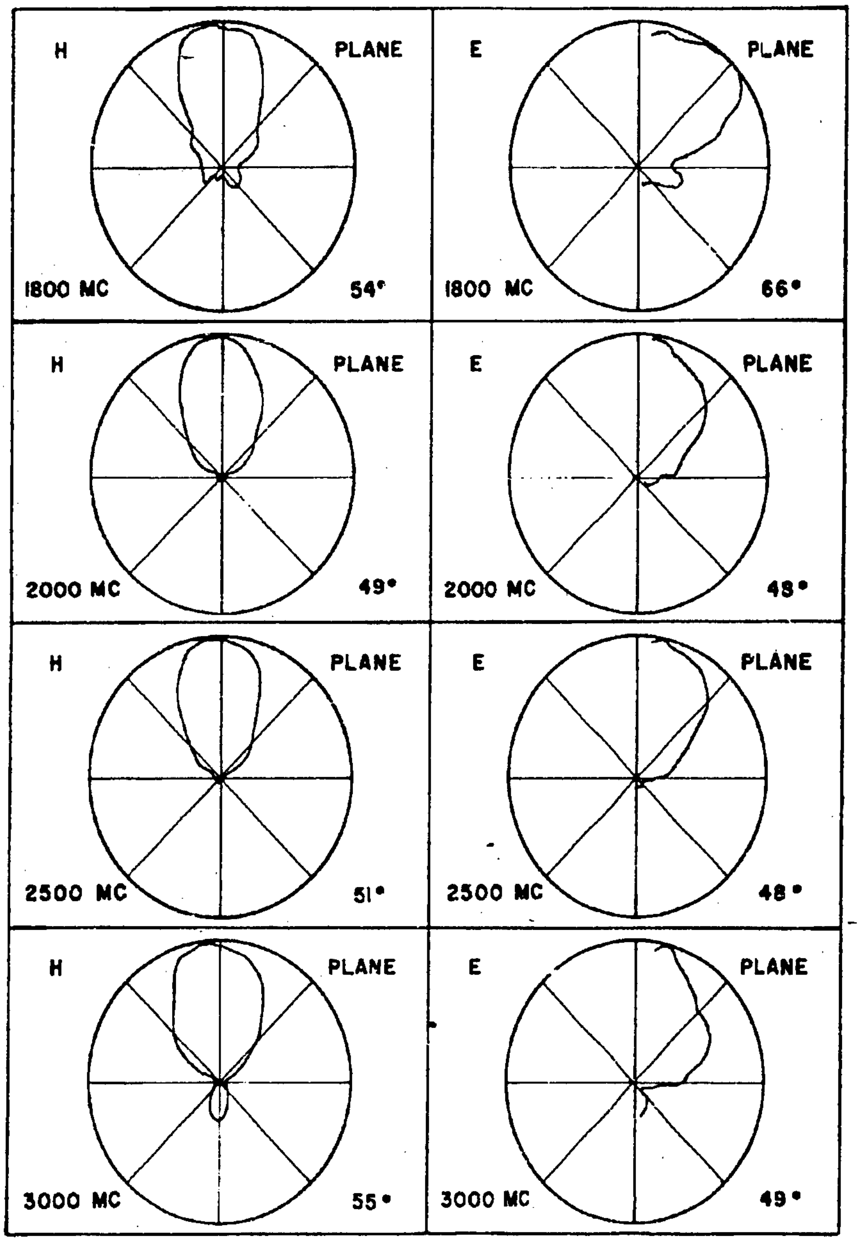


Figure 8. Radiation patterns of FSA-1, $\tau = .78$, $\alpha_E = 25^\circ$, $\alpha_S = 12.5^\circ$

transverse dimension of the structure. It would be most desirable if the antenna had a 10 db F-B ratio at the frequency where the largest slot was $\lambda o/2$ in length. For FSA-1 a frequency of 593 Mc. was calculated from the structure size, while pattern measurements gave 700 Mc. Thus, the actual cutoff (based on the 10 db F-B criterion) is 18% higher than the structural cutoff. Other types of log-periodic antennas exhibit a similar behavior.

In any case, the low frequency cutoff of a given structure is somewhat dependent on the parameters τ and α . For slot arrays at least, which are most likely to be used at microwave frequencies, the small increase in physical size over the $\lambda/2$ dimension is of no consequence.

Returning again to the patterns of Figures 7 and 8, it is noted that the average directivity calculated from the beamwidths is just about the same as would be expected from a LP dipole array with the same τ and α_E.[9] This is a reassuring result. The pattern at 1800 Mc is included because it is the worst one that was measured, however, at both 1700 and 1900 Mc very clean and unidirectional patterns were obtained.

An impedance plot of FSA-1 is given in Figure 9. A VSWR of 2.3:1 with respect to 93 Ω was measured for FSA-1 over the range 600-2000 Mc. It should be noted that impedance measurements in this frequency range are difficult to do accurately, so some of the scattered points may be due to that cause. Blocks of Eccosorb placed underneath the ground screen served to absorb any downward radiation from the bilaterally symmetric antenna.

All of the printed circuit antennas were constructed of 1/32 in. teflon impregnated fibreglass board, with 2 oz. copper on one side. Drawings were generally made two or three times life-size, then photographically reduced so as to provide a negative of the desired size thus, good accuracy could be obtained economically.

Before concluding this section, a few other folded slot designs and modifications will be discussed briefly. Although not a lot of work has been done on the new models, they do serve to show that the choice of parameters is not particularly critical, and that a wire grid outline of the center conductor is a satisfactory substitute for the printed version.

The smallest α_E angle (between array axis and outer extremity of slots) used so far has been 18^0 with a τ of .82. An α_S of 9.5^0 defined the length of the phasing slots. Some representative patterns of model FSA-5 are shown in Figure 10.

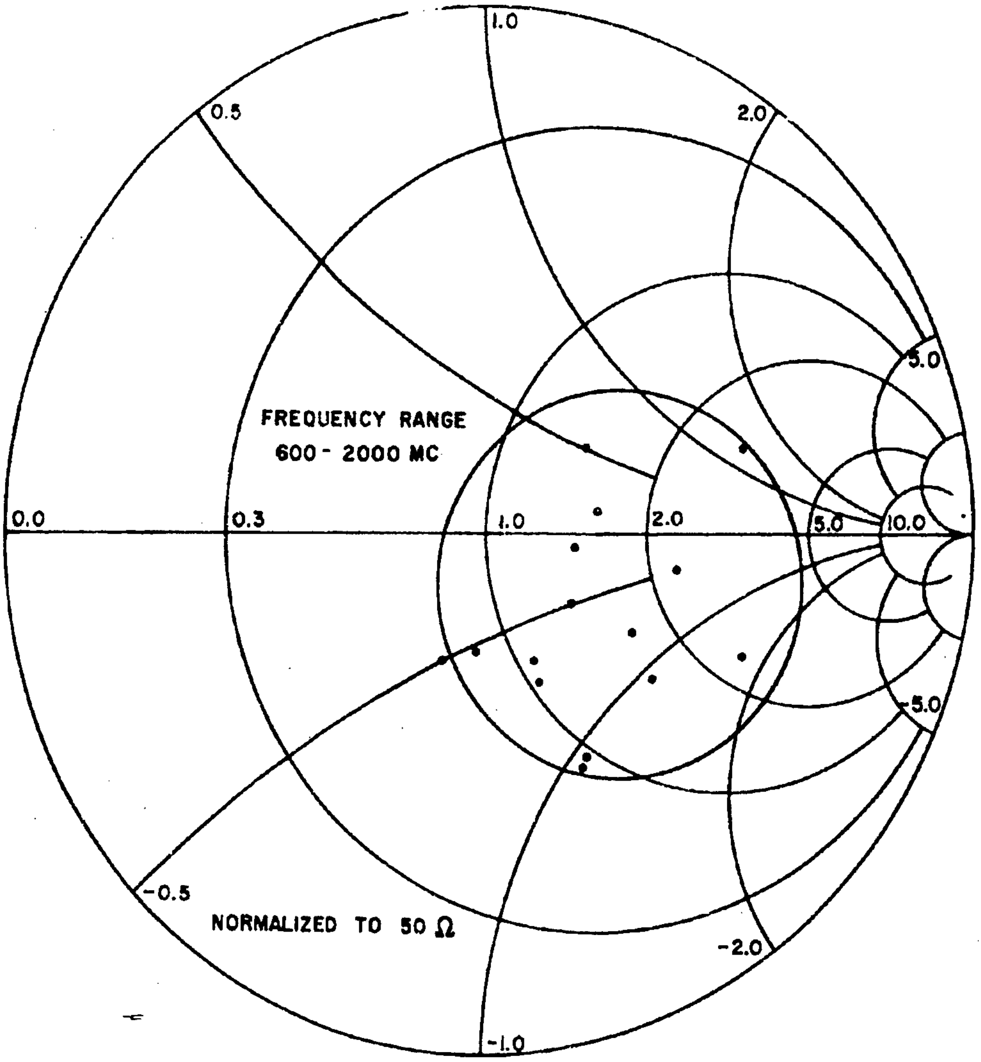


Figure 9. Impedance of FSA-1, $\tau = .78$, $\alpha_E = 25^\circ$, $\alpha_S = 12.5^\circ$

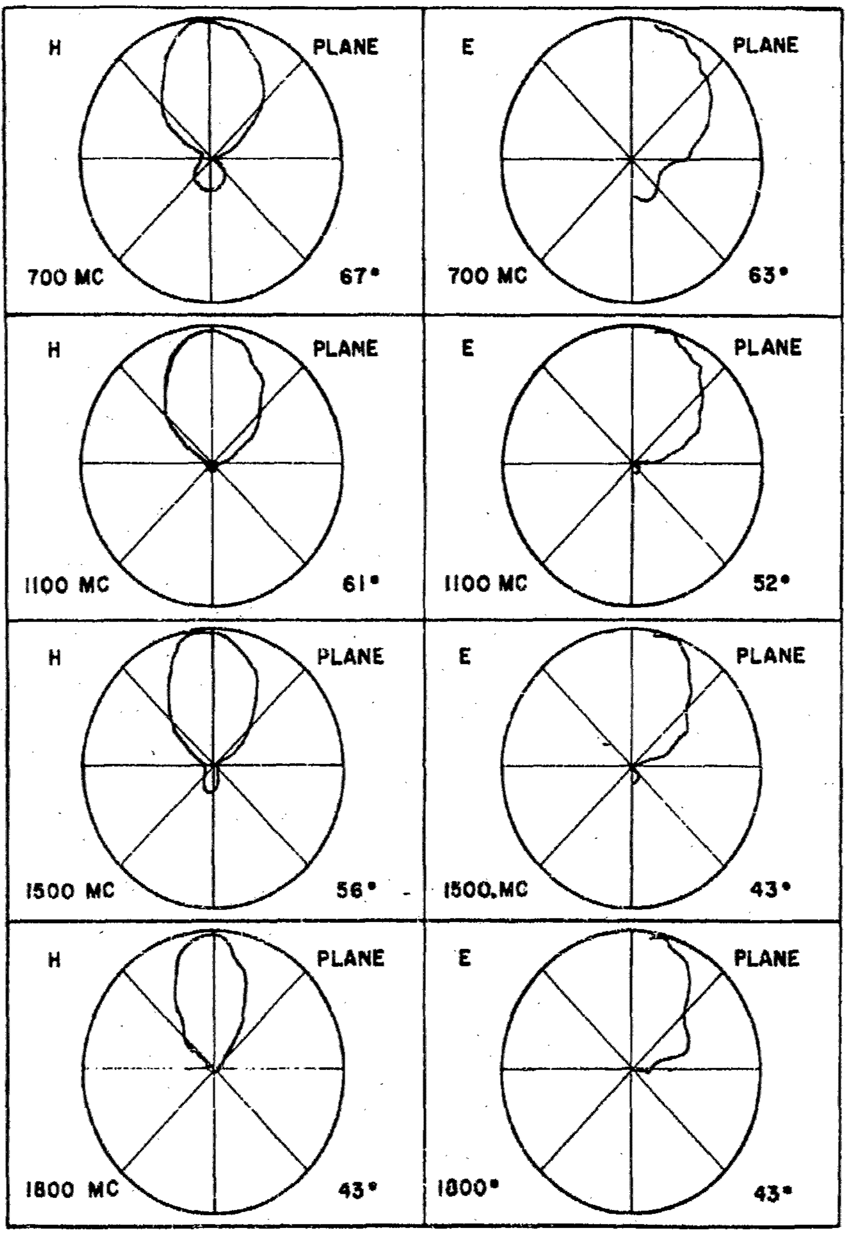


Figure 10. Radiation patterns of FSA-5, $\tau = .82$, $\alpha_E = 18^{\circ}$, $\alpha_S = 9.5^{\circ}$

For this design the actual cutoff was about 17% above the structural cutoff of 590 Mc. Due to the length of the array (because of the low α_E angle) and the limited size of the pattern aperture plate (14 in. x 14 in.) the smallest slot resonated at about 2010 Mc. At 1800 Mc effects of the front truncation were beginning to appear, while at 2000 Mc the pattern began to split into two distinct lobes. Cross-polarized energy (horizontal) was measured at several frequencies and found to be below -35 db. The average E and H plane beamwidths were 53° and 60° respectively for the 700-1800 Mc range.

In the printed antennas discussed so far, the center conductor of each slot element covered a rather large portion of the area with copper. This causes no problem when bilaterally symmetric arrays are considered; but, if attempts are made to eliminate radiation from one side of the ground plane by the use of cavity backings, it would seem that the extensive surfaces of the slot center conductors could hinder the exit of energy from the cavity volumes. For this reason, the slot center conductors were simply outlined with a wire grid (so as to reduce their blocking characteristics to a minimum) on model FSA-3E. Its patterns, shown in Figure 11, are noticably better than FSA-3C's which used the printed circuit type conductor. However, in every case when a cavity backing was added, partial pattern breakup took place. More will be said of this in the next section. The average beamwidths of FSA-3E were 58° and 64° for the E and H planes respectively.

One last folded slot antenna should be mentioned. Model SA-6B (original numbering scheme) employed an α_E of 30° --the largest so far attempted. The other significant parameters were $\alpha_S = 15^\circ$ and $\tau = .71$. Because of the low value of τ the antenna consisted of only six widely spaced elements. Even so, the pattern variations were not too great and the design can be considered practical for many applications. Undoubtedly, models with even higher α_E angles can be built, but their directivity would probably suffer more than the additional size reduction would be worth. The particular model tested here had average E and H plane beamwidths of 66.4° and 66.9° respectively for the 700-2000 Mc range.

3.3 Cavity Backed Slot Arrays

Perhaps it is best to state at the outset that so far cavity backed designs have been, for the most part, unsuccessful. Two general approaches are being pursued in the present work 1. The simple addition of $\lambda/4$ deep individual

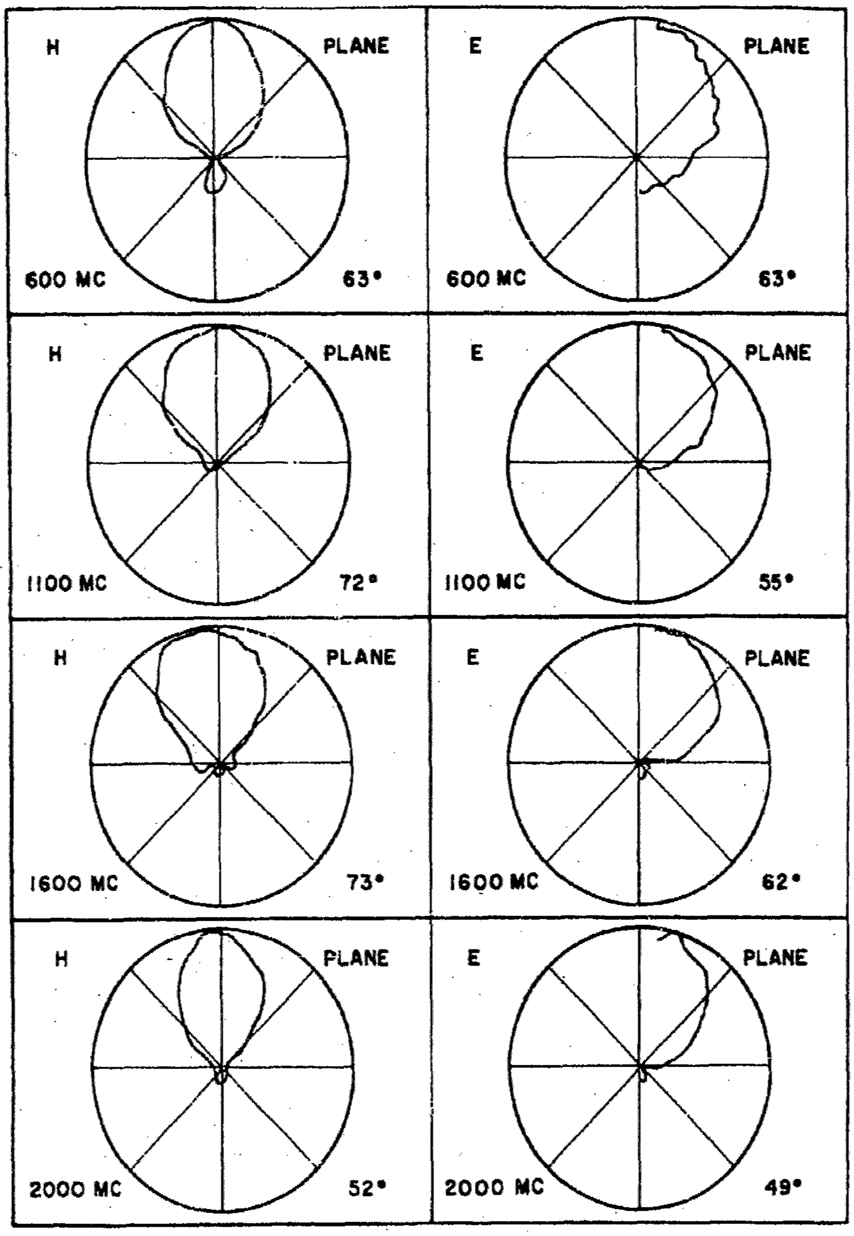


Figure 11. Radiation patterns of FSA-3E, $\tau = .8$, $\alpha_E = 20^\circ$, $\alpha_S = 10^\circ$

cavities to each element of a successful bilaterally symmetric folded slot array; 2. The design of a single folded slot element plus cavity to secure the desired resonant frequency and impedance; then the combination of a number of these elements to form a log-periodic array.

The most promising approach so far is the first one mentioned--on the basis of radiation pattern performance. Some typical examples of pattern degradation are shown in Figure 12. Individual cavities, $\lambda o/4$ (free space) deep were added to one side of each slot element of a reasonably well performing LP slot array. It should be stated that the phasing cables of SA-2A and SA-2D were considerably different in length; both arrays represent the best phasing adjustment that was found. At 600 Mc the action of cavities is to reduce the front-to-back ratio from 8 db to 2.06 db. This effect was present on all cavity-backed designs that have been tested to date. Again at 900 Mc the front-to-back ratio is reduced from 21.8 db to 8.2 db. Although the pattern of SA-2A is not particularly good at 1300, the damaging effects of the cavities can be clearly seen in the pattern of SA-2D. This is repeated at 1800 Mc. Not shown in Figure 12 are some of the better patterns of SA-2D which lend encouragement to this approach to unilateral flush-mounted LP antennas.

The second approach consisted of studying a single folded slot element plus cavity and adjusting its resonant frequency and impedance level before incorporation into a log-periodic array. It was recognized that a bilateral folded slot element can have one resonant frequency and impedance level by itself, and an altogether different resonant frequency and impedance level after the addition of a cavity backing. From past experience it was decided that a real impedance of 100 Ω would be satisfactory. It was also decided that the resonant frequency (where the impedance was 100 Ω real) of the slot plus cavity should be the same as that of the slot alone. Now if the cavity backing is assumed lossless it can add only pure reactance to the slot impedance--outside of doubling the radiation resistance. Thus, the frequency at which the reactance of the cavity goes to zero is of primary interest, since it must coincide with the slot resonant frequency. A cavity which is $\lambda o/4$ deep at the slot resonance will not have zero reactance there because of the waveguide effect. That is, the cavity backings should be considered as sections of waveguide which are excited in the dominant mode by the slot. The guide wavelength in such a system can be several times the free space wavelength, implying that, for

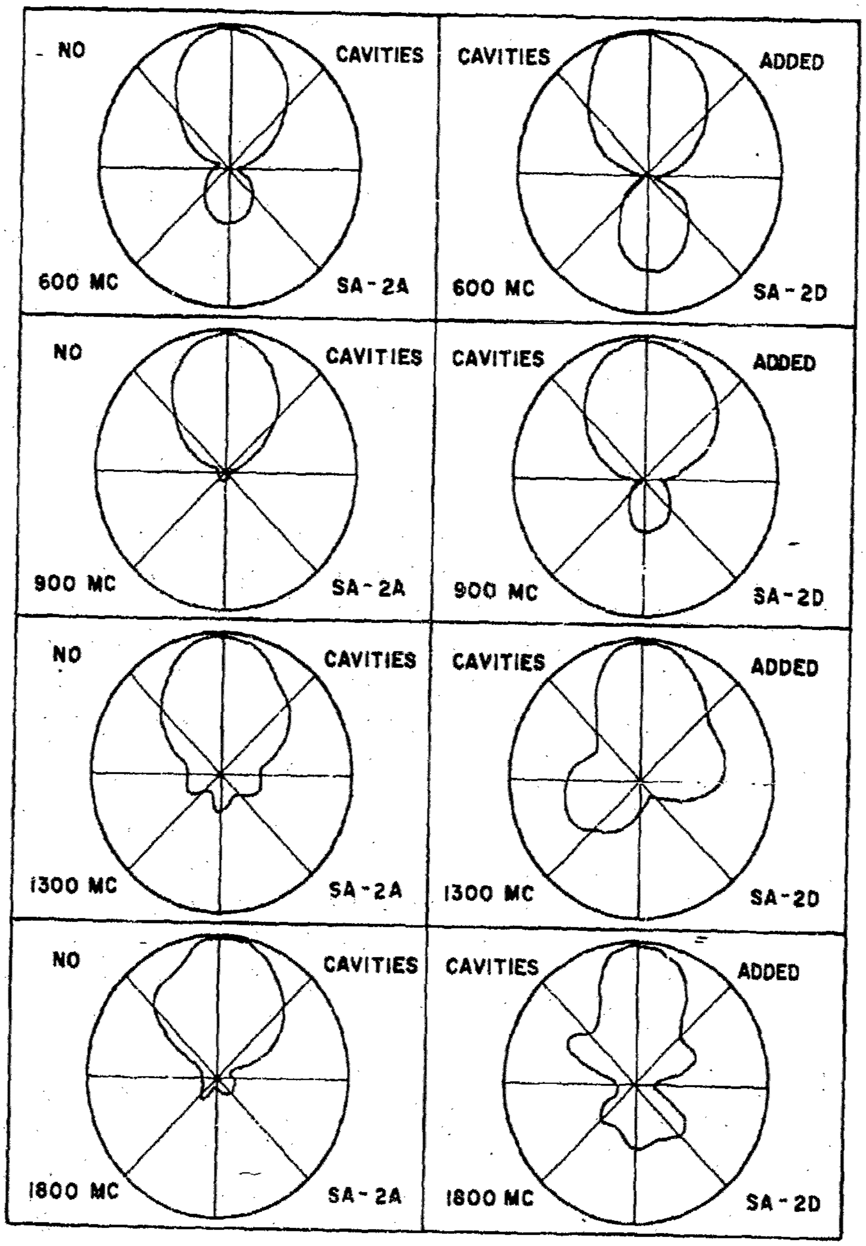


Figure 12. Effect of the addition of cavities

resonance, the cavities must be $\lambda g/4$ deep instead of $\lambda o/4$. By using a cavity of adjustable depth, the correct length was easily determined.

The use of a folded slot element rather than a simple slot allows the resonant impedance to be widely varied without appreciably affecting the resonant frequency. How this is achieved is illustrated in Figure 13a. By making the electric current conductors of unequal size in the folded dipole or the magnetic current conductors in the folded slot a wide range of input impedances are available. In the actual slot plus cavity tested the center conductor of the folded slot radiator was of the wire grid type already described, and was considerably displaced from the center of the slot. After very few adjustments the desired impedance level and resonant frequency of the slot-cavity combination were secured. It was also gratifying that the depth of the cavity necessary for resonance turned out to be almost exactly what was predicted theoretically (about .45 λo for the size waveguide chosen).

Using similar proportions a whole series of slot-cavity combinations were then incorporated into a single log-periodic array. The parameters used were: $\tau = .75$, $\alpha_E = 25^0$, and $\alpha_S = 12.5^0$. However, the resulting radiation patterns and impedance were very poor. In fact the antenna tended more often to be endfire then backfire. And, although the mean impedance of the array was 55 Ω as desired, the accompanying VSWR ranged from 4:1 to 8:1. Because of these discouraging results and because of the large amount of work required in the construction of a series of log-periodic cavities, further work has ceased for the time being.

Before concluding, a somewhat different line of attack on the problem of converting a bilaterally radiating LP slot array into a unilateral device will be mentioned. The idea basically results upon the fact that the far field patterns of a small loop and a slot ($L \approx \lambda/2$) are identical. If, then, a loop and a slot could be simultaneously excited with the proper phase and magnitude relations, it would be possible to cancel the far field of the slot everywhere in the chosen half-space. Figure 13b shows an arrangement that gives partial cancellation in the half-space containing the loop. An array of three sheet metal loops with mean circumferences of .65 λ at slot resonance gave 10 db average cancellation over a frequency range of 400-1200 Mc. Configurations with fewer loops, or with loops of thin wire have, so far, shown less cancellation. Unfortuantely the first attempt at combining a number of such unilateral slots into a log-periodic array failed.

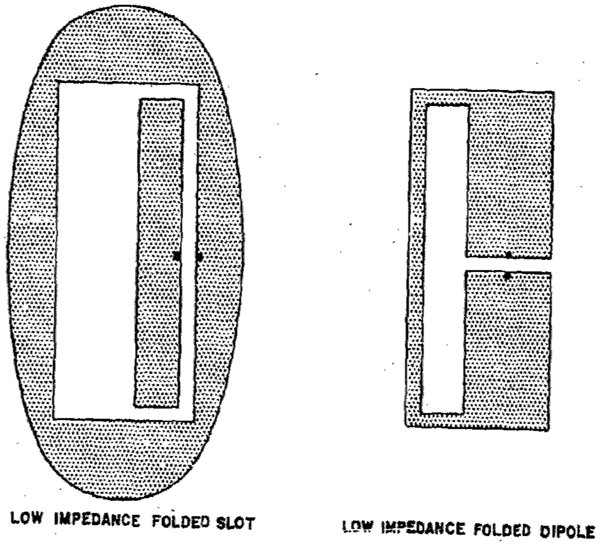


Figure 13a. Impedance reduction with folded elements

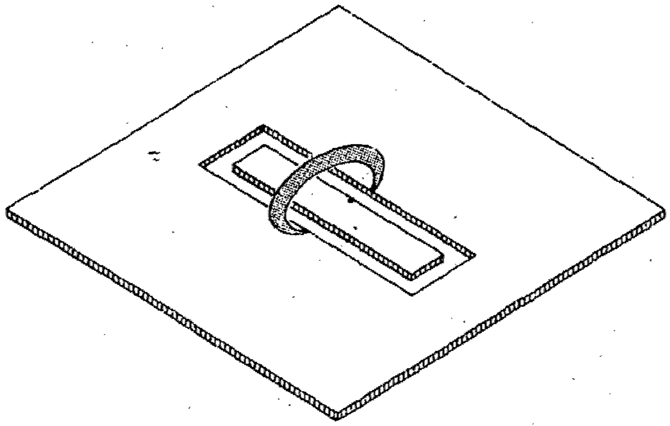


Figure 13b. Unilateral far-field cancellation of slot by loop

4. CONCLUSIONS AND FUTURE PLANS

Although the ultimate goal has not yet been achieved, certainly the present work is a substantial step along the road to a satisfactory flush-mounted LP antenna. Indeed, if one were willing to accept a 3 db loss in efficiency, a successful LP slot array can already be built by providing one of the folded slot designs with an absorbing cavity. In addition, a valuable new family of log-periodic designs has been discovered as a result of this program.

Future plans include a continuing study of the folded slot arrays and associated work on cavity backings. Whether the piece-meal approach of designing a single cell, or modification of an operating bilateral antenna by means of resonant cavities or loops will lead to success, only further work can tell.

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