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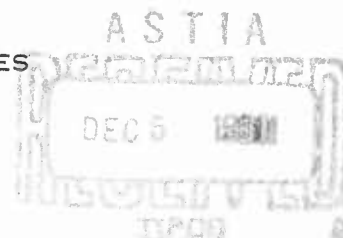
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THE BACKFIRE ANTENNA, A NEW TYPE OF DIRECTIONAL LINE SOURCE

HERMANN W. EHRENSPECK

AUGUST 1961

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
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ABSTRACT

The backfire antenna is a new type of surface-wave radiator. It consists of an ordinary endfire structure (Yagi, dielectric rod, and so forth) terminated by a plane reflector. The surface wave launched at the feed travels along the endfire structure until it impinges on the reflector; it then travels back toward the feed and radiates into space in a direction opposite to that of normal endfire operation.

The gain of the backfire antenna is between 4 and 6 db higher than that of an ordinary endfire antenna of the same length; conversely, to achieve the same gain, the backfire antenna needs to be only between $1/4$ to $1/3$ as long as the ordinary endfire antenna. The side and back lobes can be kept extremely low.

The backfire antenna will have wide application in all cases in which the transverse dimension of the reflector does not violate stringent low-silhouette requirements.

ACKNOWLEDGMENTS

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CONTENTS

1. Introduction	1
2. Principle of Normal Endfire Antenna and Backfire Antenna	1
2.1 Normal Endfire Antenna (Yagi Antenna as Example)	1
2.2 Backfire Antenna	3
3. Development of a Backfire Antenna From a Yagi Endfire Antenna	5
4. Function of Surface-Wave Reflector	5
5. Gain of a Backfire Antenna	8
6. Dimensions and Shape of Surface-Wave Reflector	8
7. Experimental Setup	9
8. Experimental Test of Backfire Principle	12
9. Measurements on Backfire Antenna	14
9.1 Gain and Halfpower Beamwidth as a Function of Reflector Size	14
9.2 Bandwidth of the Radiation Pattern of Backfire Antennas	14
10. Applicability of Backfire Principle	17
11. Practical Applications for Backfire Antennas	17
12. Two Practical Types of Backfire Antenna	19
12.1 Horizontally Polarized Backfire Antenna 1.50λ Long	19
12.2 Vertically Polarized Backfire Antenna for 20-db Gain	19
13. Conclusions	19
References	24

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1.	Amplitude and Phase Plot of the Nearfield of a Yagi Array 6λ Long	2
2.	Amplitude Distribution in Virtual Aperture of 6λ Yagi Antenna	4
3.	Principle of Yagi and Backfire Antenna	6
4.	Sketch of Backfire Antenna	7
5.	Experimental Setup for Measuring Element Currents, Phase Velocity, and Pattern of Yagi and Backfire Antennas	10
6.	Experimental Setup for Plotting Amplitude and Phase Distribution in Nearfield of Antennas	11
7.	Farfield Patterns of Yagi and Backfire Antenna 2λ Long in Horizontal Plane	13
8.	Farfield Patterns of Yagi Antenna 12λ Long and 2 Backfire Antennas of Same Length for Two Sizes of Surface-Wave Reflector M	15
9.	Farfield Patterns of Backfire Antenna 1.2λ Long for 3 Different Sizes of Surface-Wave Reflector M	16
10.	Farfield Patterns of Backfire Antenna for Several Frequencies, Antenna Length 2λ , Reflector Radius 2λ	18
11.	Sketch of Horizontally Polarized Backfire Antenna, Length 1.5λ , Gain 14.5 db	20
12.	Farfield Pattern of Horizontally Polarized Backfire Antenna 1.5λ Long in Vertical and Horizontal Plane	21
13.	Sketch of Vertically Polarized Backfire Antenna on Ground, Length 3.6λ , Gain 21.0 db	22
14.	Farfield Pattern of Backfire Antenna of Fig. 13 in Horizontal Plane	23

THE BACKFIRE ANTENNA, A NEW TYPE OF DIRECTIONAL LINE SOURCE

1. INTRODUCTION

The backfire antenna belongs in the category of surface-wave antennas. Because the main lobe of its radiation pattern lies in the longitudinal axis of the surface-wave structure, we may consider it as a member of the large group of endfire antennas. Common to these antennas is a surface wave that travels along the axis with a phase velocity smaller than that of light. The energy is fed into the antenna at one side and propagates from here to the opposite end where it is radiated into space as from the aperture of a horn. A typical example of this antenna group is the Yagi antenna.

In an earlier work¹ the Yagi antenna was treated as a surface-wave antenna and a method for obtaining maximum gain from it was discussed. It was shown that the energy of the surface wave travels along the structure in a cylindrical wave channel and its termination forms the virtual aperture that radiates the energy into space. In first approximation the radiation pattern is, as reported in another work,² a function of the amplitude and phase distribution within this aperture.

2. PRINCIPLE OF NORMAL ENDFIRE ANTENNA AND BACKFIRE ANTENNA

2.1 Normal Endfire Antenna (Yagi Antenna as Example)

Because the basic principle of the normal endfire antenna is of great importance in understanding the backfire antenna, it is helpful to give a more detailed explanation of its performance by discussing Figs. 1 and 2.

Figure 1 is an amplitude phase plot of the nearfield of a 6λ long Yagi antenna on a large ground plane. The points lying in a line mark the loca-

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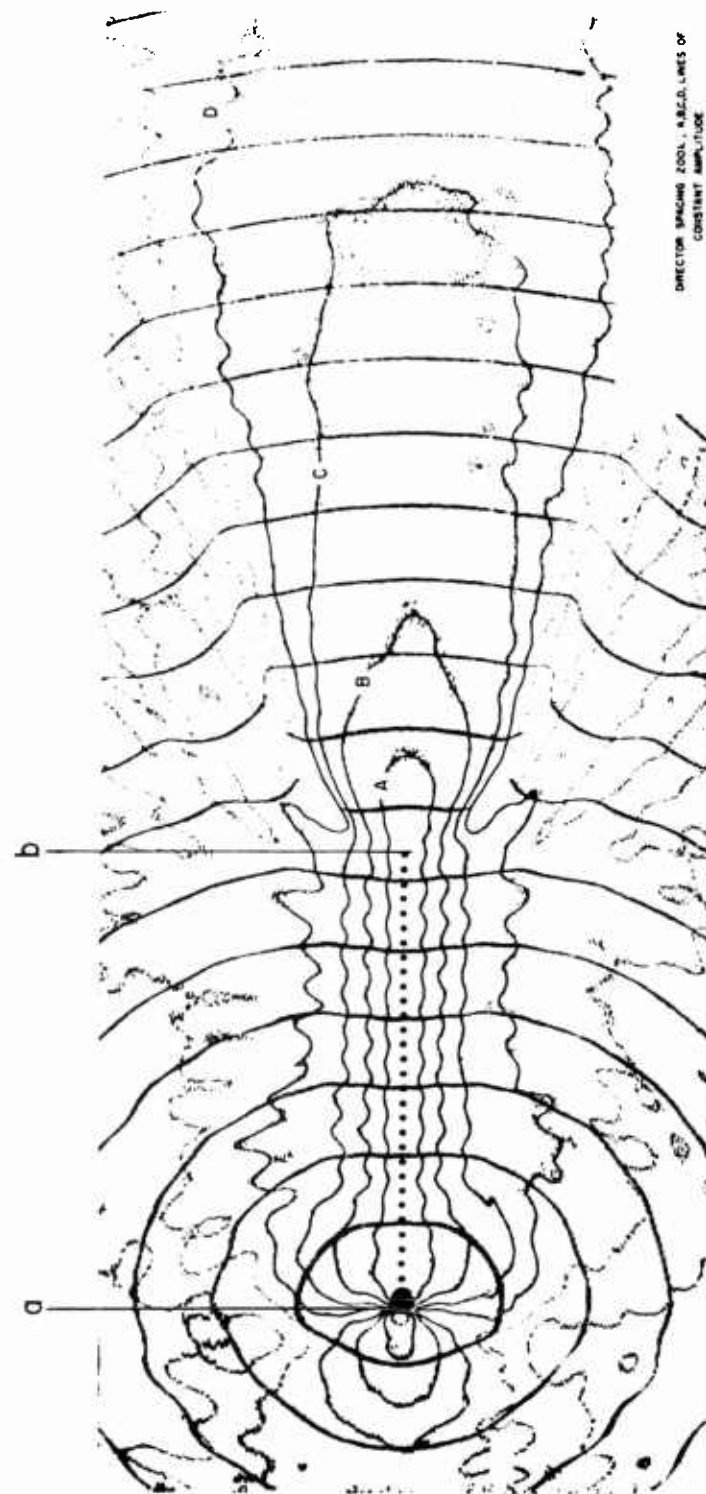


FIG. 1. Amplitude and phase plot of the nearfield of a Yagi array 6λ long.

tion of the single half dipoles inserted in the ground plane. The feeder-reflector combination is on the left side and the wave channel, containing the surface-wave energy, extends from a to b. The lines perpendicular to the longitudinal axis are lines of constant phase, 360° apart, and the lines that run parallel to the axis within the wave channel and spread out later are lines of constant amplitude, decreasing in steps of 5 db as the distance from the axis decreases. If the definition for the width of the virtual wave channel, introduced in² is applied,* the wave channel has a width of about 3λ . The virtual aperture of the Yagi is located on the right end of the wave channel in a plane through b and transverse to the direction of propagation of the surface wave. It can be clearly seen that the energy is radiated from here into space as from the aperture of a large horn.

Figure 2 shows a cross section of the wave channel at its termination and thus presents the actual amplitude distribution in the virtual aperture. The curvature of the lines plotted in amplitude levels of 3-db distance from each other indicates that the wave channel has, in first approximation, a symmetric cylindrical form. The smaller energy packages on both sides of the channel are of no importance, because their amplitude level is more than 20 db below the maximum energy level. Nearly all of the surface-wave energy is, therefore, concentrated in a cylindrical wave channel of 3λ diameter. If the Yagi is adjusted for maximum gain in the endfire direction, the phase front in the virtual aperture is nearly plane.

2.2 Backfire Antenna

If a plane reflector is placed in the virtual aperture of a normal endfire antenna, for example a Yagi, the surface wave traveling in the direction of this reflector and impinging on it, will be reflected and forced to travel a second time along the antenna, but now in the opposite direction. If the phase velocity and the distance of the plane reflector from the last director are properly adjusted, the energy is radiated in a sharper beam in the direction opposite the former direction of the main beam.³ Using the concept of the virtual aperture,² the radiation now takes place in a new enlarged virtual aperture, located at the feeder side of the original endfire antenna. Because of the reversed direction of the main beam the new antenna was called "backfire" antenna.

*This definition is based on the assumption that energy levels more than 20 db below the maximum in the wave channel do not give an essential contribution to the radiation pattern.



FIG. 2. Amplitude distribution in virtual aperture of 6λ Yagi antenna.

3. DEVELOPMENT OF A BACKFIRE ANTENNA FROM A YAGI ENDFIRE ANTENNA

The development of a backfire antenna from a Yagi is shown in the two drawings of Fig. 3. In both sketches the letters have the same meaning, F is the feed, R a linear reflector, and D the directors. The plane surface-wave reflector marked M may be a rectangular or semicircular metal plate. The broken lines VA indicate the location of the virtual aperture for both antennas. The energy is traveling along the surface-wave structure in the direction of the arrows and is radiated from the virtual aperture with the pattern indicated by its main beam.

An example of a backfire antenna, as it may be built for practical use, is shown in Fig. 4. It has an overall length of 2λ and the spacing between the half dipoles is 0.200λ . The same spacing is used for the linear and the plane reflector. It has been found that two additional reflectors, symmetrical to both sides of the longitudinal axis of the backfire, as indicated in Fig. 4, have an important influence on the amplitude and phase distribution in the virtual aperture and therefore on the pattern. This effect was not mentioned in Ref. 3. The relatively high backlobes in the pattern shown there can be drastically reduced by adjusting the side reflectors.

4. FUNCTION OF SURFACE-WAVE REFLECTOR

The function of the plane surface-wave reflector on a backfire antenna is not the same as that of a plane reflector placed a small distance behind a linear antenna for the purpose of producing a pattern with directivity in one direction. In this latter case the plane reflector causes interference between the direct and reflected wave such that for an appropriate spacing between dipole and reflector a maximum gain is achieved in the forward direction. In the case of the backfire antenna such action by the plane reflector would be entirely ineffectual, since there is only a negligible direct wave with which the reflected wave could interfere. (This interference could thus produce only a negligible increase in gain.)

The function of the surface wave reflector on the backfire antenna can be explained only on the basis that the reflector images the original endfire structure, thus in effect doubling it in length and setting up a standing wave along it. Because the energy of the surface wave impinging on the plane

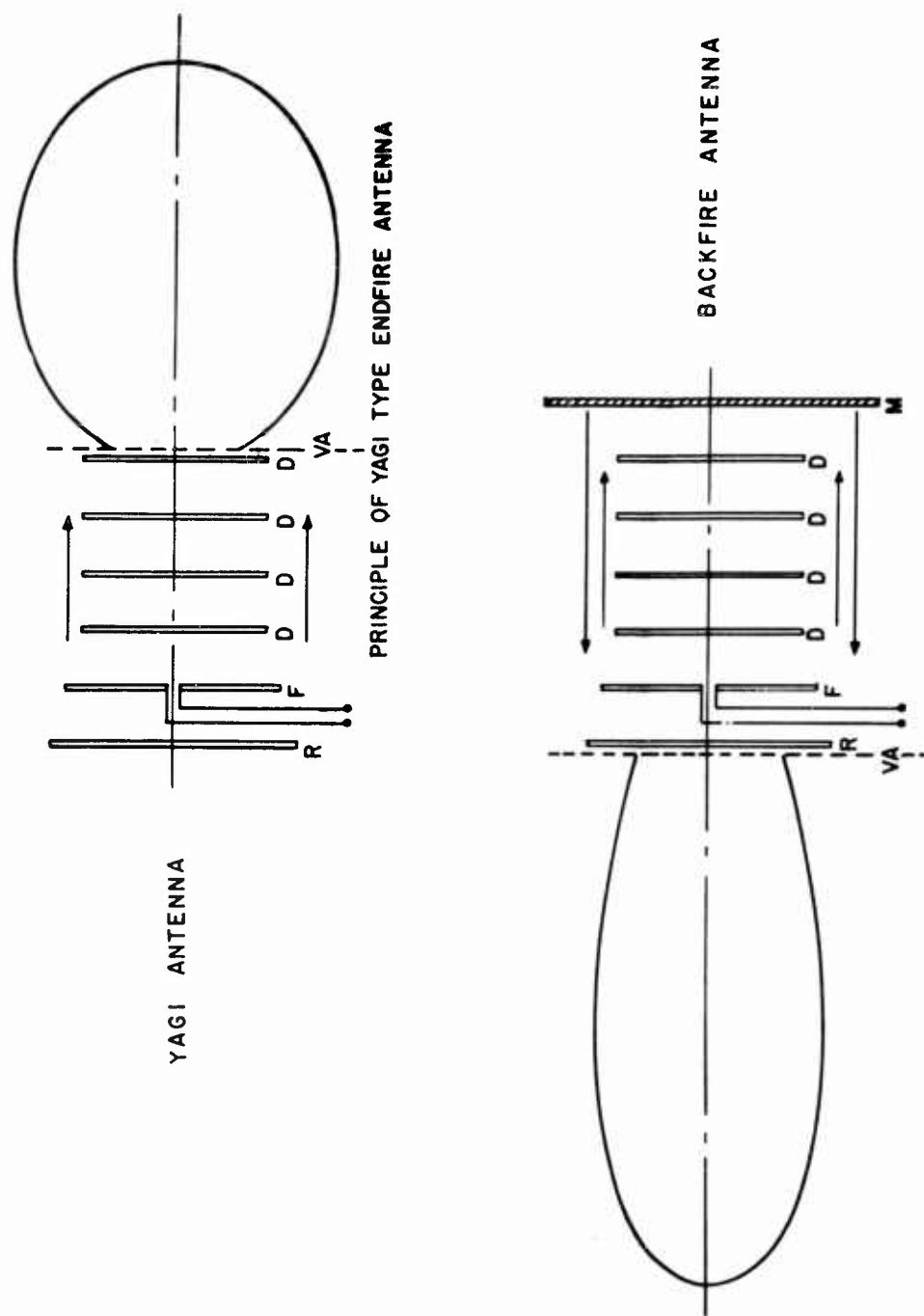


FIG. 3. Principle of Yagi and backfire antenna.

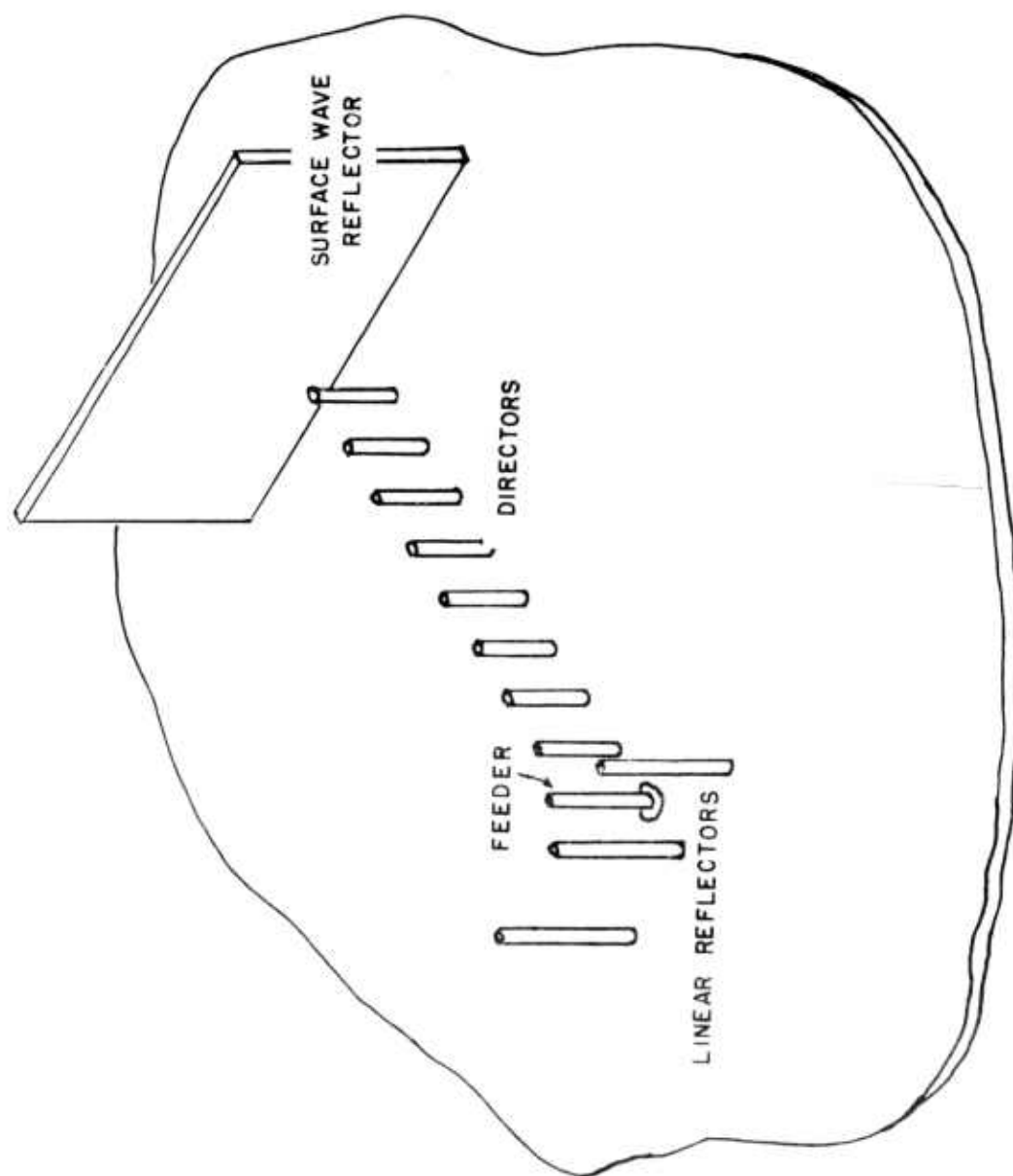


FIG. 4. Sketch of backfire antenna.

reflector arrives concentrated in a narrow channel, only a relatively small metal surface is needed for the imaging. Discussion of the precise radiation mechanism will be deferred until a later publication.

5. GAIN OF A BACKFIRE ANTENNA

As has been extensively discussed,¹ the gain of an endfire antenna is a function of its length as well as of the phase velocity of the surface wave traveling along the antenna structure. It can be said in general that the larger the phase velocity is (as it approaches that of light) the higher is the gain. There exists, however, an optimum phase velocity for any given length, below and above which the gain decreases.^{1, 4} For a longer antenna another optimum phase velocity exists, and the gain is higher than before. If we build a number of endfire antennas, each increasing in length, and with the phase velocity adjusted for its optimum value, the gain will increase with increasing antenna length. All these considerations can also be applied to the backfire antenna. Because of doubling the effective length by use of the backfire principle, the phase velocity of a converted backfire antenna has to be readjusted for a new optimum value.

According to the general conditions for obtaining maximum gain from endfire antennas,^{1, 3} doubling the effective length would be expected to cause a 3-db gain above that of a normal optimized endfire antenna having the same length. Measurements have shown, however, that under best conditions, an increase of 5 to 6 db in gain may be obtained. A complete explanation for this result cannot yet be given, but it is connected with the complicated current distribution of the backfire antenna. In order to solve this problem, extensive calculations and measurements of the radiation pattern and of the amplitude and phase distribution in the nearfield of the backfire antenna have been started. The pattern calculations are based on current and phase measurements of the individual dipole elements of a variety of backfire antennas.

6. DIMENSIONS AND SHAPE OF SURFACE-WAVE REFLECTOR

The surface-wave reflector of a backfire antenna should be large enough to catch as much as possible of the surface-wave energy for reflection into the backfire direction. Because most of the energy is concentrated in the relatively narrow wave channel, as shown in Fig. 2, it is sufficient to ex-

tend the plane reflector to the width of the virtual aperture. It can be shown that this virtual aperture is a function of the phase velocity, which has to be increased with increasing structural length.

Because the surface wave propagating along the antenna has a plane phase front, the reflector must be plane in order to obtain maximum reflection into the backfire direction. The reflector can be built as a metal plate or may be made from a net of wires or a number of metal rods closely spaced. It is of great advantage that the reflector does not need any curvature and therefore can be constructed in a very simple way.

7. EXPERIMENTAL SETUP

For the experimental investigations of the backfire antenna a setup was used that allowed a fast and easy change of all parameters involved, especially the length and phase velocity. All measurements reported were performed on a Yagi antenna that had been converted to backfire and constructed on a circular plate fitting flatly into a large ground plane. The single elements, made from small brass rods, could be adjusted in height by moving them up and down into the plate. The spacing was kept constant to 0.200λ . All measurements were performed in X band at a wavelength of 3.3 cm. The ground plane had a size of about 60λ by 120λ . Radiation patterns could be achieved by rotating the circular plate with the backfire as transmitting antenna, and leaving the receiving antenna at a constant position. The metal ground plane with the rotating circular plate, and the receiving antenna at a distance of about 100λ is shown in Fig. 5. The probe near the row of half dipoles was used for measuring the phase velocity and current distribution on the antenna.

Amplitude and phase distribution in the near field of the Yagi and converted backfire were measured with the AFCRL automatic amplitude phase plotter.⁵ The experimental setup used for these nearfield measurements is shown in Fig. 6. One can see the endfire antenna on the ground plane, the probe for testing the nearfield, and the nearfield plot coming out.

All measurements were performed in a microwave reflection-free room as shown in the photograph. All gain measurements were referred to the feed radiation alone for constant energy. Therefore all gain figures in decibels represent the gain of the imaged Yagi or backfire antenna above

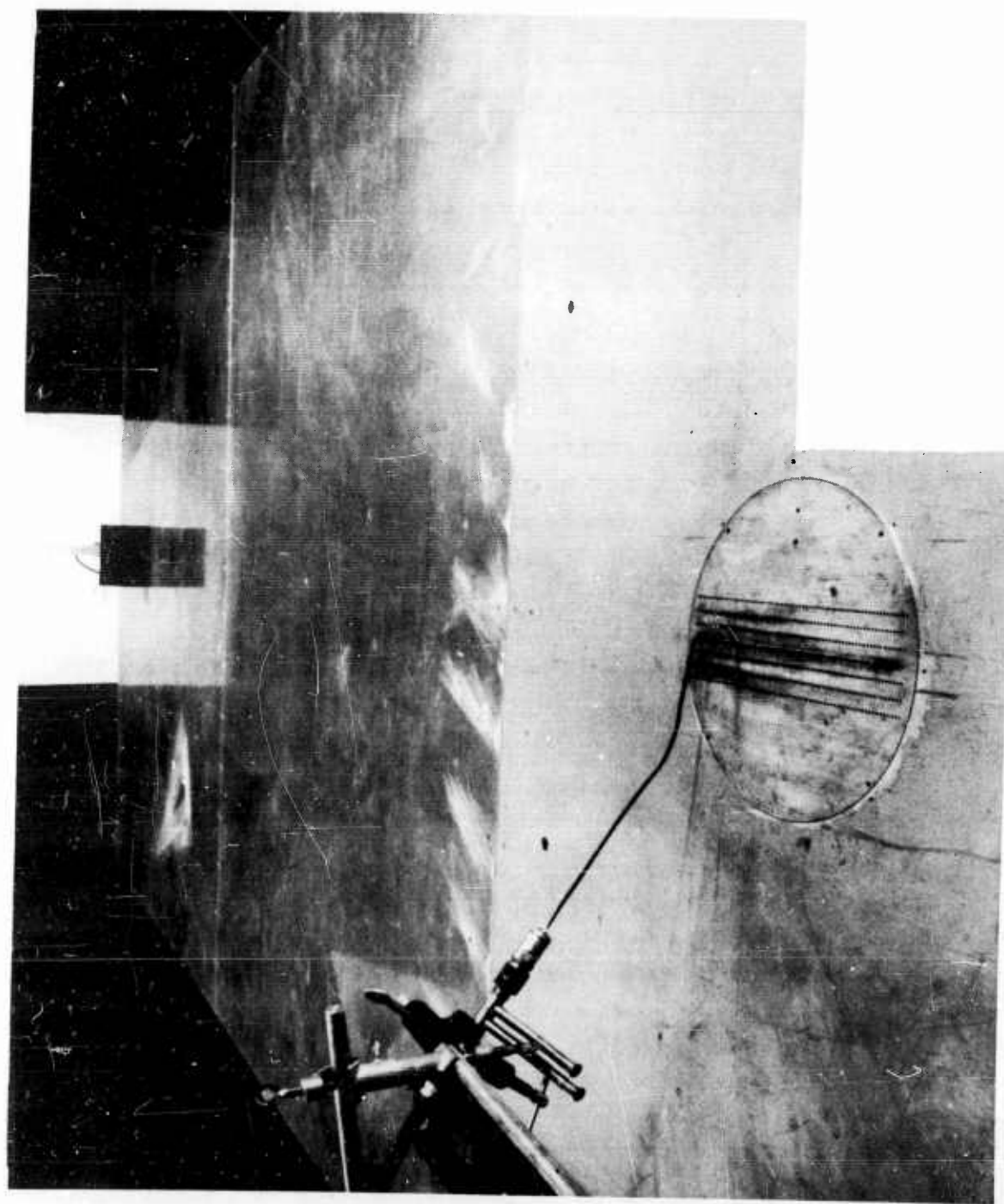


FIG. 5. Experimental setup for measuring element currents, phase velocity, and pattern of Yagi and backfire antennas.

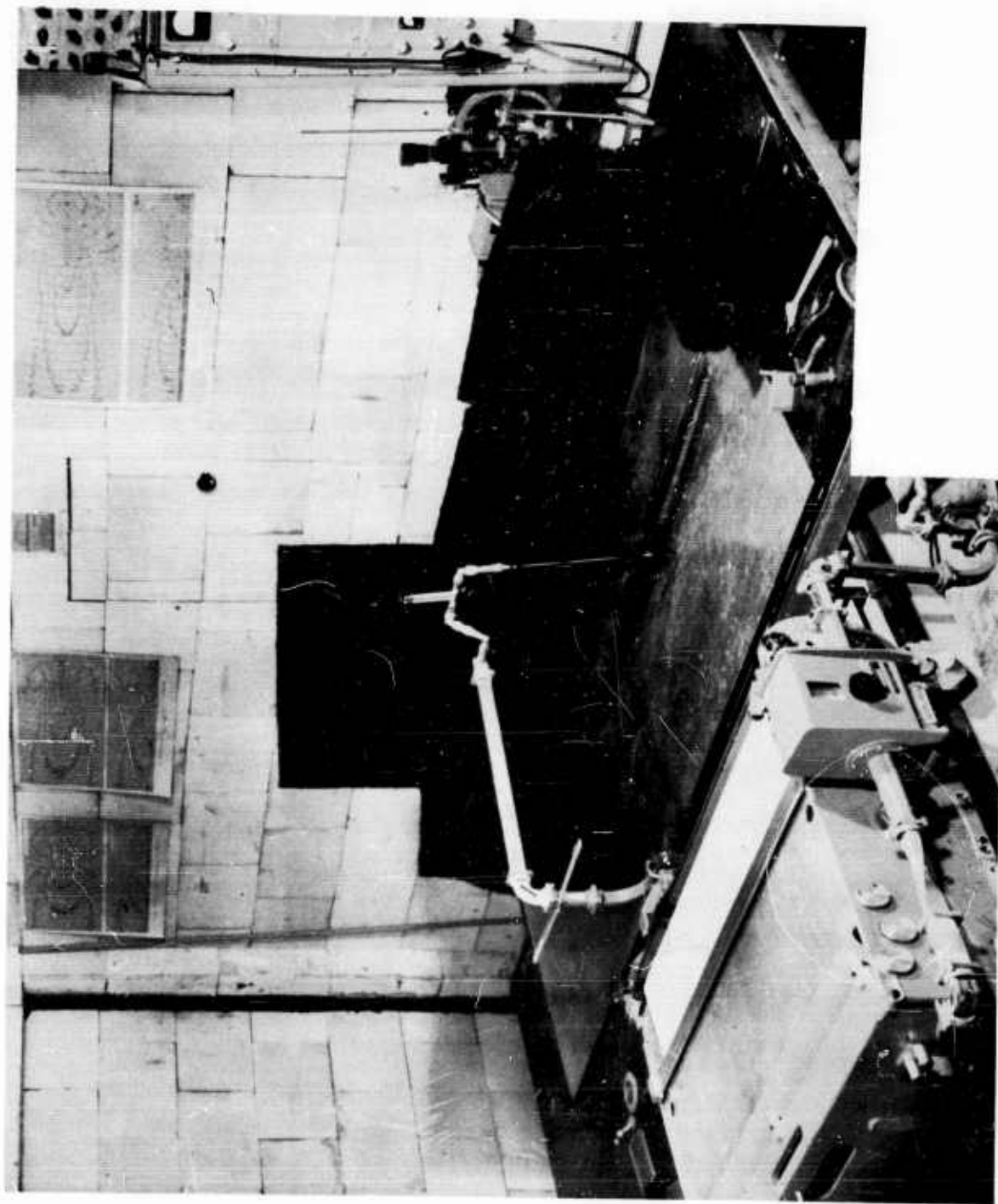


FIG. 6. Experimental setup for plotting amplitude and phase distribution in nearfield of antennas.

the fed half dipole, or the gain of the free space Yagi or backfire above dipole.

8. EXPERIMENTAL TEST OF BACKFIRE PRINCIPLE

The backfire principle was tested on a 2λ long Yagi antenna that had been converted to the backfire as shown in Fig. 4. In order to get optimum performance from the backfire, four structural changes had to be made:

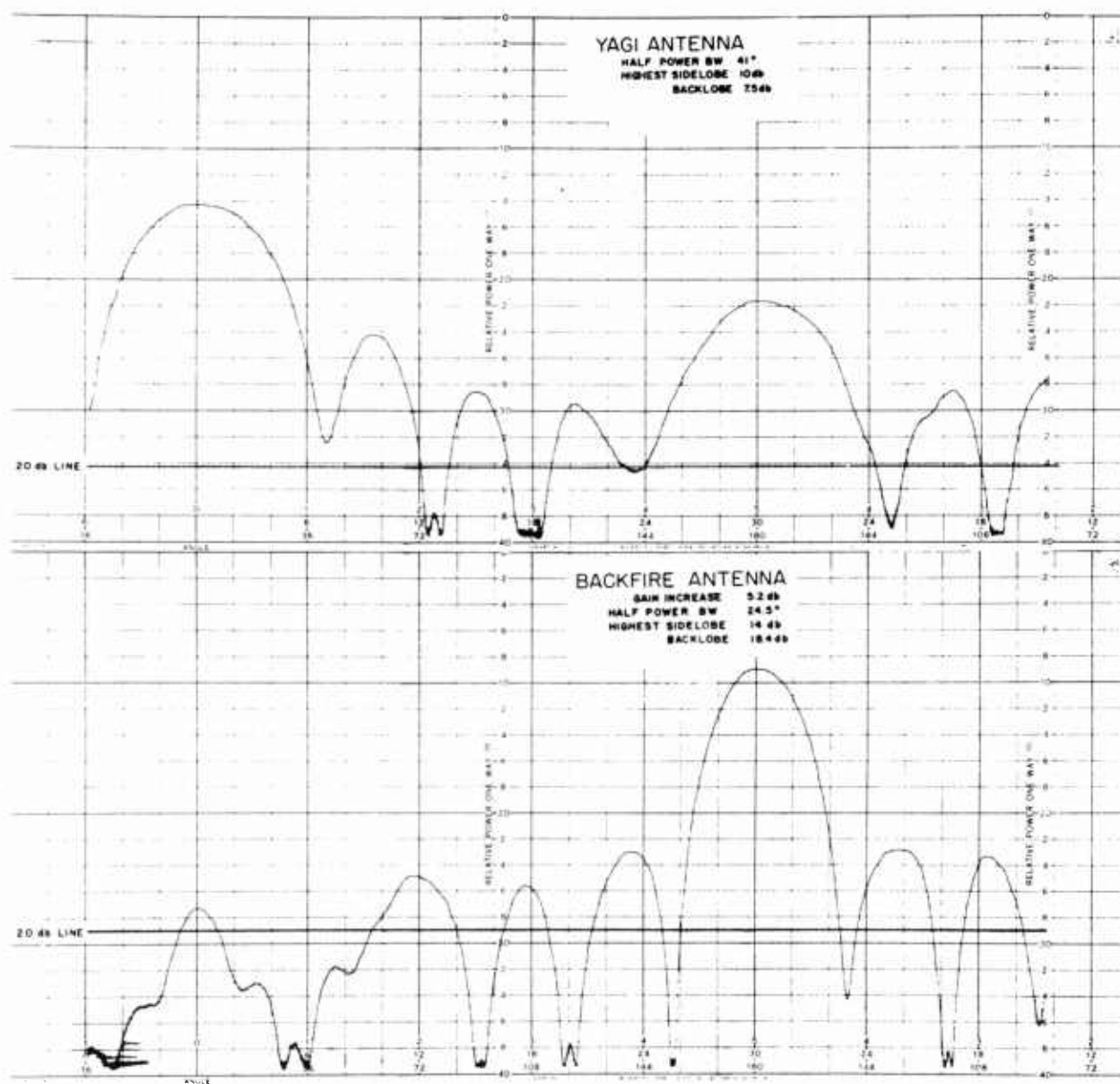
1. The Yagi had to be turned around by 180° in order to get the main beam of the backfire into the same direction at which the Yagi previously had its main beam.

2. A plane surface wave reflector had to be mounted on the radiating end of the antenna. Its size had to be about that of the extension of the virtual aperture. In our case it had to expand at least 1λ on both sides of the axis of symmetry. We chose a rectangular metal plate 1.25λ by 2.50λ . Its distance from the last director was adjusted so that the field strength reached its maximum in the backfire direction.

3. The height of the directors had to be adjusted to approximately the optimum value for a Yagi of doubled length. This adjustment was also made empirically for maximum field strength in the backfire direction.

4. The feed had to be newly matched, because its input impedance had been changed by the presence of the plane reflector and the new height adjustment.

With the converted backfire antenna a gain increase of 5.2 db was obtained over the gain of the Yagi antenna having the same length. The half-power beamwidth of the main beam was at the same time decreased from 41° to 24.5° . The radiation patterns of the Yagi and the backfire in the horizontal plane are shown in Fig. 7. It can be noted that the application of the backfire principle to a normal endfire antenna also has a favorable influence on the sidelobe and backlobe level. In our case the first and highest sidelobe decreased from 10 db for the Yagi to 14 db for the backfire, and the backlobe from 7.5 db to 18.4 db. By using a larger reflector of 1.50λ by 3.00λ the first sidelobes and the backlobe even decreased to 14.4 db and 21.1 db respectively.



BACKFIRE OF FIG 4

REFLECTOR 125 X 2.50λ

FIG. 7. Farfield patterns of Yagi and backfire antenna 2λ long in horizontal plane.

9. MEASUREMENTS ON BACKFIRE ANTENNA

9.1 Gain and Halfpower Beamwidth as a Function of Reflector Size

The radiation pattern of the backfire antenna is strongly influenced by the dimensions of the surface-wave reflector. For an experimental investigation of this effect, the pattern and gain of a 1.2λ long backfire antenna were measured in the horizontal plane for 5 different sizes of surface-wave reflector between 0.5λ by 1.0λ and 1.5λ by 3.0λ . They are shown in Figs. 8 and 9. For comparison Fig. 8 also contains the pattern and gain of the 1.2λ Yagi, from which the 1.2λ backfire antennas were developed. The results are summarized in Table 1.

TABLE 1. Beamwidth, Sidelobes, and Gain as a Function of Reflector Size

Reflector Size λ	Half Power Beamwidth in Degrees	First Sidelobe db	Back Lobe db	Gain Above Dipole db	Gain Increase db
0 (Endfire Antenna)	49	11.4	10.4	9.6	0
0.50×1.00	34	10.3	6.7	10.3	0.6
0.75×1.50	30	11.4	10.0	12.5	2.9
1.00×2.00	28	14.6	16.6	14.4	4.7
1.25×2.50	30	14.7	21.0	14.7	5.1
1.50×3.00	32.5	13.6	24.6	13.8	4.2

Even with a reflector of 0.5λ by 1.0λ the half-power beamwidth is remarkably decreased. The gain, however, does not increase correspondingly, because too much energy passes by the reflector, causing a high backlobe. With a reflector of 1.0λ by 2.0λ a gain increase of almost 5 db is obtained. Using a reflector of 1.25λ by 2.50λ results in a total gain increase of 5.1 db and a very favorable pattern with 14-db sidelobes and 21-db backlobes in the horizontal plane and all lobes below 20 db in the vertical plane (for vertical polarization in both cases).

9.2 Bandwidth of the Radiation Pattern of Backfire Antenna

For the measurement of the bandwidth of the radiation pattern a 2λ long backfire antenna that had a semicircular surface-wave reflector of $2-\lambda$ radius

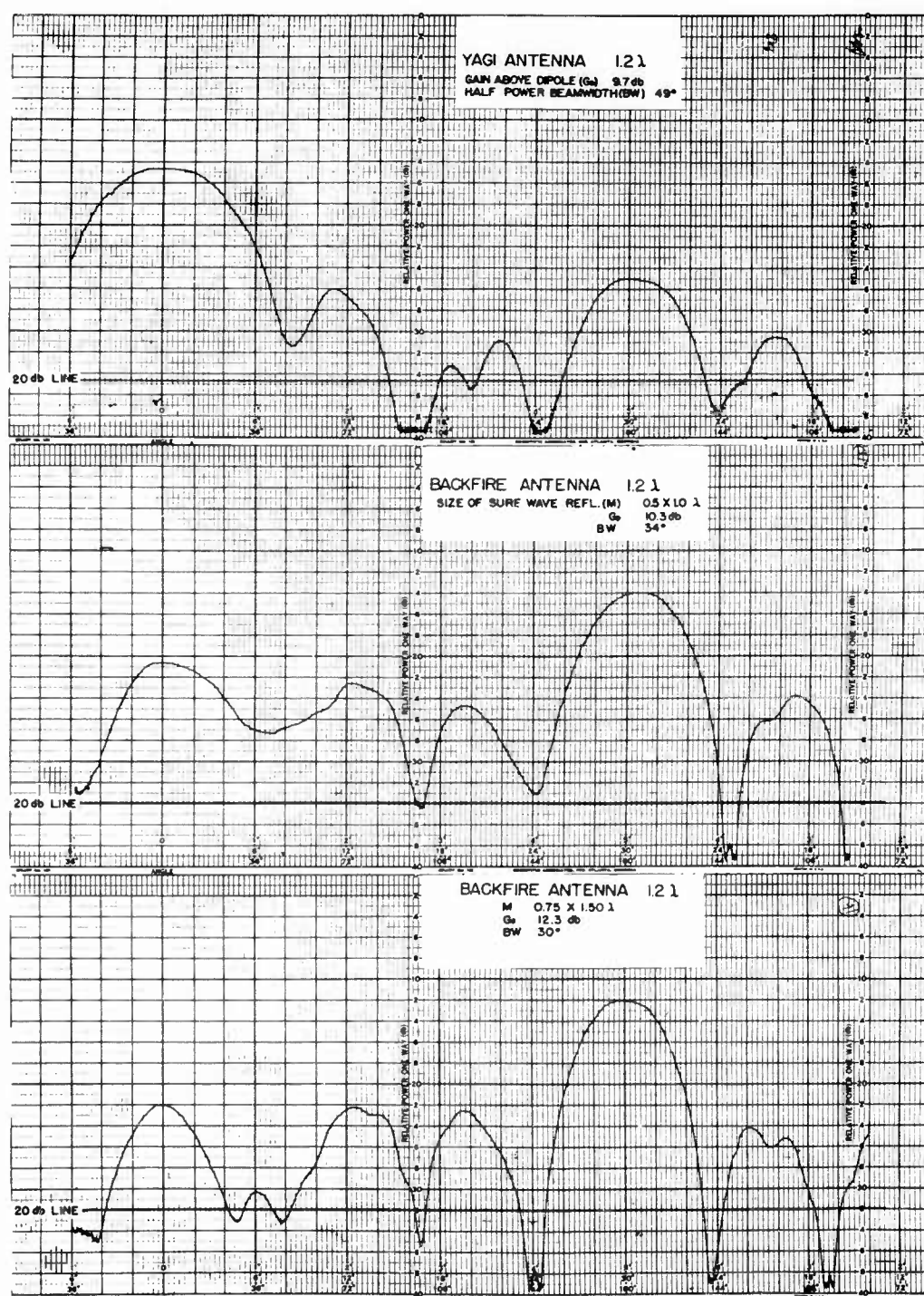


FIG. 8. Farfield patterns of Yagi antenna 12λ long and 2 backfire antennas of same length for two sizes of surface-wave reflector M.

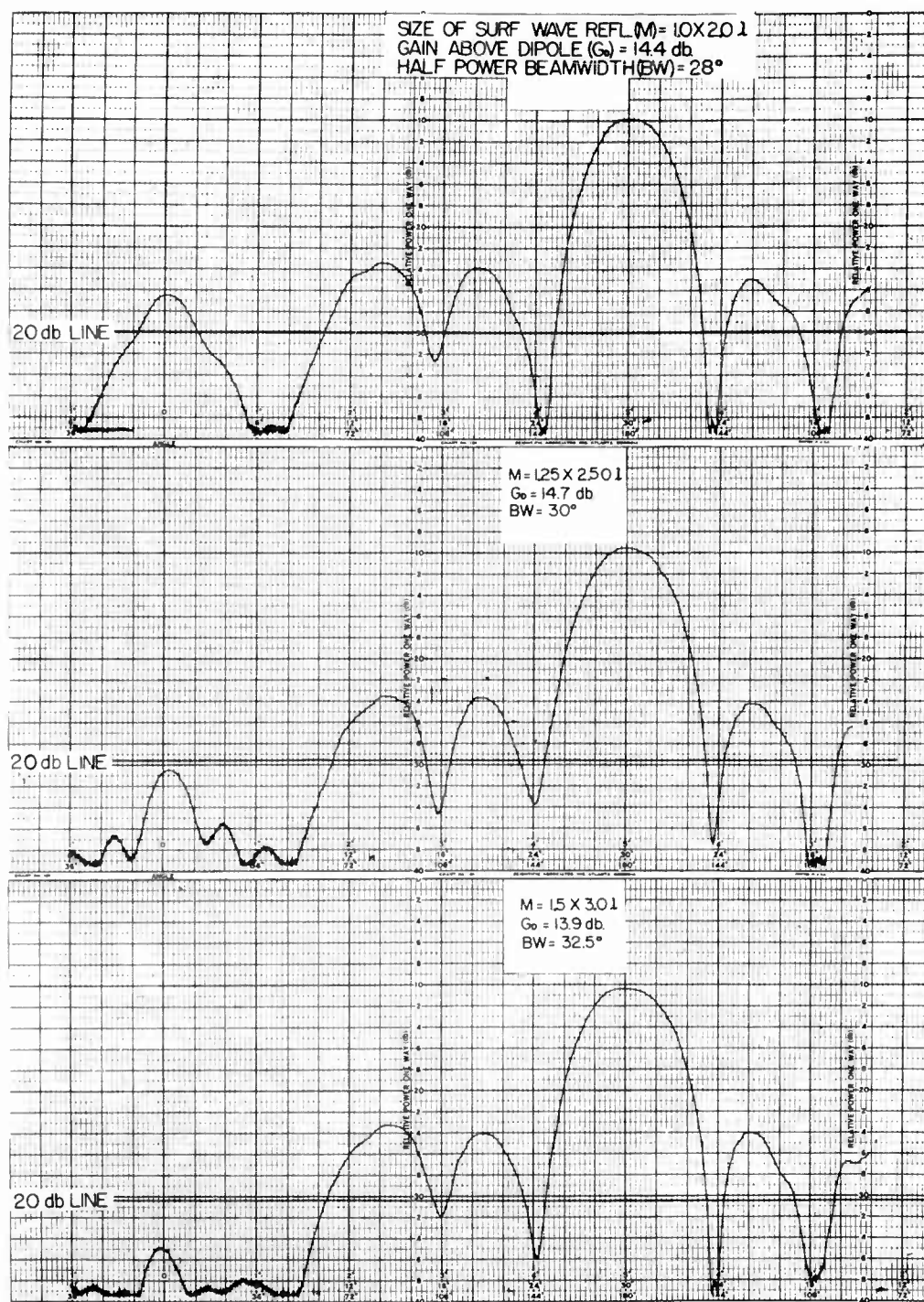


FIG. 9. Farfield patterns of backfire antenna 1.2λ long for 3 different sizes of surface-wave reflector M.

was used. Unfortunately the frequency band of the power source used for these measurements was limited to 20 percent. The measured patterns, shown for a frequency range from 8500 to 10,000 Mcps in Fig. 10, indicate that the half-power beamwidth of the radiation pattern is nearly the same within most of this range, and that only the sidelobe level is changing. The backfire antenna was adjusted for 9500 Mcps. The upper frequency limit for a still satisfactory performance of this backfire antenna could not be measured. From the results obtained it can be estimated that the frequency bandwidth for a good performance of a backfire antenna is about 20 percent or even higher.

The input impedance characteristic of the backfire antenna has not yet been measured. For the reported measurements the antenna was retuned for any frequency changes. Because of the small changes necessary for the transformer adjustment we may assume that the bandwidth of the input impedance of a backfire antenna is not narrow at all.

10. APPLICABILITY OF BACKFIRE PRINCIPLE

The essential gain increase of a backfire antenna over a Yagi of the same length is based on the existence of a surface wave on the antenna and its reflection on the plane surface-wave reflector. Consequently the backfire principle can be applied to all endfire antennas that are based on a phase-retarded surface wave on the antenna structure. Some of these are the disk antenna,⁶ the cigar antenna,⁷ the dielectric rod antenna,⁸ and the combination of the Yagi and dielectric antennas.⁹

Under certain conditions even the gains of already existing endfire antennas may be increased without extensive work. Whether the antenna is a symmetric free-space model or is imaged on a conducting ground or a large metal plane, makes no difference.

11. PRACTICAL APPLICATIONS FOR BACKFIRE ANTENNA

The backfire antenna may be used with best success when antennas with gains between 10 and 25 db are needed. Otherwise such gain figures could only be obtained by very long Yagis or parabolic antennas. The backfire may also be used with good results if an antenna with low side and back lobes is wanted.

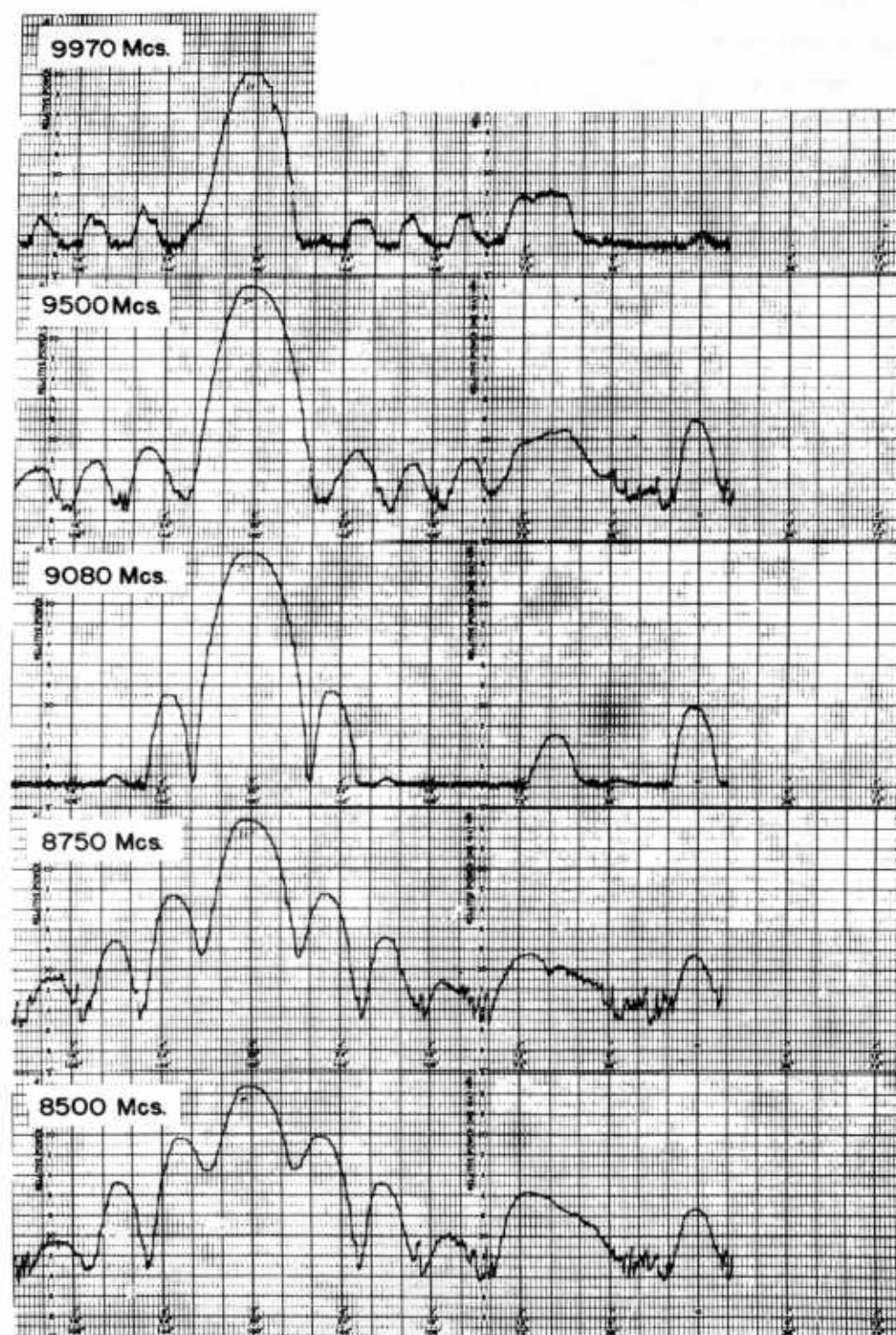


FIG. 10. Farfield patterns of backfire antenna for several frequencies. Antenna length 2λ , reflector radius 2λ .

For obtaining gain figures higher than 20 db one may use several staggered backfire antennas in front of one common surface-wave reflector.

12. TWO PRACTICAL TYPES OF BACKFIRE ANTENNA

12.1 Horizontally Polarized Backfire Antenna 1.50λ Long

This antenna, shown in Fig. 11, is developed from a 1.2λ long Yagi antenna and has a quadratic surface-wave reflector of 2.0λ by 2.0λ 6 dipoles, and the feed, which may be a simple or a folded dipole. Three of the six dipoles are directors, the three others reflectors. The spacing is generally 0.300λ .

The gain of this backfire antenna is 14.5 db above dipole; the half-power beamwidth is 25.5° in the horizontal and 28° in the vertical plane. The patterns of the antenna in both planes are shown in Fig. 12.

To obtain the same gain from a Yagi antenna would require a length of about 6λ and 24 dipoles, if the same spacing of 0.300λ were chosen.

12.2 Vertically Polarized Backfire Antenna for 20-db Gain

This antenna, shown in Fig. 13 is constructed from two single backfire antennas 3.6λ long. They are mounted on a conducting ground plane at a distance of 1.5λ from each other using one common semicircular surface-wave reflector of $2.5-\lambda$ radius. The gain of this antenna is about 21 db and its half-power beamwidth is 13.5° . The highest side and back lobes are respectively 14 db and 22 db below the maximum radiation in the main beam. The pattern of this antenna in the horizontal plane is shown in Fig. 14.

13. CONCLUSIONS

The backfire antenna is a new type of directional antenna that should have many applications.

The backfire principle is applicable to practically all surface-wave antennas and increases their gain by 4 to 6 db without increasing their lengths; conversely, it takes only $1/3$ to $1/4$ of the length of a normal endfire antenna to obtain the same gain.

In competitive situations the advantage of the much shorter length must be weighed against the demand for the plane surface-wave reflector.

It is a further advantage of the backfire antenna that the sidelobe and backlobe level may be reduced drastically by using linear reflectors in the

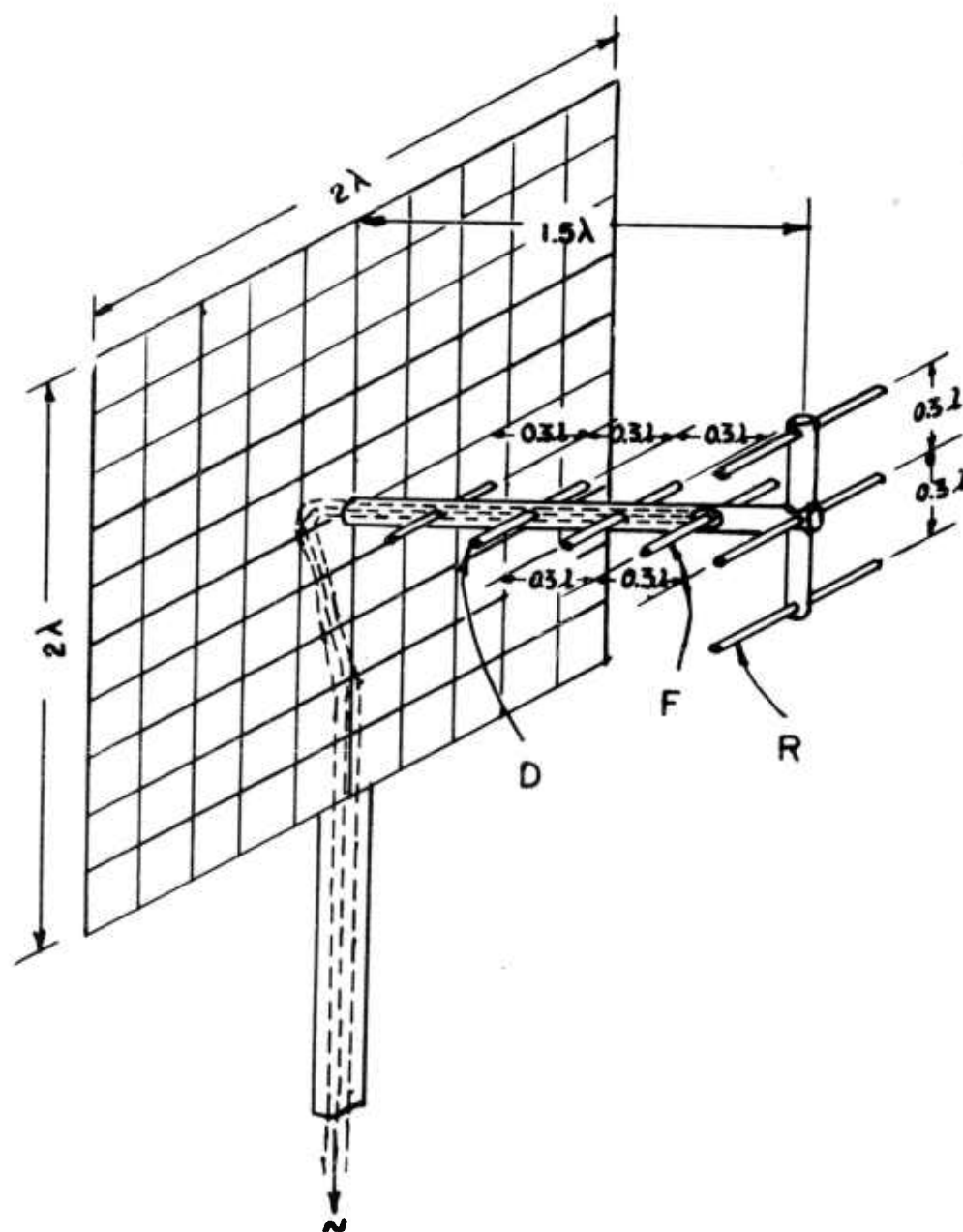
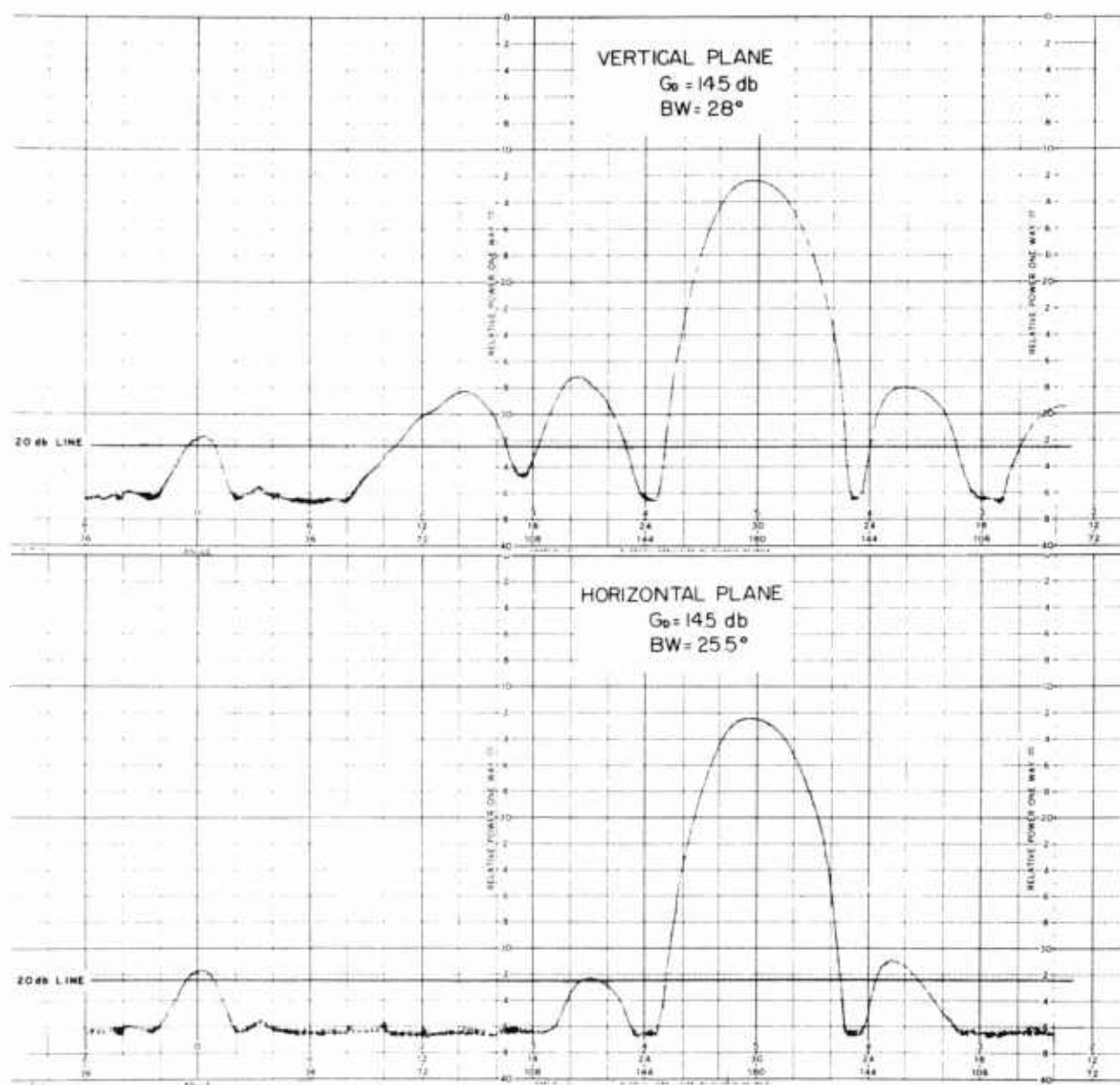


FIG. 11. Sketch of horizontally polarized backfire antenna, length 1.5λ , gain 14.5 db.



BACKFIRE OF FIG 11

MODEL MEASUREMENT AT 3000 KMC

FIG. 12. Farfield pattern of horizontally polarized backfire antenna 1.5λ long in vertical and horizontal plane.

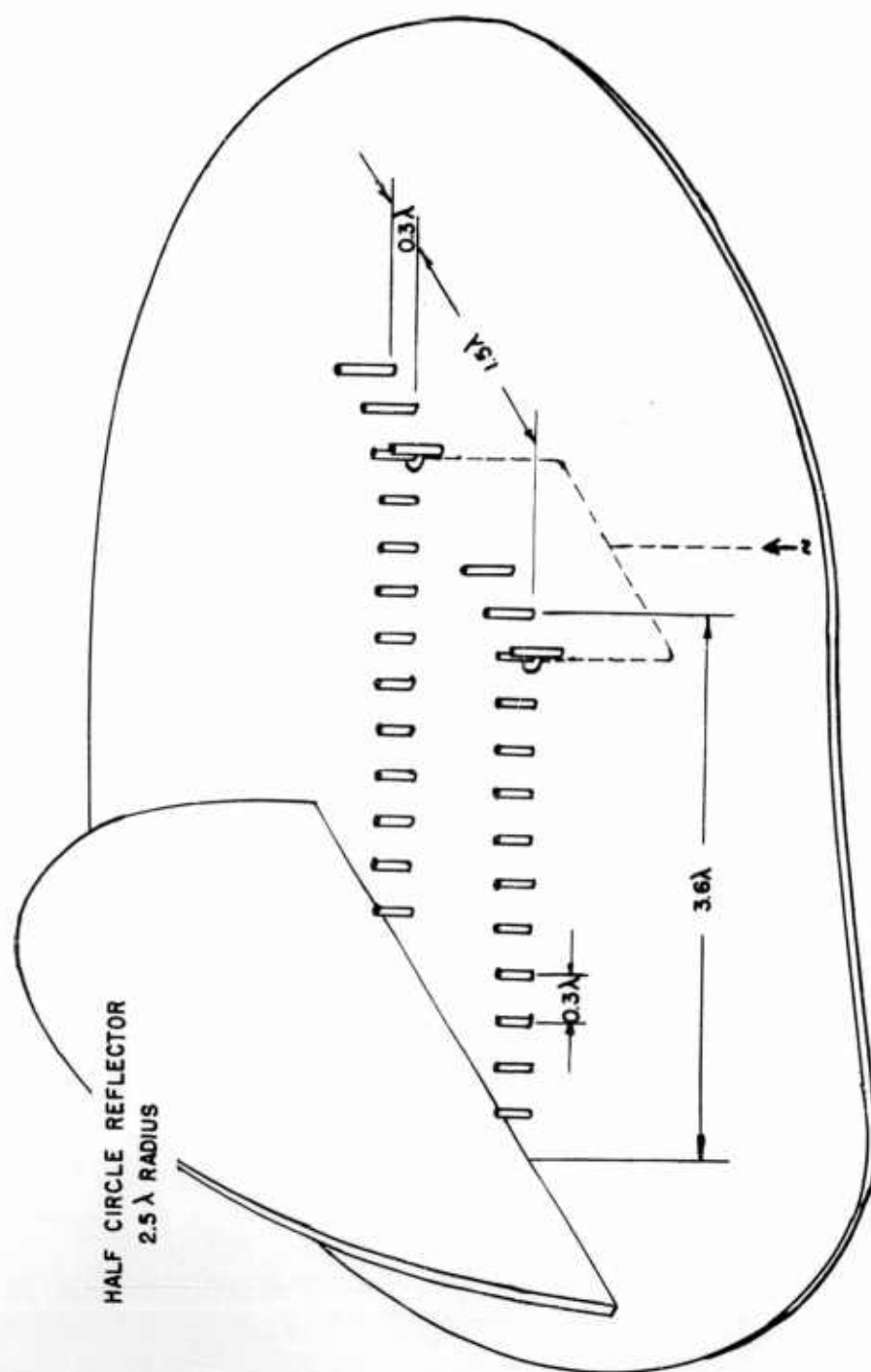
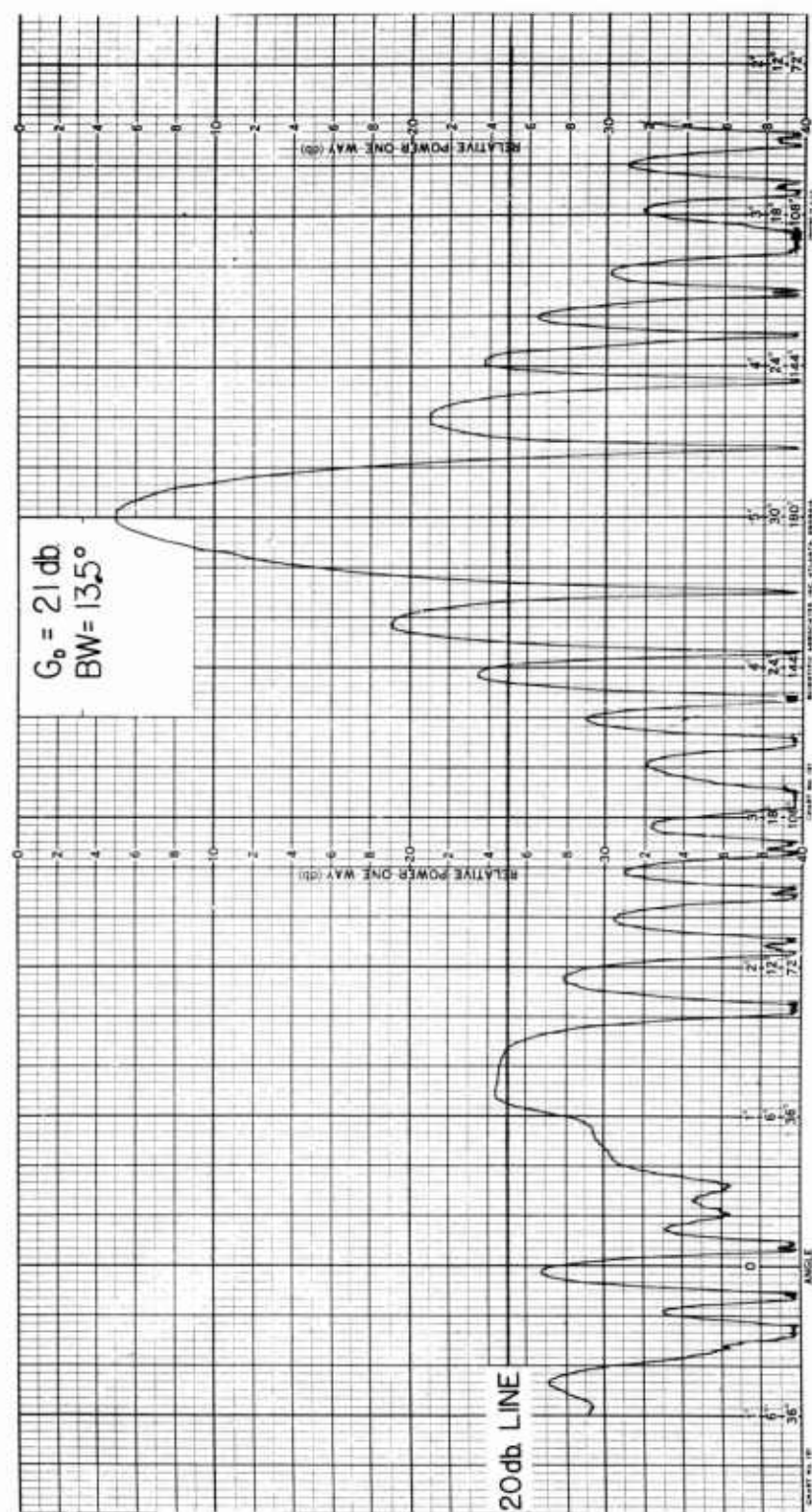


FIG. 13. Sketch of vertically polarized backfire antenna on ground, length 3.6 λ , gain 21.0 db.



virtual aperture. The backfire antenna yields gain figures that can ordinarily be obtained only with very long endfire antennas or paraboloidal dishes.

The backfire antenna may be especially important as a television antenna for fringe areas where high gain and low sidelobe reception is necessary.

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