A STUDY OF ELECTROMAGNETIC WAVE REFLECTIONS FROM SMALL RESONANT CONDUCTING ELEMENTS

By

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A STUDY OF ELECTROMAGNETIC WAVE REFLECTIONS FROM SMALL RESONANT CONDUCTING ELEMENTS

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PREFACE

Microwave reflections from arrays of resonant conducting elements have not been studied to any great extent. The purpose of this study was to experimentally obtain the field patterns for several resonant element arrays. To help the reader understand the experimental results, part of the paper is devoted to a theoretical analysis of reflecting antennas.

I would like to express my appreciation to Dr. Attie L. Betts for his valuable assistance in all matters pertaining to this study; to Paul A. McCollum and Edmund W. Schedler, Jr., for their assistance in assembling the equipment used in the experimental study; and to David L. Johnson for his careful study and constructive criticism of the manuscript.

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INTRODUCTION

The use of microwaves in the fields of communications and detection has become quite extensive in the past ten years. At the present time an even more concentrated effort is being made to extend the applications of microwaves in these two fields. The rapid advancements in electronics were undoubtedly due to the second world war. Under these conditions, most of the development was done under government supervision and most of the equipment and applications were for war time use. However, in the last few years more attention has been turned to the use of microwaves in many civilian fields.

This ever-increasing interest in the use of microwaves has created more and more problems. The problems created by ultra-high-frequency waves presented themselves much quicker than they could be solved; even though much effort was concentrated on solving them. In general, techniques used in working with longer wavelengths could not be used with these very short wavelengths. This necessitated the development of many new techniquues, some of which are not yet completely satisfactory.

The reflection of microwaves is one aspect of the overall microwave problem which has been given a considerable amount of attention. Since the development of television and radar, more emphasis has been placed on the study of reflections from dummy antennas. These antennas were needed for directing or reflecting energy into desired patterns. The use of ultra-high frequencies made it possible to have half-wave antennas of a reasonable physical length. With these smaller antennas, a study of many antenna arrays could be made.

There are many unsolved problems in connection with microwave reflections, even though much work has been done in the field. The object of this research was to study the reflections from small resonant conducting elements. Most of the study was experimental in nature; however, a brief theoretical study is made of reflecting antennas in an electromagnetic field. There are many difficulties which arise in both types of analysis. These difficulties will be discussed in detail in a later section of this paper.

Before the detailed analysis is described, a general discussion of the experimental study would no doubt be informative. A source of microwave power and microwave receiver were located at approximately the same point. Directly in front of the transmitter and receiver, the small conducting elements were mounted on a plywood frame. Using this arrangement, energy could be transmitted toward the elements, and reflected energy from the elements could be detected by the receiver. By evaluating the received energy, the reflecting properties of the elements could be obtained.

There could be many variations in the number and orientation of the small elements. As for the orientation, this study was concerned with elements polarized horizontally in a vertical plane. The elements were rotated about a horizontal axis to obtain a vertical-plane field pattern. A clearer picture of the arrangement can be obtained from Figure 7. The number of elements varied from nine to sixty-three depending on the pattern.

Two basic patterns were used. One pattern consisted of elements spaced one-half wavelength in both the horizontal and vertical directions. The other pattern consisted of elements spaced in such a manner as to have one-half wavelength between their centers in the horizontal direction and one-half wavelength between elements in the vertical direction. The frequency used was 2800 megacycles per second. At this frequency, a wavelength is 10.8 centimeter; therefore patterns made of a large number of elements could be analyzed.

THEORETICAL ANALYSIS

The theoretical analysis of the resonant elements will be considered before the experimental analysis to give the reader a better understanding of the experimental work. It will be helpful to know exactly how the elements act in an electromagnetic field. There are several approaches which could be used in analyzing these elements; therefore the author has chosen what seems to be the most straightforward approach.

Half Wave Dipole

The resonant elements will be referred to as reflecting antennas. A reflecting antenna is a receiving antenna with the terminals of its load short-circuited.[1] The antennas to be considered are resonant at the excitation frequency which is impressed upon them. It will be assumed that the antenna is excited by a plane wave. This assumption is valid, because the study was conducted with the elements fairly distant from the source of power.

For a more detailed study of the situation, one dipole in an electromagnetic field will be considered. If the dipole is excited by a plane wave, some of the wave energy will be absorbed by the dipole and some of the energy will be scattered

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[1] S. A. Schelkunoff and H. T. Friis, Antennas Theory and Practice, (New York, 1952), p. 242.

by the dipole. The scattered energy may also be considered as energy which was absorbed and reradiated by the dipole. However, when absorbed energy is referred to in this paper, it will mean energy which is lost due to I^2R loss in the antenna.

Since the antenna is resonant, it should act like a resonant electrical circuit if a circuit analogy is used.[2] To use this type of analogy, the antenna must have capacitance, inductance, and resistance. To attain these three properties, it could be assumed that the element has capacitance between its ends, and inductance and resistance in the lead between its ends. At resonance the amplitude of the dipole oscillation is a maximum, and its impedance is nearly all resistive.

Some of the power intercepted by the dipole is scattered, and some is absorbed, depending on the relative magnitudes of the radiation and ohmic resistances. At this point, it would probably be helpful to explain these resistances. The ohmic resistance is simply the resistance of the material from which the antenna is constructed. The radiation resistance is defined as the average radiated power divided by the square of the effective value of current in the antenna.[3] The total resistance of the antenna is the sum of the radiation resistance and the ohmic resistance.

The energy relationships of the dipole antenna are very interesting. The incident wave acts as an emf applied to

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[2] J. C. Slater, Microwave Transmission (New York, 1942), p. 236.

[3] H. H. Skilling, Fundamentals of Electric Waves (New York, 1948), p. 179.

the antenna, causing a power input of 1/2 $i^2(R_o+R_r)$ to the antenna.[4] Of this power 1/2 i^2R_o is the absorbed power, and 1/2 i^2R_r is the reradiated power. In the above expressions R_o is the ohmic resistance, R_r is the radiation resistance, and i is the maximum value of current in the antenna. If the antenna were a receiving antenna, the absorbed power would be the useful power. In this case the ohmic resistance would be the resistance of the transmission line connected to the antenna plus the antenna copper resistance. For maximum absorbed power the line should be matched to the radiation resistance, since the antenna copper resistance is negligible. For a matched condition half of the power would be absorbed and half would be reradiated. However, in the case of the reflecting antenna, the load terminals are short-circuited. This makes the line resistance become zero; leaving only the very small antenna copper resistance to absorb power. In most reflecting antennas the antenna copper resistance is very small; therefore very little of the total power is absorbed. This is a very desirable quality of a reflecting antenna, since its main function is to reradiate power.

The energy flow in the space around a reflecting antenna will now be briefly discussed. Assume that a plane wave is falling on a reflecting antenna such that Poynting's vector is perpendicular to the antenna axis. The antenna is set into electrical oscillation and reradiates energy. The energy re-

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[4] J. C. Slater, Microwave Transmission, p. 238.

radiated from the antenna is in the form of a spherical wave. Poynting's vector for the spherical wave will be perpendicular to the surface of a sphere surrounding the antenna. Poynting's vector for the combined field will be a quadratic made up of three types of terms. One type of term will have $\bar{E}$ and $\bar{H}$ of the plane wave appearing in it. Another type of term will contain $\bar{E}$ and $\bar{H}$ of the sperical wave. The last type of term will contain cross combinations of plane and spherical wave terms. Terms containing $\bar{E}$ of the plane wave and $\bar{H}$ of the spherical wave would be of the third type.[5]

Now if each term in Poynting's vector is integrated around a closed surface enclosing the antenna, some interesting facts will be revealed. The integration of the plane-wave terms will be zero, because as much energy is entering the surface as is leaving the surface. The integration of the spherical-wave terms will show a net outward flow of energy which is equal to the reradiated power. The only terms left are the mixed terms which on integration show a net inward flow of power. This net inward flow is the energy dissipated as heat in the antenna, and is a very small quantity for reflecting antennas. The energy flow around a reflecting antenna has been discussed briefly in the two preceding paragraphs. For a thorough development of the energy flow refer to Microwave Transmission by J. C. Slater.

Thus far a general analysis has been made for a single

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[5] Ibid., p. 237.

dipole; however, for most antenna work specific quantities must be known. For this reason several relations for antenna calculations will be discussed.[6] The impedance of a half-wave reflecting antenna will be considered first. Since the antenna is resonant, there are no reactive terms, therefore the impedance is entirely resistive. The total resistance of the antenna is given by

$$R = R_o + R_r$$

where R_o is the ohmic resistance, and R_r is the radiation resistance. For a reflecting antenna the ohmic resistance can be neglected, leaving only the radiation resistance which is given by

$$R_r = \pi/6 \sqrt{\mu/\varepsilon}$$

where μ is the permeability of free space, and ε is the permittivity of free space.

The power absorbed by the half-wave reflecting antenna can be calculated by the following expressions:

$$P = P_o + P_r$$

$$P_o = \frac{V^2 R_o}{2(R_o+R_r)^2} , \quad P_r = \frac{V^2 R_r}{2(R_o+R_r)^2}$$

where P is the total absorbed power, P_o is the power dissipated in heat, P_r is the reradiated power, $V = E_o d$, d is the length of the antenna and E_o is the electric field intensity over the distance d.

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[6] Ibid., p. 243.

Two relations which are often useful are the effective absorption areas. For a general antenna these areas are given by

$$A_o = \frac{d^2 R_o \sqrt{\mu/\varepsilon}}{(L\omega - 1/C\omega)^2 + (R_o + R_r)^2}$$

$$A_r = \frac{d^2 R_r \sqrt{\mu/\varepsilon}}{(L\omega - 1/C\omega)^2 + (R_o + R_r)^2}$$

where A_o is the effective absorption area for power lost in heat, and A_r is the effective area for reradiated power. The preceding expressions would of course become simpler for a resonant antenna. The reactive terms would drop out, and d would become $\lambda/2$.

Another expression which is useful in antenna calculations is the expression for the Q of the antenna. This expression is

$$Q = \frac{\omega L}{R_o + R_r}$$

where L is the inductance of the antenna.

Most of the relationships needed for analyzing a reflecting antenna are given above; however, there is one other thing which might be mentioned. In the preceding material it was mentioned that the ohmic resistance is negligible for a reflecting antenna, and it is negligible in most cases. However, in order to give a complete analysis of the antenna it will be mentioned further. Since the frequencies are in the UHF region, the ohmic resistance must be calculated by skin-effect relations. These relations will not be given here; however, they can be found in most books on antennas or electromagnetic waves.

Antenna Arrays

In the preceding discussion only one element was considered. To give a better understanding of antenna arrays, more than one element will be considered in the following discussion. Suppose that we have two reflecting antennas a distance d apart and perpendicular to the plane of the paper. Figure 1 shows this arrangement.

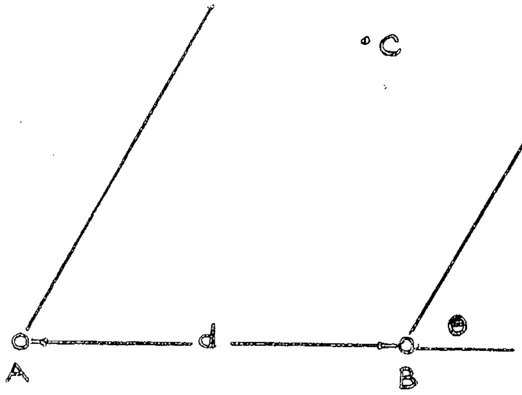

Figure 1

It will be assumed that the currents in each antenna are the same in both phase and magnitude. For this case the field intensity at some distant point C will be proportional to

$$2 \cos \left(\frac{\pi d}{\lambda} \cos \theta\right).^{7}$$

If d is $\lambda/2$ and θ is zero then the field intensity vanishes. In other words the field intensity along the line joining the two elements is zero. When θ is $\pi/2$ or 90° and d is $\lambda/2$ then the field intensity becomes a maximum of 2.

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[7] S. A. Schelkunoff and H. T. Friis, Antennas Theory and Practice, p. 30.

This is a rather condensed development; however, it shows that the field at a distant point from two radiating antennas is dependent on the difference in phase of the two antenna waves.[8]

Suppose that we now consider two antennas with currents that are not in phase. For this case direction from the antennas, phase of the antenna currents, and separation of the antennas must all be considered. This can become rather complicated unless simple arrangements are considered. For example consider the antennas in Figure 1, and suppose their currents are 180° out of phase. If the distance d is $\lambda/2$ then the radiation pattern will be opposite to the previous example. Maximum radiation would be along the line $\overline{AB}$, and zero radiation would be at 90° to the line $\overline{AB}$.

One more thing should be considered before the discussion on antenna arrays is closed. This factor is the effective point of radiation of an antenna array. If two elements are considered, the radiation at a distant point looks as though it is coming from half way between the two elements.[9] In fact, for any antenna array, an effective point of radiation can be obtained. If the array is symmetrical and the elements are all excited the same then the center of the array can usually be considered the effective point of radiation.

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[8] *Ibid*., p. 31.
[9] *Ibid*., p. 31.

EXPERIMENTAL DETERMINATION OF FIELD PATTERNS

The reflection or scattering of electromagnetic waves from resonant antennas can be calculated provided the number and arrangement of antennas does not become too complicated. When the number becomes large and the arrangement becomes complicated the calculations also become very complicated. For this reason an experimental approach was used to determine the field patterns for the complicated element arrangements. The experimental approach was much easier, and it also provided information on the diffulties encountered in making such experimental measurements.

Equipment

The equipment used for making the field pattern studies was, for the most part, conventional 3,000 megacycle equipment. For the purpose of explanation it can be divided into three groups: the transmitter, the receiver, and the apparatus used for mounting the elements. In the following three paragraphs the functions of each of the three groups will be explained. A better understanding of the equipment can be obtained from the pictures in Figures 2, 3, 4, 5, and 6.

The transmitter used to produce the initial power was a lighthouse tube oscillator operating at a frequency of 2,800 megacycles. The carrier was pulse-modulated at a repetition frequency of 240 p.p.s. This made it possible to use several stages of audio amplification in the receiver. To obtain

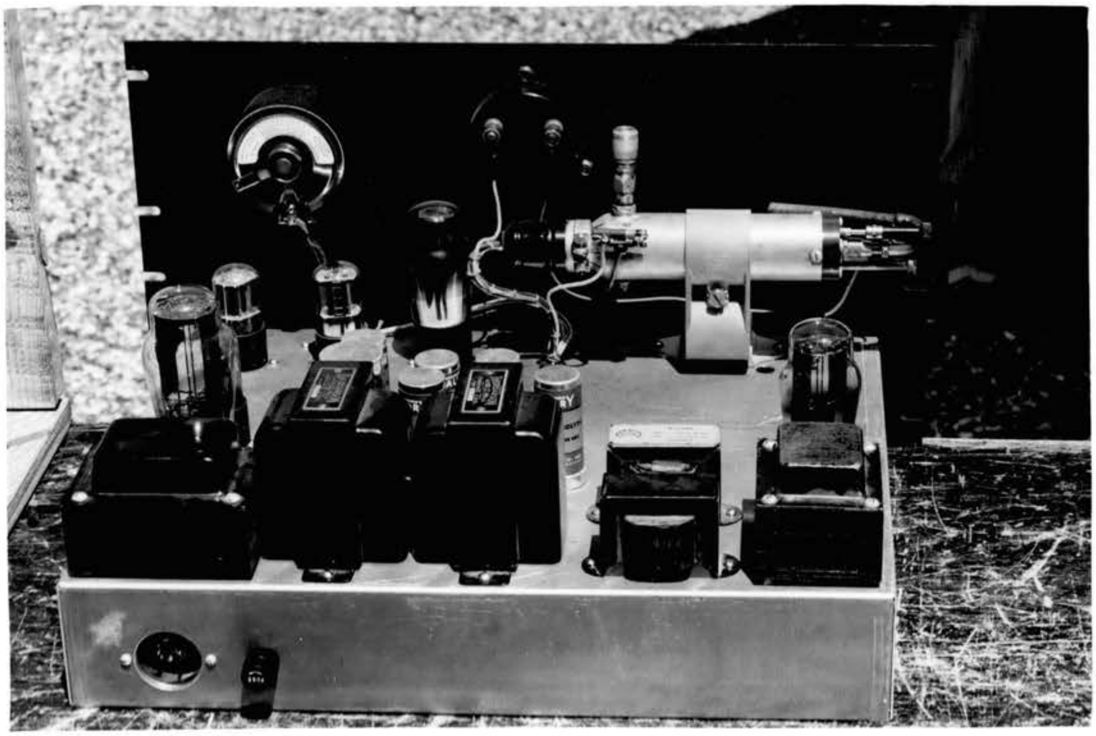


Figure 2. Transmitter

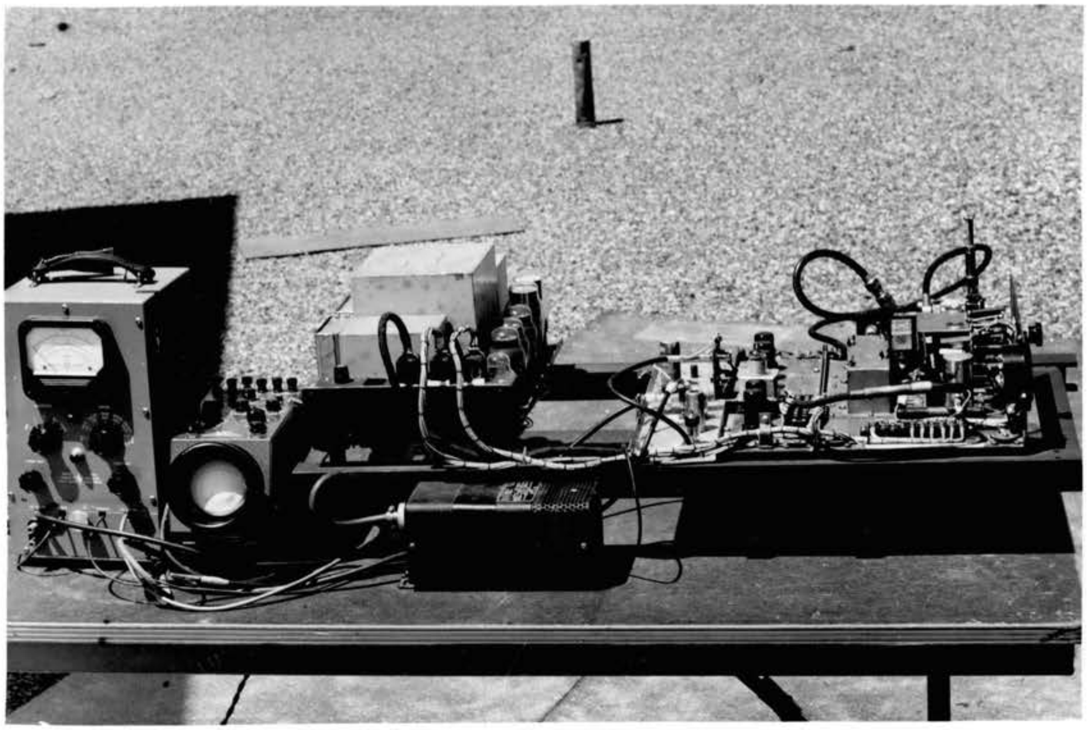


Figure 3. Receiver

Figure 4. Transmitting and Receiving Antennas

Figure 5. Plywood Board

Figure 6. Arrangement of Equipment

the desired directivity a parabolic antenna was used. About 5 milliwatts, a rather small amount of power, was radiated by the transmitter antenna; however, this was sufficient to obtain field patterns.

The receiver quite naturally was of the superheterodyne type. It was made from the track receiver of radar set SCR-545. A parabolic antenna was again used to obtain the necessary gain. A crystal mixer was used due to its good noise qualities, which is an important factor at frequencies in the 3,000 megacycle per second region. To obtain the necessary amplification several stages of intermediate-frequency amplification and several stages of audio-frequency amplification were used. An arrangement was made so that large signals would not saturate the IF amplifiers. A usable output was obtained on a vacuum-tube voltmeter connected to an audio detector. Balancing circuits were also incorporated in the receiver to balance out the effects of undesirable signals.

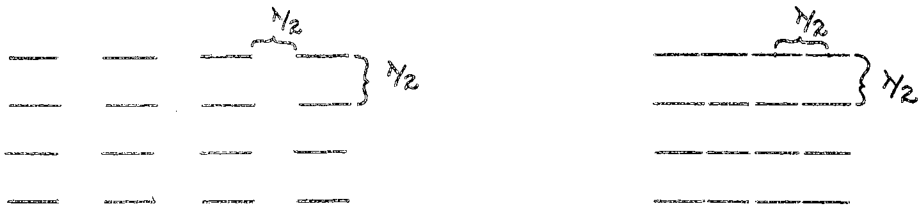
The most difficult part of the equipment to decide on was the apparatus used for holding the elements. For this application a piece of 22" by 22" by 5/8" plywood was used. The frame for the plywood was also constructed of wood. The plywood was mounted in the frame so it could be rotated about a horizontal axis through its center. The frame was mounted on a table to give it a large sturdy base. Wooden construction was used to prevent as much reflection as possible from the holding apparatus. The measurements were made out of doors, therefore a sturdy construction was necessary to keep the wind from moving the elements.

Arrangement of Experimental Equipment and Elements

The location of the experimental equipment presented several problems. The biggest problem was undesirable reflection from objects other than the elements. The reflection from the holding apparatus alone was quite large; therefore all other undesirable reflections had to be kept to a minimum. There are a great many things which can cause these reflections. Any metal object in the immediate vicinity of the experimental set-up can be very undesirable. Metal, however, is not the only thing which can cause reflections at 2,800 megacycles. Any object which is large compared to a wavelength can cause these undesirable reflections. To minimize these reflections the experimental work for this thesis was done out of doors. This location, however, was far from perfect due to the ground-reflected wave. The effect of ground reflection will be mentioned again in a later section of this paper.

The arrangement of the equipment was not the best realizable; however, it was the best which could be obtained under the circumstances. The transmitter and receiver were located at the same point. The transmitter antenna was mounted above and slightly in front of the receiving antenna. Both antennas were located approximately five feet above the ground. With this arrangement the receiving antenna did not pick up too much energy directly from the transmitting antenna. The plywood frame used for mounting the elements was located 10 feet and 7 inches in front of the transmitting antenna. Due to the interference caused by the ground-reflected wave, it was necessary to keep this distance constant throughout the entire experiment.

Two arrangements of the elements were used. First, the elements were arranged with a 1/2 wavelength spacing in both the horizontal and vertical directions. Figure 7 (a) shows this arrangement. For this arrangement four patterns were used. The first pattern contained 9 elements, the second contained 15 elements, the third contained 35 elements, and the last pattern contained 45 elements. For the second arrangement the elements were arranged with a 1/2 wavelength spacing between their centers in the horizontal direction and a 1/2 wavelength spacing between elements in the vertical direction. This arrangement is shown in Figure 7 (b). Six patterns were made for this arrangement. The number of elements used for each pattern was the same as for the first arrangement except that 25 and 63 element patterns were used for the second arrangement.



(a) (b)

Figure 7

For all arrangements the elements were mounted symmetrically about the horizontal axis of the plywood frame. With this symmetrical arrangement measurements were only taken from 0° to 90°, since rotation from 0° to -90° would give the same measurements. This, of course, neglects the effect of ground reflection.

Experimental Data and Curves

The field-pattern data were obtained by rotating the plywood frame around its horizontal axis. Voltage readings were made at the output of the receiver for different angles of rotation about the horizontal axis. Readings were made in 2° steps from 0° to 10° and in 5° steps from 10° to 90°. The 0° reading was the reading taken when the plywood plane was perpendicular to the ground. All of the element arrangements had a very sharp lobe at 0°; therefore it was decided to make the readings in 2° steps in that area.

Each reading contained both the reflection from the elements and the reflection from the holding apparatus. To find the reflection from the elements alone, data runs without the elements were made both before and after the runs with the elements. The readings made without the elements were then subtracted from the readings made with the elements to obtain the data for the elements alone. These data are given in Tables 1 through 5.

Radiation-pattern curves were obtained from the data in Tables 1 through 5. These curves are plotted in Figures 8 through 19. The arrangement and number of elements are in-

TABLE 1

EXPERIMENTAL DATA FOR ELEMENT SPACING OF ONE-HALF WAVE LENGTH HORIZONTALLY AND VERTICALLY

θ	Board	9 Elements 3 Hor. x 3 Ver.		15 Elements 5 Hor. x 3 Ver.	
Rotation Angle Degrees	Reflection Receiver Volts	9 El. + Board Receiver Volts	9 Elements Receiver Volts	15 El. + Board Receiver Volts	15 Elements Receiver Volts
0	3.40	4.10	0.70	4.65	1.25
2	2.80	3.55	0.75	3.85	1.05
4	2.20	2.60	0.40	2.70	0.50
6	1.50	1.95	0.45	1.90	0.40
8	1.20	1.65	0.45	1.65	0.45
10	1.30	1.68	0.38	1.57	0.27
15	1.55	1.85	0.30	1.90	0.35
20	1.40	1.60	0.20	1.65	0.25
25	1.60	1.75	0.15	1.75	0.15
30	1.55	1.70	0.15	1.75	0.20
35	1.60	1.60	0.00	1.80	0.20
40	1.70	1.70	0.00	1.80	0.10
45	1.60	1.60	0.00	1.60	0.00
50	1.65	1.70	0.05	1.70	0.05
55	1.70	1.75	0.05	1.90	0.20
60	1.60	1.60	0.00	1.70	0.10
65	1.55	1.55	0.00	1.60	0.05
70	1.55	1.55	0.00	1.60	0.05
75	1.55	1.75	0.20	1.75	0.20
80	1.58	1.90	0.32	2.00	0.42
85	1.58	1.90	0.32	2.10	0.52
90	1.50	1.90	0.40	2.10	0.60

TABLE 2

EXPERIMENTAL DATA FOR ELEMENT SPACING OF ONE-HALF WAVE LENGTH HORIZONTALLY AND VERTICALLY

θ	Board	35 Elements 5 Hor. x 7 Ver.		45 Elements 5 Hor. x 9 Ver.	
Rotation Angle Degrees	Reflection Receiver Volts	35 El. + Board Receiver Volts	35 Elements Receiver Volts	45 El. + Board Receiver Volts	45 Elements Receiver Volts
0	3.80	4.80	1.00	5.23	1.43
2	3.00	3.80	0.80	4.13	1.13
4	2.25	2.70	0.45	2.68	0.43
6	1.65	1.90	0.25	1.88	0.23
8	1.45	1.55	0.10	1.51	0.00
10	1.42	1.40	0.00	1.55	0.13
15	1.62	1.65	0.03	1.83	0.21
20	1.42	1.60	0.18	1.58	0.16
25	1.52	1.75	0.23	1.78	0.16
30	1.50	1.67	0.17	1.81	0.31
35	1.50	1.62	0.12	1.65	0.15
40	1.52	1.72	0.20	1.74	0.22
45	1.48	1.55	0.07	1.58	0.13
50	1.55	1.60	0.05	1.57	0.02
55	1.60	1.78	0.18	1.63	0.03
60	1.52	1.75	0.23	1.58	0.06
65	1.45	1.62	0.17	1.58	0.13
70	1.48	1.70	0.22	1.63	0.15
75	1.55	1.92	0.37	1.83	0.28
80	1.63	2.22	0.59	2.03	0.40
85	1.63	2.35	0.73	2.18	0.56
90	1.58	2.42	0.84	2.23	0.65

TABLE 3

EXPERIMENTAL DATA FOR ELEMENT SPACING OF ONE-HALF WAVE VERTICALLY AND ONE-HALF WAVE BETWEEN CENTERS HORIZONTALLY

θ	Board Reflection		9 Elements 3 Hor. x 3 Ver.		15 Elements 5 Hor. x 3 Ver.	
Rotation Angle Degrees	Before Data Run	After Data Run	9 El. + Board Receiver Volts	9 Elements Receiver Volts	15 El. + Board Receiver Volts	15 Elements Receiver Volts
0	2.45	2.90	2.55	0.10	3.20	0.70
2	1.40	1.80	1.34	0.00	1.85	0.35
4	0.53	0.81	0.62	0.09	0.80	0.23
6	0.19	0.35	0.26	0.07	0.38	0.15
8	0.20	0.32	0.27	0.07	0.35	0.13
10	0.41	0.57	0.46	0.05	0.62	0.17
15	0.59	0.69	0.63	0.04	0.77	0.16
20	0.35	0.42	0.39	0.04	0.48	0.11
25	0.59	0.74	0.63	0.04	0.80	0.17
30	0.43	0.55	0.46	0.03	0.55	0.09
35	0.45	0.54	0.46	0.01	0.53	0.06
40	0.53	0.65	0.53	0.00	0.63	0.07
45	0.43	0.53	0.47	0.04	0.54	0.09
50	0.46	0.58	0.50	0.04	0.62	0.13
55	0.54	0.70	0.58	0.04	0.72	0.14
60	0.48	0.61	0.49	0.01	0.57	0.06
65	0.39	0.51	0.43	0.04	0.49	0.07
70	0.39	0.51	0.45	0.06	0.52	0.10
75	0.40	0.53	0.47	0.07	0.55	0.12
80	0.42	0.55	0.48	0.06	0.55	0.10
85	0.45	0.58	0.49	0.04	0.54	0.06
90	0.48	0.62	0.51	0.04	0.54	0.03

TABLE 4

EXPERIMENTAL DATA FOR ELEMENT SPACING OF ONE-HALF WAVE VERTICALLY AND ONE-HALF WAVE BETWEEN CENTERS HORIZONTALLY

θ	Board Reflection		25 Elements 3 Hor. x 3 Ver.		35 Elements 5 Hor. x 3 Ver.	
Rotation Angle Degrees	Before Data Run	After Data Run	25 El. + Board Receiver Volts	25 Elements Receiver Volts	35 El. + Board Receiver Volts	35 Elements Receiver Volts
0	2.45	2.90	3.40	0.80	3.70	1.00
2	1.40	1.80	2.30	0.70	2.35	0.65
4	0.53	0.81	0.95	0.33	1.08	0.39
6	0.19	0.35	0.37	0.10	0.47	0.16
8	0.20	0.32	0.31	0.07	0.40	0.14
10	0.41	0.57	0.54	0.05	0.53	0.00
15	0.59	0.69	0.66	0.03	0.69	0.04
20	0.35	0.42	0.38	0.00	0.63	0.22
25	0.59	0.74	0.73	0.06	0.88	0.17
30	0.43	0.55	0.61	0.12	0.63	0.11
35	0.45	0.54	0.61	0.12	0.63	0.12
40	0.53	0.65	0.65	0.06	0.71	0.09
45	0.43	0.53	0.52	0.05	0.64	0.15
50	0.46	0.58	0.58	0.06	0.69	0.14
55	0.54	0.70	0.65	0.03	0.76	0.10
60	0.48	0.61	0.57	0.03	0.68	0.11
65	0.39	0.51	0.50	0.05	0.62	0.14
70	0.39	0.51	0.51	0.06	0.65	0.17
75	0.40	0.53	0.52	0.06	0.64	0.15
80	0.42	0.55	0.49	0.01	0.59	0.08
85	0.45	0.58	0.47	0.00	0.58	0.04
90	0.48	0.62	0.46	0.00	0.57	0.00

TABLE 5

EXPERIMENTAL DATA FOR ELEMENT SPACING OF ONE-HALF WAVE VERTICALLY AND ONE-HALF WAVE BETWEEN CENTERS HORIZONTALLY

θ	Board Reflection		45 Elements 3 Hor. x 3 Ver.		63 Elements 5 Hor. x 3 Ver.	
Rotation Angle Degrees	Before Data Run	After Data Run	45 El. Board Receiver Volts	45 Elements Receiver Volts	63 El. Board Receiver Volts	63 Elements Receiver Volts
0	2.45	2.90	3.69	0.89	4.87	1.97
2	1.40	1.80	2.49	0.69	3.02	1.22
4	0.53	0.81	1.03	0.28	1.32	0.51
6	0.19	0.35	0.49	0.14	0.49	0.14
8	0.20	0.32	0.42	0.14	0.40	0.08
10	0.41	0.57	0.58	0.00	0.57	0.00
15	0.59	0.69	0.97	0.18	1.04	0.35
20	0.35	0.42	0.72	0.29	0.79	0.37
25	0.59	0.74	0.94	0.19	1.01	0.27
30	0.43	0.55	0.78	0.23	0.81	0.26
35	0.45	0.54	0.82	0.29	0.87	0.33
40	0.53	0.65	0.86	0.21	0.89	0.24
45	0.43	0.53	0.72	0.21	0.75	0.22
50	0.46	0.58	0.81	0.23	0.85	0.27
55	0.54	0.70	0.94	0.24	0.99	0.29
60	0.48	0.61	0.90	0.30	0.94	0.33
65	0.39	0.51	0.85	0.35	0.91	0.40
70	0.39	0.51	0.83	0.33	0.90	0.39
75	0.40	0.53	0.79	0.28	0.86	0.33
80	0.42	0.55	0.72	0.19	0.76	0.21
85	0.45	0.58	0.67	0.11	0.70	0.12
90	0.48	0.62	0.67	0.07	0.70	0.08

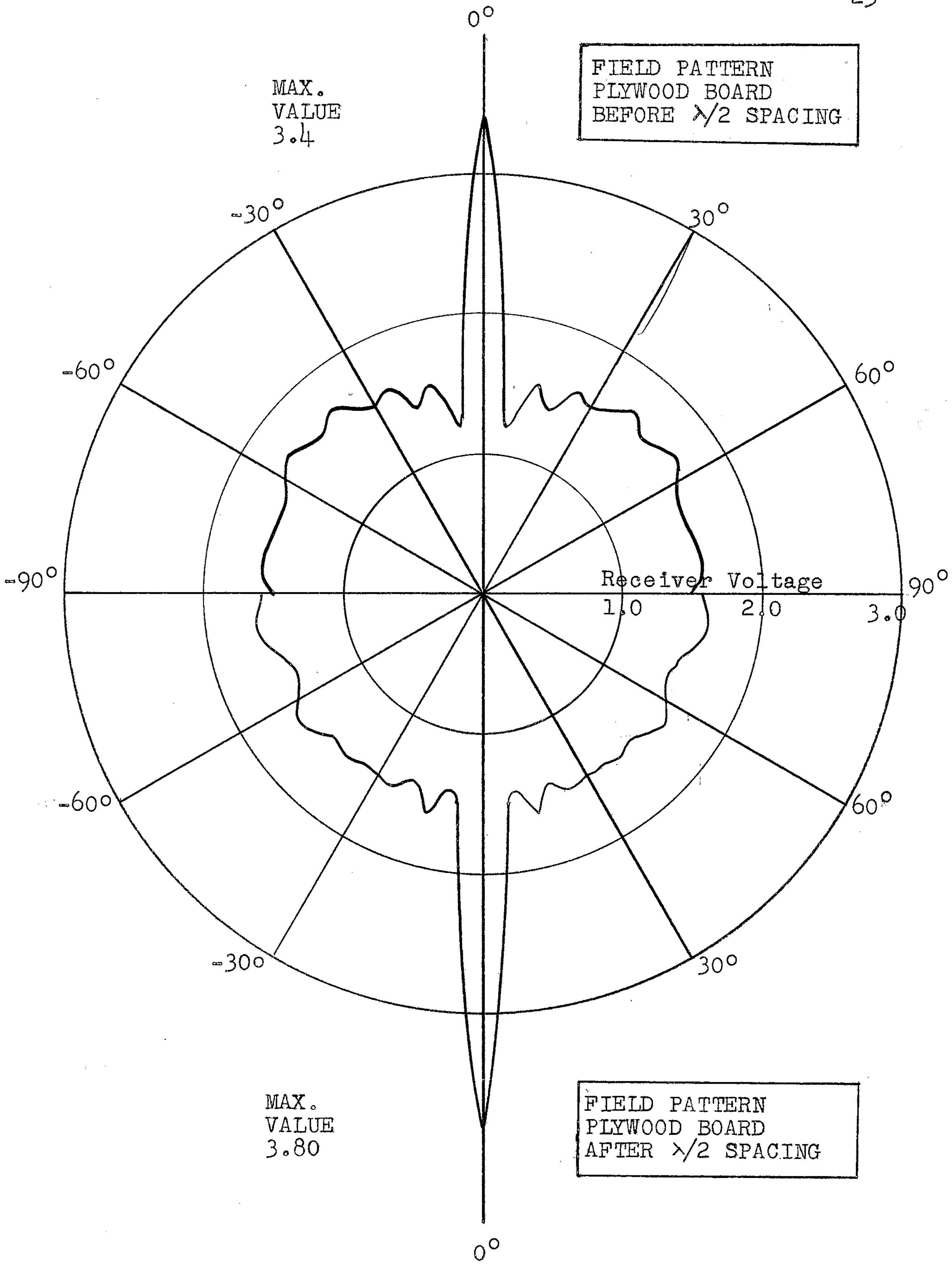

0°
MAX.
VALUE
3.4
FIELD PATTERN
PLYWOOD BOARD
BEFORE λ/2 SPACING
-30°
30°
-60°
60°
-90°
90°
Receiver Voltage
1.0
2.0
3.0
-60°
60°
-30°
30°
MAX.
VALUE
3.80
FIELD PATTERN
PLYWOOD BOARD
AFTER λ/2 SPACING
0°

Figure 8

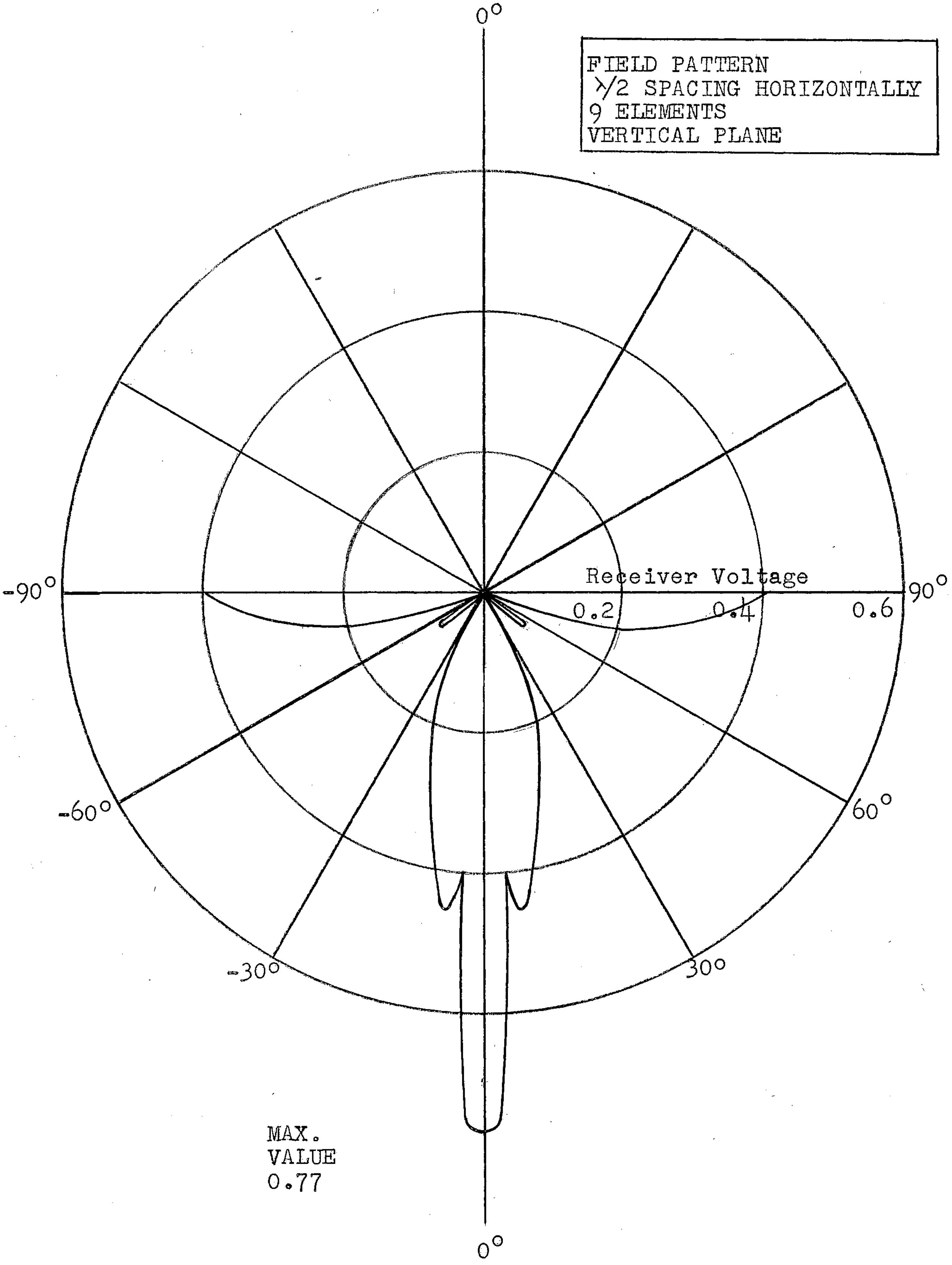

0°
FIELD PATTERN
λ/2 SPACING HORIZONTALLY
9 ELEMENTS
VERTICAL PLANE
Receiver Voltage
-90°
90°
0.2
0.4
0.6
-60°
60°
-30°
30°
MAX.
VALUE
0.77
0°

Figure 9

FIELD PATTERN
λ/2 SPACING HORIZONTALLY
15 ELEMENTS
VERTICAL PLANE

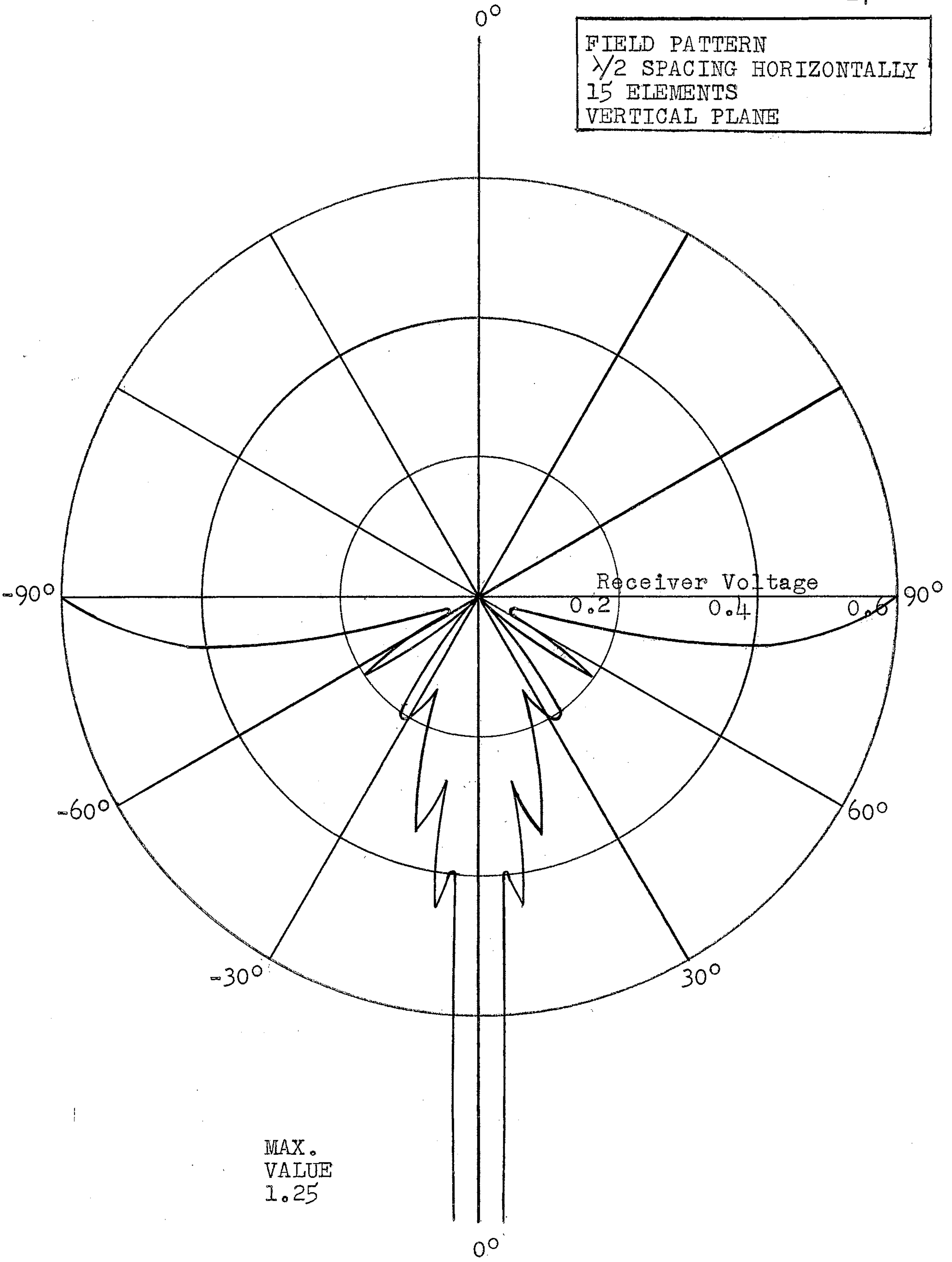
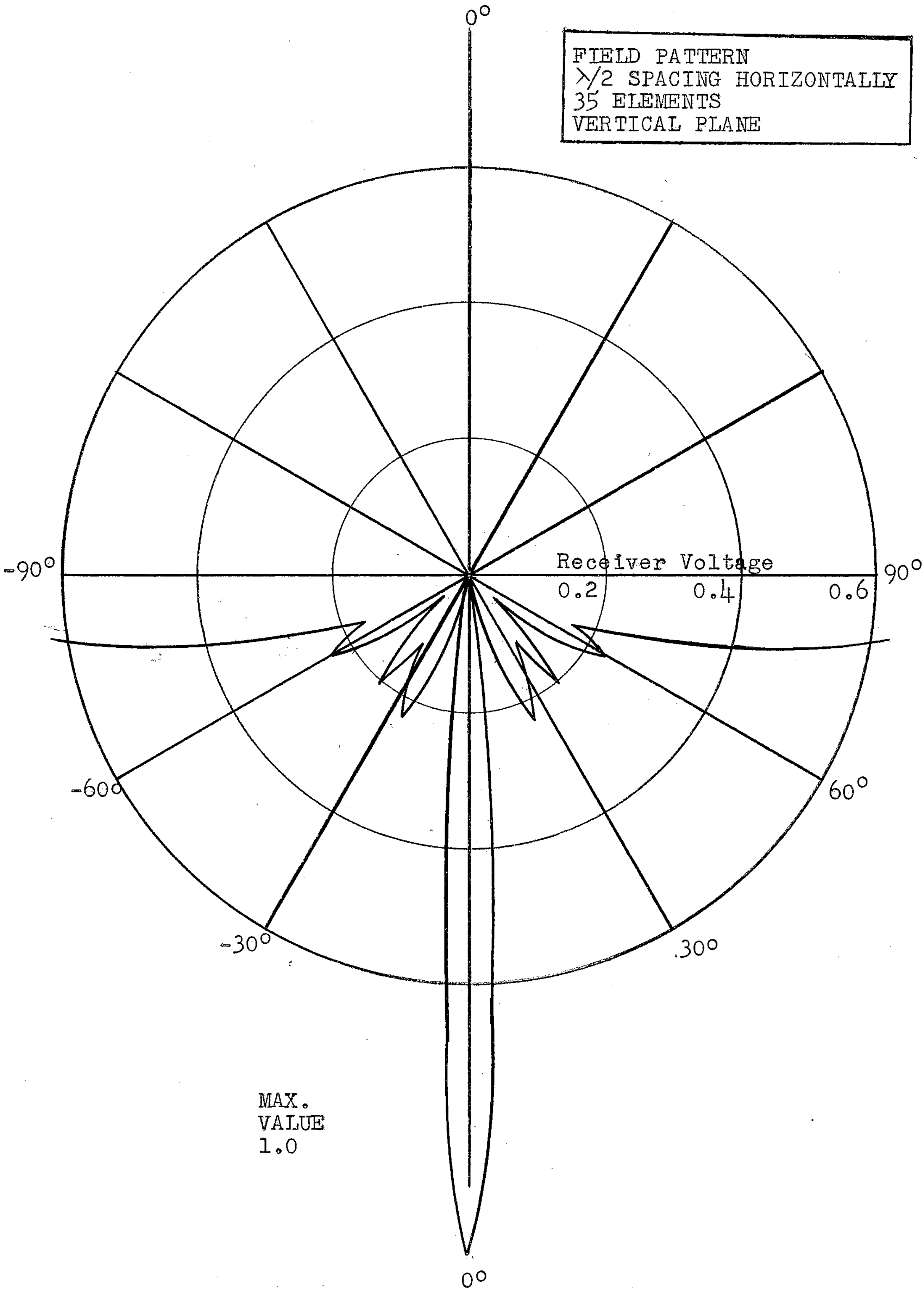


Figure 10



FIELD PATTERN
λ/2 SPACING HORIZONTALLY
35 ELEMENTS
VERTICAL PLANE

MAX.
VALUE
1.0

Figure 11

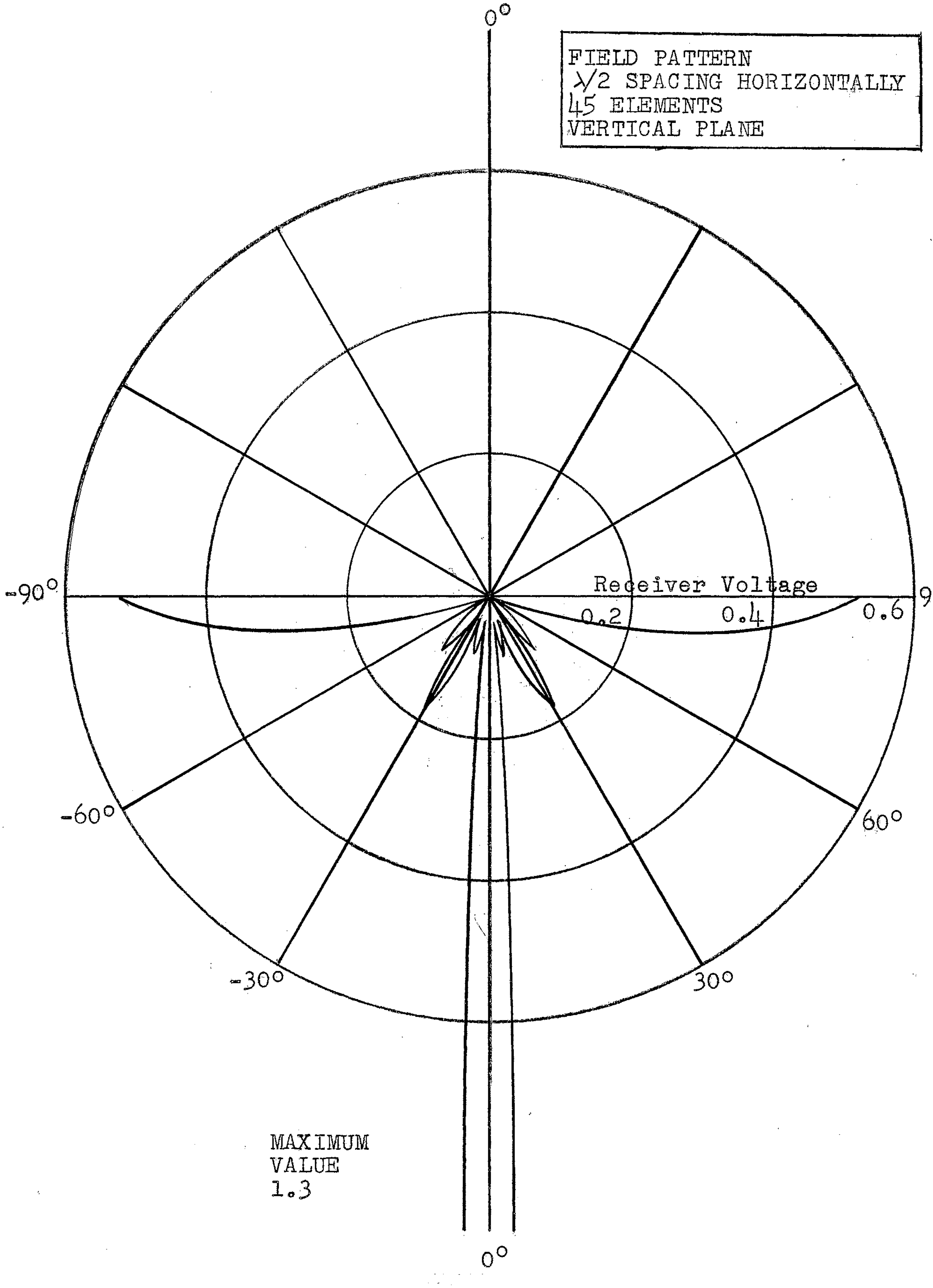

FIELD PATTERN
λ/2 SPACING HORIZONTALLY
45 ELEMENTS
VERTICAL PLANE
0°
-90°
90°
-60°
60°
-30°
30°
0°
Receiver Voltage
0.2
0.4
0.6
MAXIMUM
VALUE
1.3

Figure 12

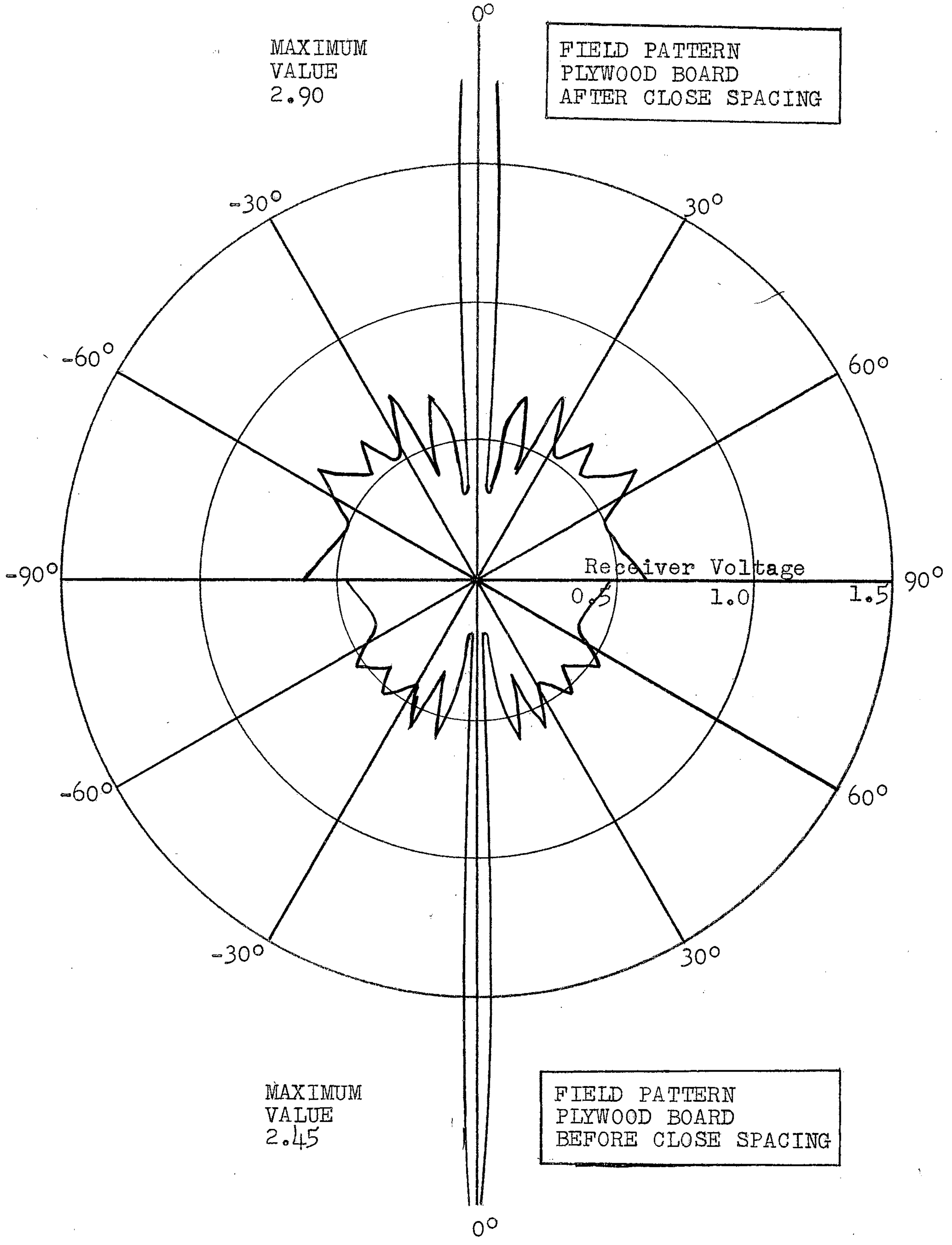

0°
MAXIMUM
VALUE
2.90
FIELD PATTERN
PLYWOOD BOARD
AFTER CLOSE SPACING
-30°
30°
-60°
60°
-90°
90°
Receiver Voltage
0.5
1.0
1.5
-60°
60°
-30°
30°
MAXIMUM
VALUE
2.45
FIELD PATTERN
PLYWOOD BOARD
BEFORE CLOSE SPACING
0°

Figure 13

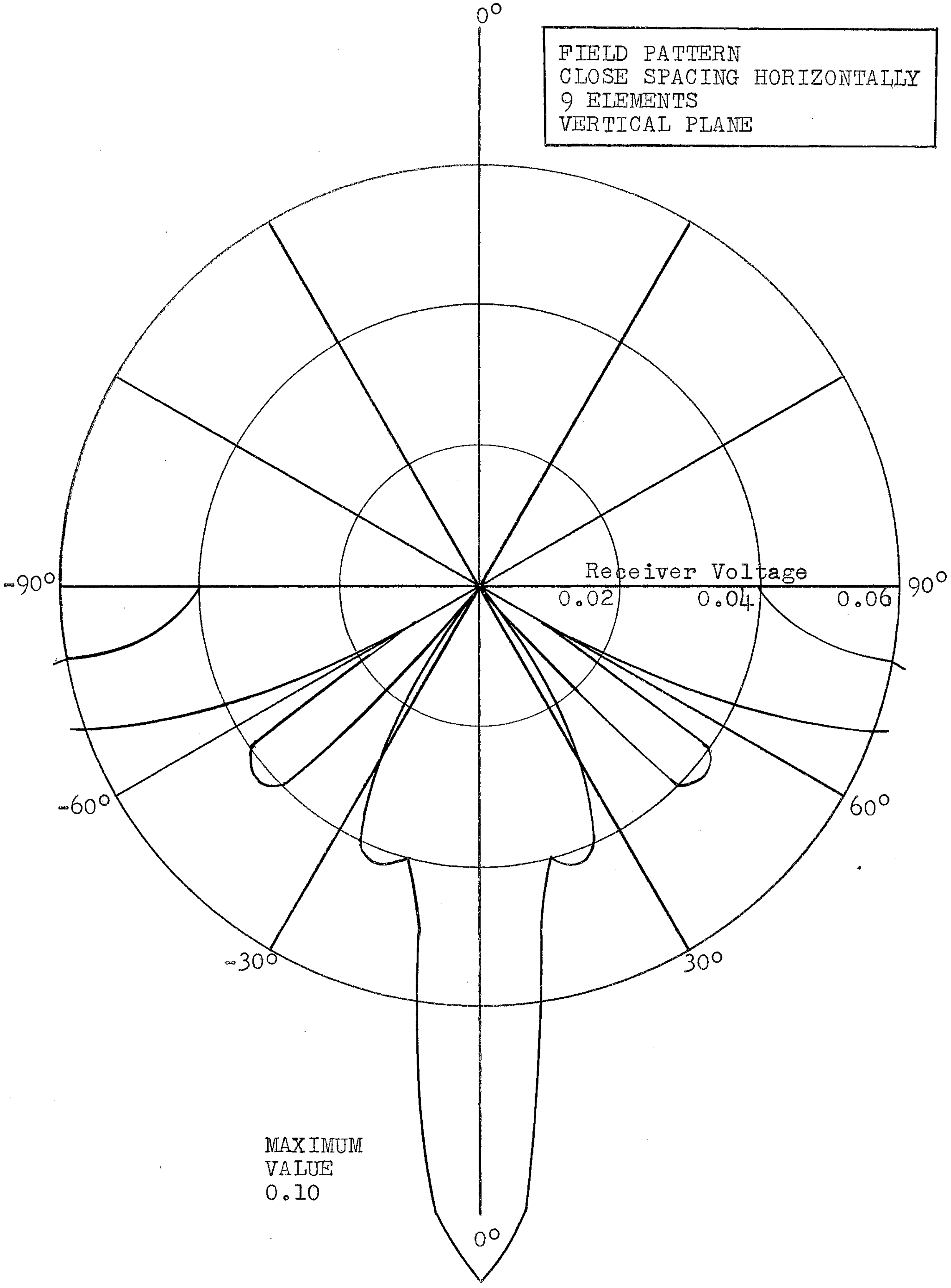

FIELD PATTERN
CLOSE SPACING HORIZONTALLY
9 ELEMENTS
VERTICAL PLANE
0°
-90°
90°
Receiver Voltage
0.02
0.04
0.06
-60°
60°
-30°
30°
MAXIMUM
VALUE
0.10
0°

Figure 14

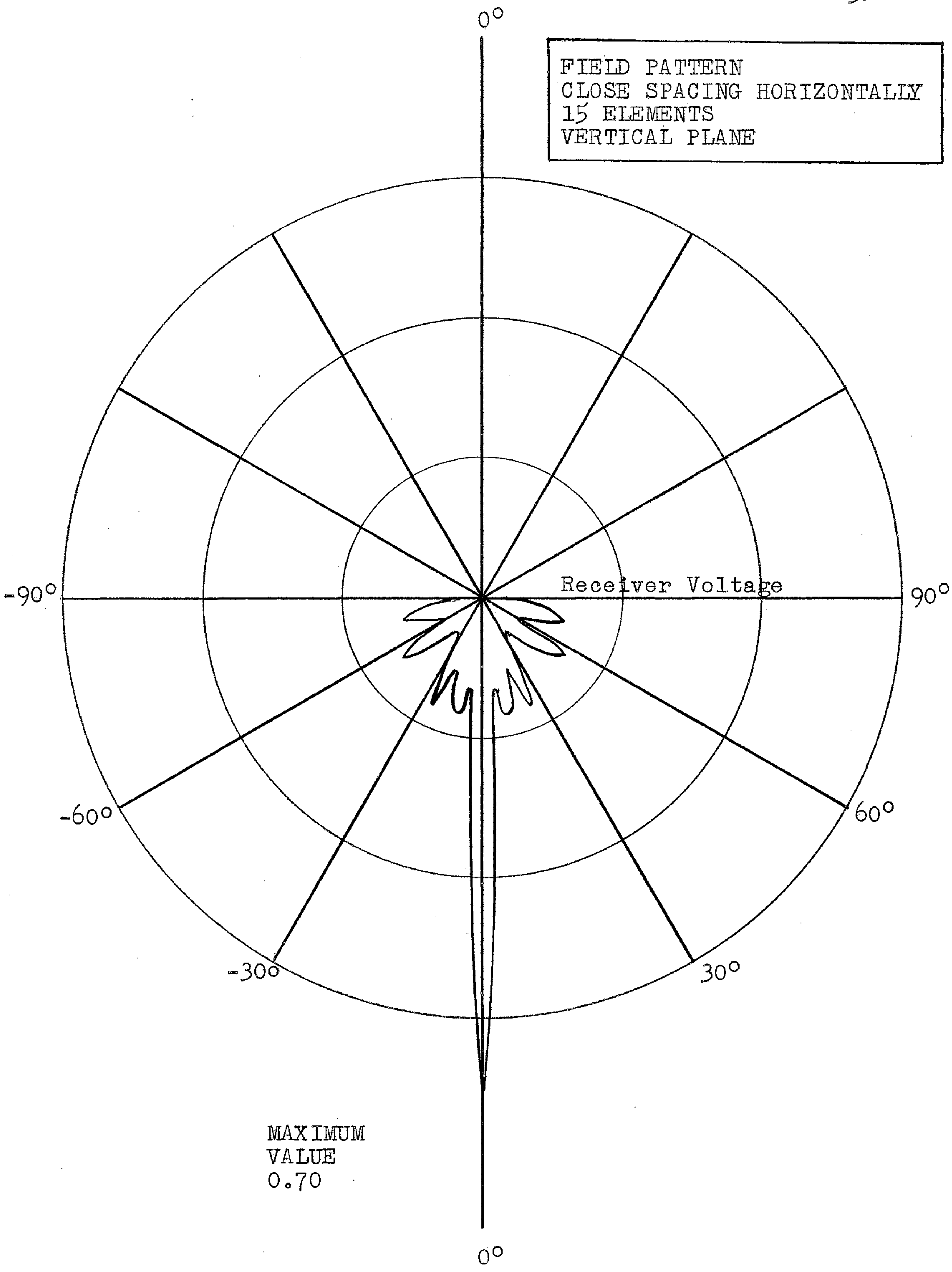

0°
FIELD PATTERN
CLOSE SPACING HORIZONTALLY
15 ELEMENTS
VERTICAL PLANE
-90°
Receiver Voltage
90°
-60°
60°
-30°
30°
MAXIMUM
VALUE
0.70
0°

Figure 15

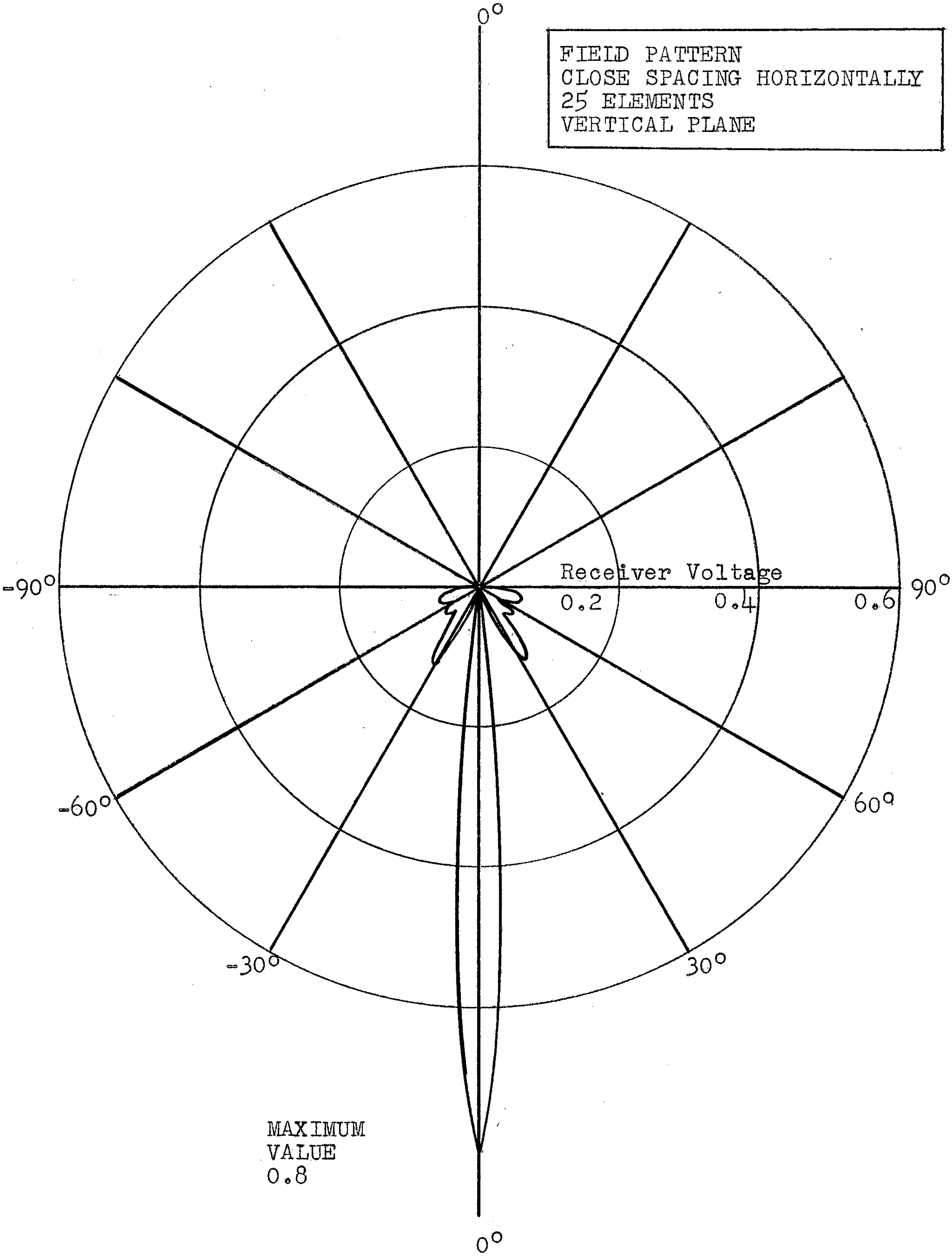

0°
FIELD PATTERN
CLOSE SPACING HORIZONTALLY
25 ELEMENTS
VERTICAL PLANE
Receiver Voltage
0.2
0.4
0.6
-90°
90°
-60°
60°
-30°
30°
MAXIMUM
VALUE
0.8
0°

Figure 16

FIELD PATTERN
CLOSE SPACING HORIZONTALLY
35 ELEMENTS
VERTICAL PLANE

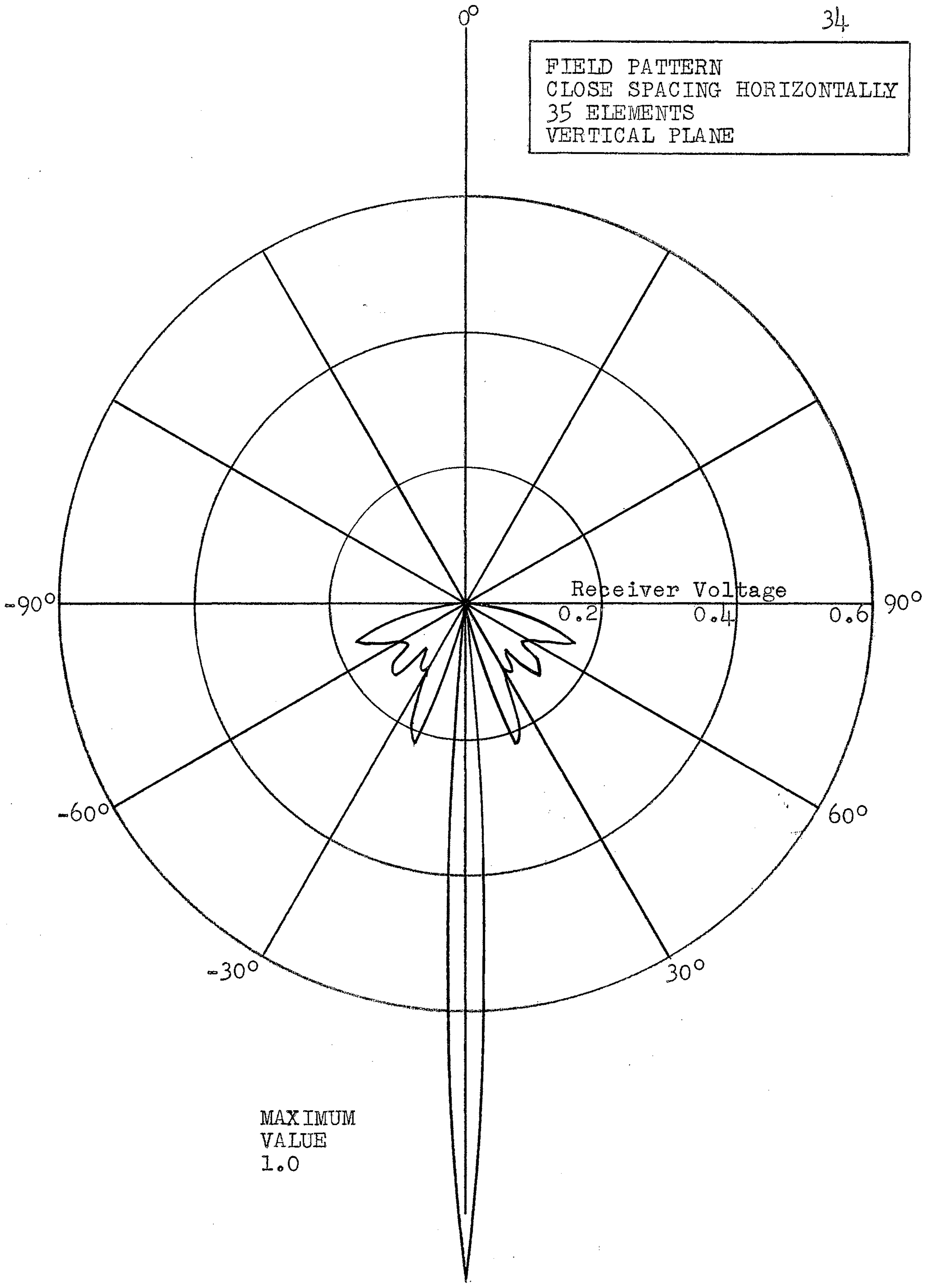


Figure 17

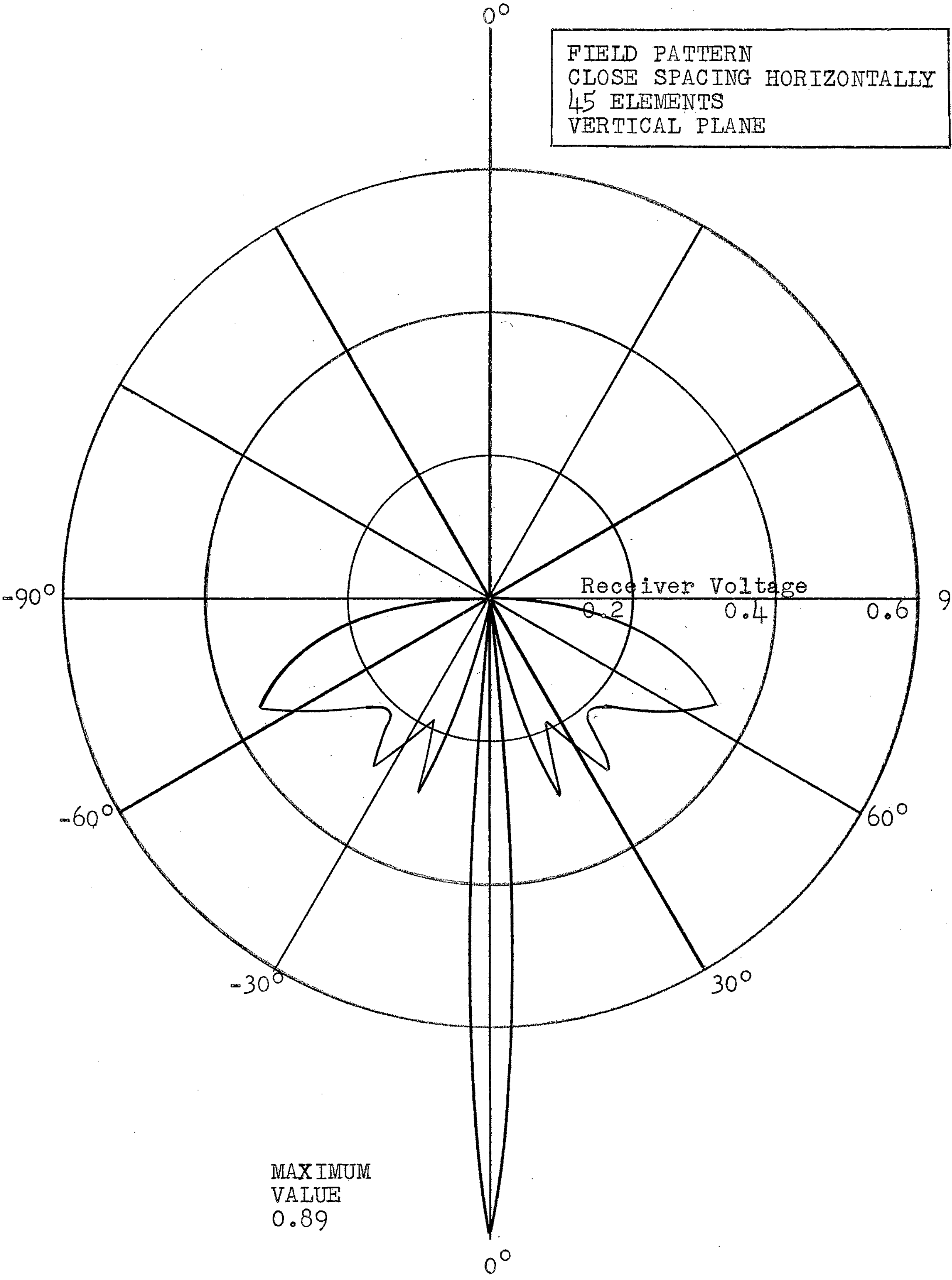

FIELD PATTERN
CLOSE SPACING HORIZONTALLY
45 ELEMENTS
VERTICAL PLANE
0°
-90°
90°
-60°
60°
-30°
30°
0°
Receiver Voltage
0.2
0.4
0.6
MAXIMUM
VALUE
0.89

Figure 18

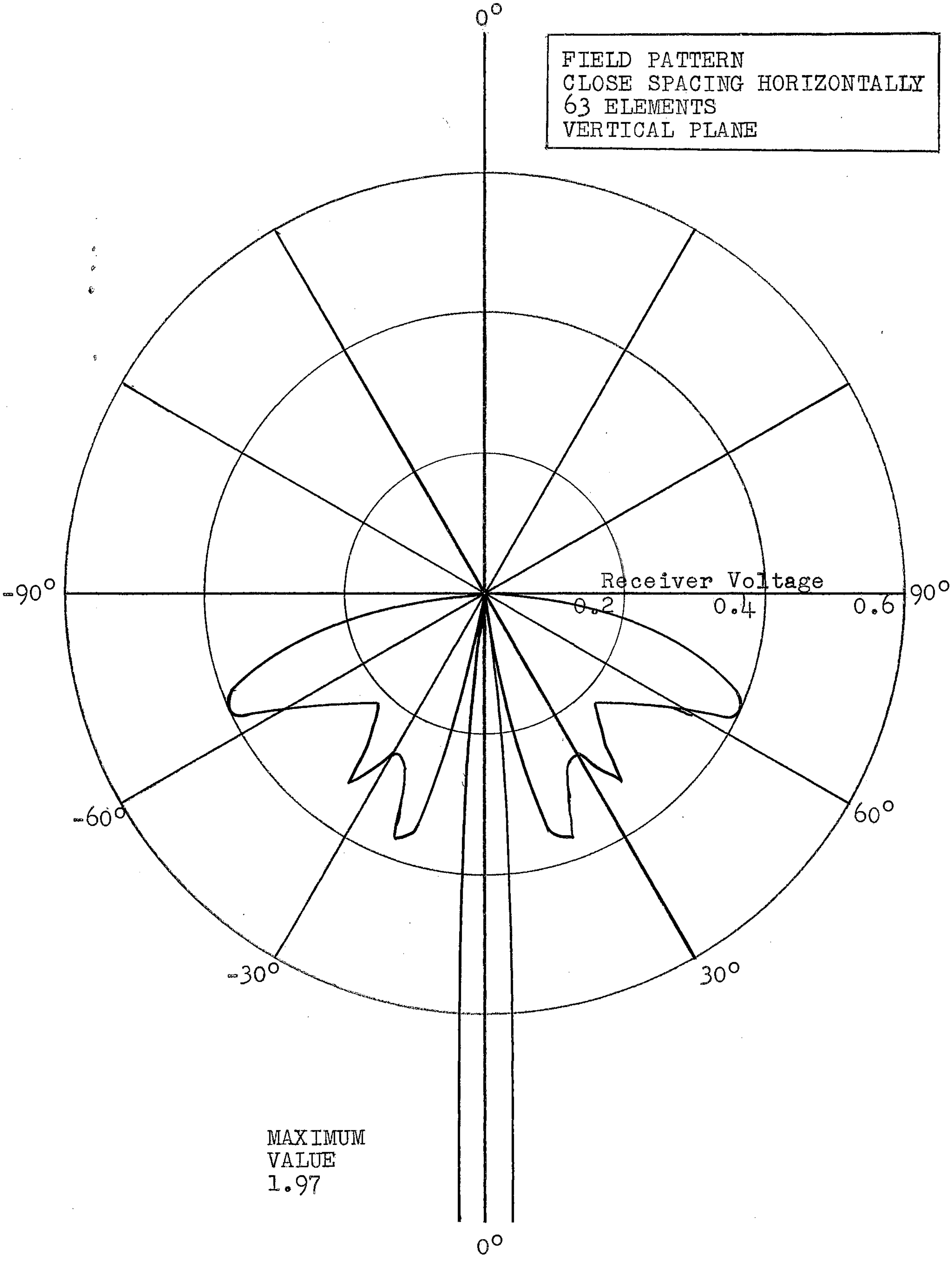

FIELD PATTERN
CLOSE SPACING HORIZONTALLY
63 ELEMENTS
VERTICAL PLANE
0°
-90°
90°
-60°
60°
-30°
30°
0°
Receiver Voltage
0.2
0.4
0.6
MAXIMUM
VALUE
1.97

Figure 19

dicated on each curve. A little explanation would probably be helpful in understanding exactly what the curves show. In the first place the curves are a plot of a voltage value versus angle of rotation of the element patterns. Since the pattern was rotated about a horizontal axis the curves are a vertical-plane radiation pattern. They show the angle at which the greatest amount of power is reradiated and the relative amounts of reradiation for the other angles.

Experimental Difficulties

There were several difficulties encountered in obtaining the experimental data, some of which have already been mentioned. Considering the frequency used it is not hard to see why most of the following difficulties were encountered. One of the biggest difficulties which has already been discussed was undesired reflections. Some of this undesired reflection was ground reflection which could not be avoided. Since ground reflection was present, it interfered with the direct wave. This interference caused a periodic fading and reinforcing of the direct wave. Whether the direct wave was opposed or aided depended on whether the ground-reflected wave was out of phase or in phase with the direct wave at the receiving antenna. From this it can be seen that the amount of energy received and consequently reradiated was dependent on where the elements were with respect to the transmitting antenna. To overcome this difficulty all of the measurements were made with the elements at exactly the same point with respect to the transmitting antenna. As long as this distance remained constant, accurate relative field patterns could be obtained.

Keeping the distance constant between elements and antenna was another difficulty. Since a wavelength was 10 centimeters a very small movement changed the amount of reflected energy. To try to keep this error small, sturdy construction of supports was used.

CONCLUSIONS

Discussion of Results

The primary objective of this study was to determine the field patterns of reflecting antenna arrays. The curves which were explained in a previous section show these patterns for several arrays. From a directivity standpoint it is relatively easy to understand what the curves mean. The thing which is often difficult to explain is why an array gives a particular type of curve. In the following section a brief explanation of the arrays and their radiation patterns will be discussed.

It must be remembered that the curves are vertical-plane radiation patterns and that the elements were horizontally polarized. For all types of antenna arrays the radiation in a certain direction is a function of the phase of the energy from each element. If the phase of the energy is the same in each element, then the distance between elements is an important factor. Both of these factors were important in this experiment.

The radiation curves for the half-wave spacing of elements in both the horizontal and vertical directions will be considered first. The curves are shown in Figures 8 through 12. All of these curves have two prominent lobes. One of these prominent lobes is in the vicinity of 0°, and the other is in the vicinity of 90°. These lobes are rather easily explained by antenna-array theory. Consider first the lobe at 0°. When the array is at 0° the plane wave from the transmitter is essentially exciting all elements the same in both phase and magnitude. Since the phase of the absorbed energy is the same for all elements, their reradiated energy will have the same phase. Since the elements are a half wavelength apart and their energies are in phase, the reradiated energy will add in a direction perpendicular to the array plane. In other words the receiver used in the experiment was in the strongest reradiated field.

Slightly different conditions exist when the array is at 90°. In this position the plane of the array is parallel to the direction of propagation of the exciting wave. Since the element rows are spaced 1/2 wavelength apart, they are successively excited 180° apart. With this condition existing, the maximum signal is reradiated parallel to the element plane toward the receiver. This accounts for the large lobe at 90° on the curves. This lobe, however, is not as large as the 0° lobe. The reason for this is that the lobe is probably wider than the 0° lobe, therefore causing more ground-reflection interference at the receiver.

At other angles between 0° and 90° there is little radiation due to destructive interference. An occasional small lobe and sometimes a rather large lobe appear, probably due to the geometry of the array. In other words at certain angles a small amount of energy from all elements is in phase, therefore causing a radiation in that direction. It would be a very difficult graphical job to determine whether these lobes are in their proper place. Several experimental runs were made under varying conditions. Even though the data were not exactly the same, they were relatively the same. The lobes for the same array appeared at the same angle for each run.

The curves for the half-wave spacing between elements in the vertical direction and half-wave spacing between element centers in the horizontal direction are in most respects the same as the previous curves. However, there is one striking difference. This difference is that there is very little or no reflection at 90° for this spacing. The large lobe at 0° and the smaller lobes between 0° and 90° can be explained by the same reasoning used for the previous curves. At the present time no explanation except some sort of destructive interference can be offered for the condition at 90°.

No correlation can be made between the relative magnitudes of the radiation curves for the two spacings, because the data for both arrangements were not taken at the same time. However, a speculation can be made about these magnitudes. For an array of the same number of elements in both spacings, the reradiated energy should be approximately the same at 0°.

Probably a word should be said about the relative magnitudes of the curves of the same pattern, that is, curves for the same spacing but with a different number of elements. From the curves it can be seen that the magnitude of the reflections does not increase proportionally with the number of elements. In fact in some cases it is lower for a larger number of elements. For instance, in the first set of curves the pattern with 35 elements has a maximum magnitude of 1.00, while the same pattern with 15 elements has a maximum magnitude of 1.25. There could be several reasons for this decrease. One reason might be an incorrect measurement. Another reason might have to do with the ground-reflected wave. The ground-reflected wave for one pattern may not have been the same as that for another pattern. The first reason is probably the more correct.

One very striking property of the arrays studied is the highly directive property around 0°. At very small angles from 0° the reflected energy becomes relatively small. The lobes are not more than 10° wide for most patterns. As a matter of fact, an antenna arrangement similar to the element arrays represented by curves 14 through 19 is often used. This arrangement is called the pine-tree antenna, and is used for its highly directive qualities.[1]

Suggestions for Future Work

There are still many aspects of the reflection from resonant conducting elements which are not known. Much more work could be done in practically any phase of the reflection field. For instance, it would be interesting to know how the reflections from the resonant elements compare with reflections from flat conducting sheets of the same size. Also work could be

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[1] S. A. Schelkunoff and H. T. Friis, Antennas Theory and Practice (New York, 1952), p. 40.

done on the problem of measuring the exact amount of energy which is reflected under certain conditions. Conducting elements could be compared to reflecting devices which are not made of conducting material. All of these problems and many more are not yet completely solved. It is hoped that this paper will serve as a help to those doing work on these and other problems in the field of microwave reflections.

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