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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Radiation patterns produced by arrays of axial slots on a conducting cylinder are studied theoretically and experimentally to develop directive antenna systems for use on electrically small aircraft or missiles. The design of the array is mainly governed by the considerations of required field discriminations between various directions. A method has been developed for the design of a reduced-height waveguide cavity-backed slot which can be used as an individual radiating element of the array. Impedance and radiating properties of the slot element are studied and discussed.

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TABLE OF CONTENTS

I. INTRODUCTION

1.1 Preliminary Remarks

The present report discusses the results of an investigation to determine an antenna configuration that will result in the best single beam antenna pattern for application on electrically small vehicles. More specifically, the objective of the research reported herein is to determine the best arrangement of radiating elements for an antenna system to produce a single beam pattern for application on an electrically small aircraft or missile. The antenna is to operate in the low VHF range (30 MHz - 200 HHz; λ = 10 m - 1.5 m). The electrically small vehicle is approximated by a perfectly conducting circular cylinder of diameter approximately equal to 2 meters ($ka \sim 0.2\pi - 1.33\pi$ over the band 30 MHz - 200 MHz) and of infinite length. The assumption of infinite length considerably simplifies the theoretical analysis. Since the research discussed here has been a continuation of our previous investigation on the same topic, it is appropriate to summarize the results obtained previously. This is done in the next section.

1.2 Previous Results

The results of the theoretical and experimental investigation conducted previously on the same problem have been discussed in [1] and [2]. These results indicate that with the help of an array of axial slots suitably located on a circular cylinder it is possible to obtain a single beam pattern over a certain range in the upper part of the band of frequencies of interest. For the given size of the cylinder it appears that the pattern is less than optimum at the lower end of the frequency band. The VSWR results indicate that it would be possible to achieve the design goal of 1:3 VSWR over the band of frequencies of interest.

In the theoretical analysis reported in [1] and [2], the required phase of excitation of elements to produce a beam in a certain desired direction was obtained by approximating the array by a section of a circular array of isotropic sources. For the given radius of the cylinder and the frequencies of interest the approximation was found to yield satisfactory results. Patterns produced by 2, 3 or 4 axial slots were studied in detail. The beam directions of the arrays were designed to be along 45°, as measured from the straight down direction. The agreement between theoretical and experimental results, as discussed in [1] was found to be satisfactory.

1.3 Goals of the Present Research

The present research, which is an extension of that discussed in Section 1.2 has the following goals:

(i) Redesign the array so as to illuminate a region perhaps 30° to 75° as measured from the nadir.

(ii) Establish a lower frequency limit in terms of diameter $/\lambda$ for which it is possible to obtain a 10 dB difference in the illumination over the 30° to 75° angle spread. The discrimination is to be between the illuminated side and the corresponding same angle on the shadowed side.

(iii) Slot spacings other than $\pi/4$ will be investigated.

(iv) Conduct experimental studies to verify some of the findings of the theory.

(v) Develop an improved design for the radiating element.

1.4 General Description of the Problem

Let us represent the fuselage of the aircraft by a conducting infinite cylinder of radius a. The coordinate system used and the orientation of the system are shown in Fig. 1, where the axis of the cylinder is oriented along the z-axis. We shall

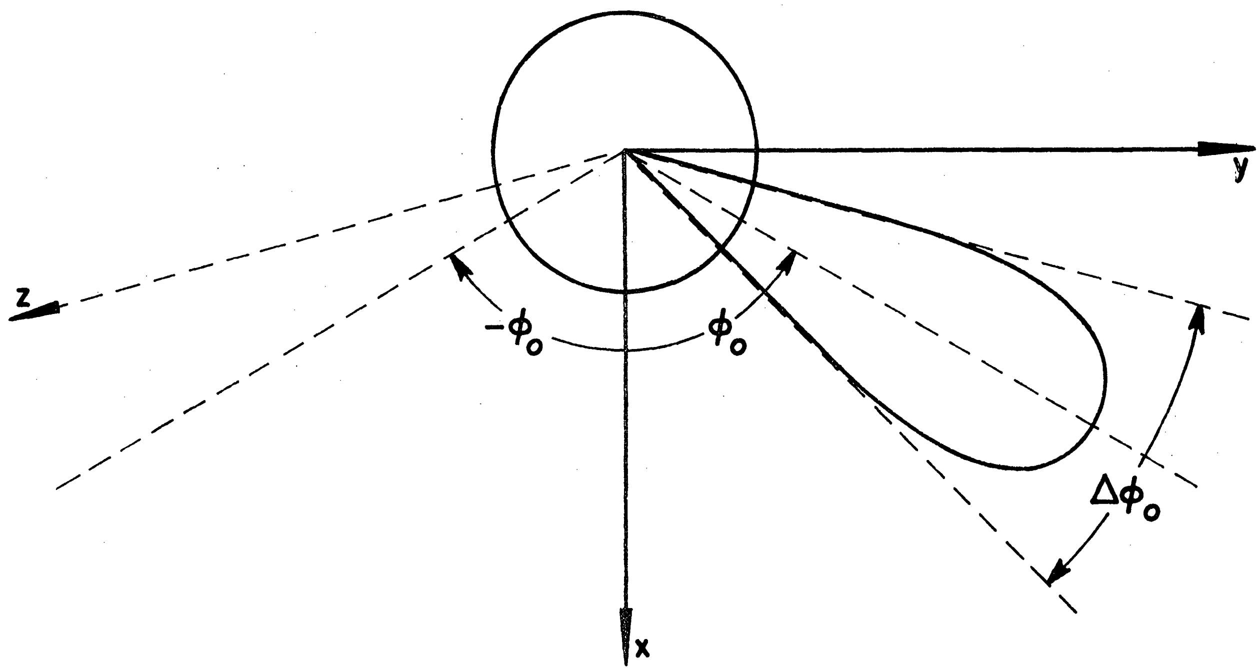


FIG. 1: Idealized pattern and the coordinate system used.

refer to the x-y plane as the vertical or elevation plane, the y-z plane as the horizontal plane and the x-z plane as the longitudinal plane.

The desired beam produced by the antenna should be normal to the z-axis and be directed as shown in Fig. 1. The antenna should also have some directivity in the y-z or the horizontal plane; however, in the present report, we are not concerned with the horizontal plane patterns. Ideally there should not be any radiation beyond the range

$$\phi_0 - \frac{\Delta\phi_0}{2} \leq \phi \leq \phi_0 + \frac{\Delta\phi_0}{2} ,$$

where $\Delta\phi_0$ is the beamwidth between nulls in the vertical plane pattern. As shown in Fig. 1, the ideal requirement is such that the field in the image direction $-\phi_0$ is zero. The field discrimination ratio is defined to be the ratio of fields in the directions ϕ_0 and $-\phi_0$. Another quantity of interest is the field in the direction $\phi = 0^o$, i.e., looking down. For a given size of the cylinder, the design goal is to obtain an antenna system such that the discrimination ratio is large and the field in the direction $\phi = 0^o$ is small.

In addition to the above, the antenna system should have a bandwidth of 5 MHz with a VSWR equal to 1:3. This implies that at 30 MHz the required bandwidth would be about ± 8 percent and about ± 1.25 percent at 200 MHz.

To obtain the desired patterns we use the technique of arraying a number of elementary radiators around the cylinder. Axial slot radiators are considered for the reason that they need a minimum amount of protrusion from the cylinder surface.

1.5 Outline of the Report

Radiation patterns produced by arrays of 2, 3 and 4 axial slots on a perfectly conducting circular cylinder of infinite length are numerically computed and discussed in Chapter II. Both uniform and nonuniform spacing between the slot elements are considered. Variations of the patterns as functions of frequency are studied in detail. The feasibility of obtaining the desired patterns for the given size of the cylinder are also discussed.

Chapter III mainly discusses the results of an experimental study at 3 GHz to obtain an improved design for a slot element on a reduced-height waveguide cavity. Special attention has been devoted to reduce the waveguide height as much as possible. This has been done because the waveguide height ultimately determines the amount of protrusion of the antenna system from the cylinder surface. The results indicate that it is possible to fabricate a radiating slot 0.125" wide in a waveguide cavity whose height is 0.125": The impedance and radiating properties of the waveguide slot elements are also discussed. Finally some limited results are given for the patterns produced by 2-element slot arrays. Experimental results confirming the findings of theoretical studies of 3 and 4-slot arrays were discussed in [1]. For this reason we have not conducted any experimental study of 3 and 4-slot array patterns.

Chapter IV gives our conclusions.

II. THEORETICAL AND NUMERICAL ANALYSIS

In this chapter we discuss the results obtained by numerical computation of theoretical expressions for the far field patterns produced by various arrays of axial slots located on the surface of a conducting circular cylinder of infinite length. The far field pattern produced by an elementary axial slot radiator located on an infinite circular cylinder is discussed thoroughly in the literatore [3 - 5]. Theoretical expressions for the far field patterns produced by an array of axial slots located on the surface of an infinite cylinder have been developed in our earlier report [1]. Before discussing the detailed results, we quote in the next section the appropriate theoretical expressions for the far field patterns.

2.1 Theoretical Pattern Expressions

Consider a narrow axial slot of length L located on the surface of the cylinder at $r = a$, $\theta = \pi/2$ and $\phi = \phi_\ell$ as shown in Fig. 2. Let the excitation of the slot be represented by

$$\vec{E}_s = \frac{V_\ell e^{i\psi_\ell}}{2a\Delta\phi} \cos(\pi z/L)\, \hat{e}_\phi \quad , \tag{1}$$

where,

V_ℓ, ψ_ℓ are the amplitude and phase of excitation of the slot located at $\phi = \phi_\ell$,

$2\Delta\phi$ is the width of the slot,

$e^{-i\omega t}$ is the assumed time dependence,

$\hat{e}_\phi$ is the unit vector in the ϕ-direction.

It can be shown [1] that in the absence of mutual coupling, the x-y plane of an electric field pattern of N number of sufficiently narrow axial slots, located at $\phi = \phi_\ell$, $\theta = \pi/2$ and on the surface of an infinite cylinder of radius a oriented along the z-axis may be written as

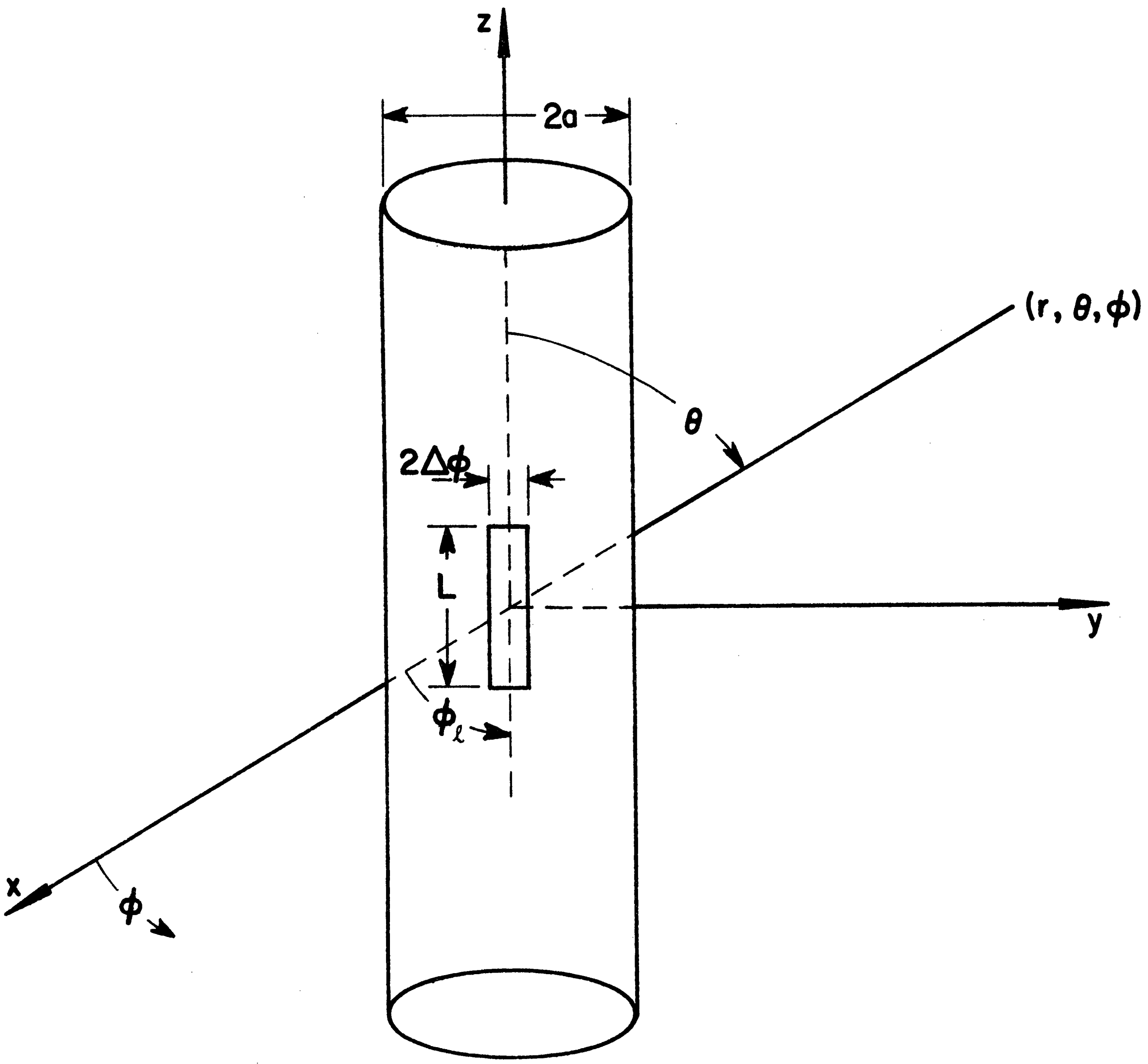


FIG. 2: Axial slot on a circular cylinder and the coordinate system used.

$$P_N(\phi) = \sum_{\ell=1}^{N} V_\ell e^{i\psi_\ell} \sum_{n=0}^{\infty} \epsilon_n \frac{(-i)^n \cos n(\phi - \phi_\ell)}{H_n^{(1)'}(ka)} , \tag{2}$$

where

$k = \omega/c$ is the propagation constant in free space,

$H_n^{(1)}$ represents the Hankel function of the first kind and order n,

the prime indicates differentiation with respect to the argument,

$$\epsilon_n = 1 \text{ for } n = 0$$
$$= 2 \text{ for } n \neq 0.$$

Note that the electric field whose pattern is given by Eq. (2) is polarized in the ϕ-direction. In the x-y plane there will be no other component of the electric field.

The array pattern expression given by Eq. (2) is in the form of a double series, one of them being infinite. It is quite difficult to obtain the required array excitation coefficients V_ℓ, ψ_ℓ for a given beam direction from the series expression given by Eq. (2). However, for small ka which is of interest in the present case, a simpler approach may be used to obtain the required phasing of the radiating elements. For this purpose we use the concepts of the equivalent section of a circular array of isotropic sources [1, 2]. It can be shown that the required phasing of the elements to obtain a beam in the ϕ_0 direction is given by:

$$\psi_\ell = ka \cos(\phi_0 - \phi_\ell) . \tag{3}$$

The amplitude excitation coefficients V_ℓ are obtained from the considerations of the pattern shapes in directions away from the main beam. The complete pattern is obtained numerically by using the first ten terms of the infinite series in Eq. (2) which are sufficient for the convergence of the series for the values of ka used. The validity of the approximation given by Eq. (3) has been confirmed both by numerical and experimental results, as reported in [1].

In order to obtain the desirable patterns within the range of frequencies of interest and for the given size of the cylinder, it appears that the physical extent of the array should be confined approximately to one quarter of the cylinder circumference. From this consideration it seems that the maximum number of slots that can be used for the array may be 3 or 4. For a larger number of slots the mutual coupling effects would become appreciable and the analysis of the array pattern would be very complicated.

2.2 Single Slot Radiation Patterns

In this section we discuss the far field patterns produced by an axial slot located at $\phi_1 = 0$ and on the surface of a conducting cylinder of radius a. Figures 3(a) - 3(c) show the x-y plane pattearns for three selected values of ka which correspond to the normalized radius ka of the cylinder of diameter 2 m at 30 MHz, 60 MHz and 200 MHz respectively. It should be noted from Fig. 3(a) that toward the lower end of the frequency band, the pattern becomes approximately isotropic over most of the range of ϕ. Between 60 MHz - 200 MHz, the pattern stays almost isotropic in the forward half-space, i.e., $-\pi/2 \leq \phi \leq \pi/2$.

2.3 Patterns of Arrays of Two Slots

Figure 4(a) shows the pattern of a pair of axial slots located at $\phi_1 = 0$ and $\phi_2 = \pi/2$ and excited uniformly, i.e., $V_1 = V_2 = 1.0$, $\psi_1 = \psi_2 = 0^o$ so that the beam maximum occurs at $\phi_0 = \pi/4$. Note that the field in the direction of the maximum ($\phi = \pi/4$) is about 8 dB longer than the field in the image direction $\phi = -\pi/4$ and that the field in the downward direction $\phi = 0$ is about 2 dB less than the maximum value. If the radiation in the upper half-space is not harmful then the 2-slot array may be found useful if the beam maximum is pointed in the horizontal direction, $\phi_0 = \pi/2$. Under this condition it can be seen from Fig. 4(a) that the field in the $\phi = \pi/4$ and $-\pi/4$ directions are approximately -8 dB and -20 dB respectively, so that the field discrimination between the fields in these two directions is 12 dB. If the desired direction is near the horizon then the field in the downward direction ($\phi = 0$ is found to be about 6 dB less than that in the former. It appears that a 2-slot arrangement may find some application in the lower end of the frequency band. The excitation of

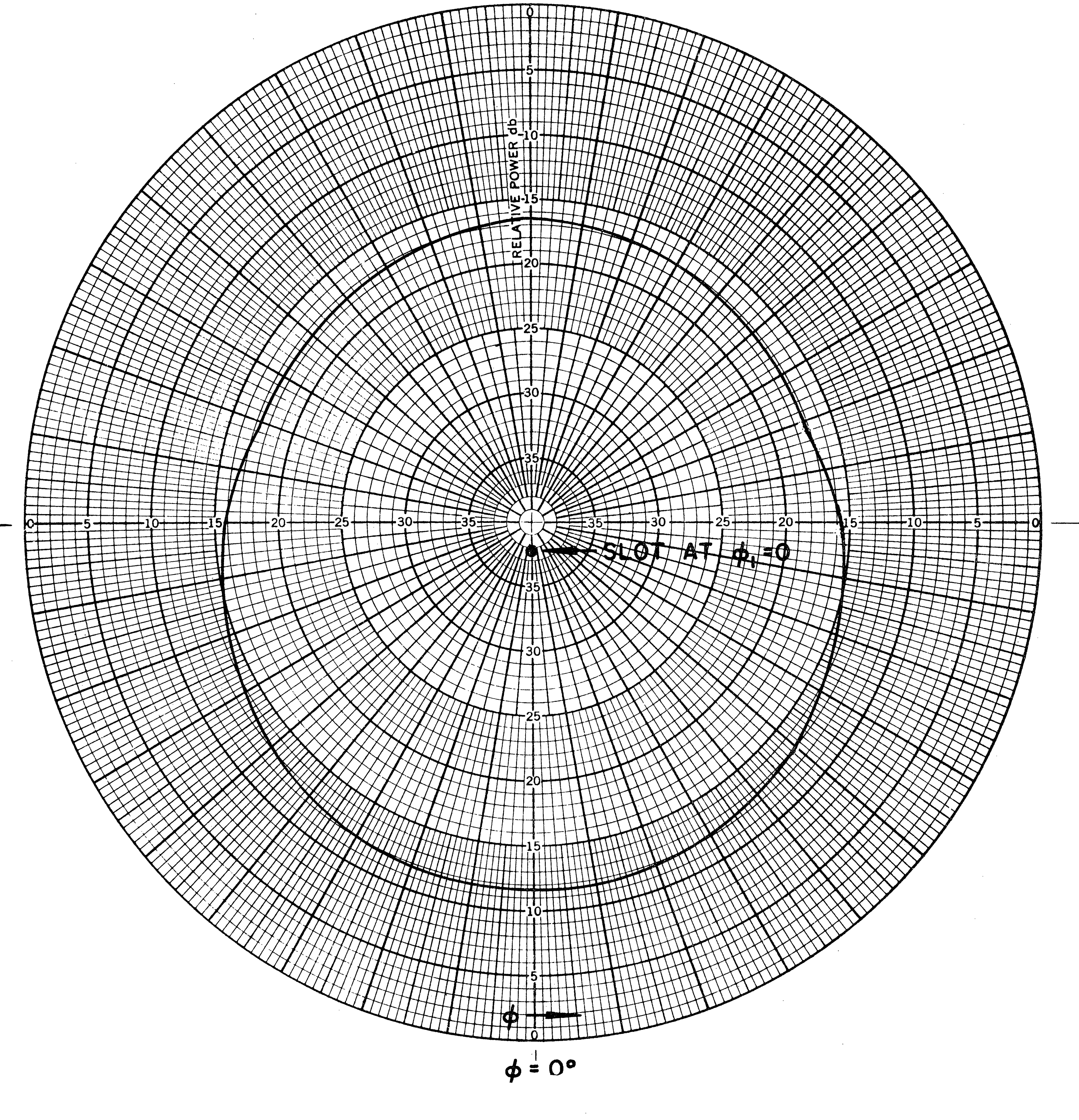


FIG. 3(a): Theoretical pattern of an axial slot on the surface of a conducting cylinder, ka = 0.2π.

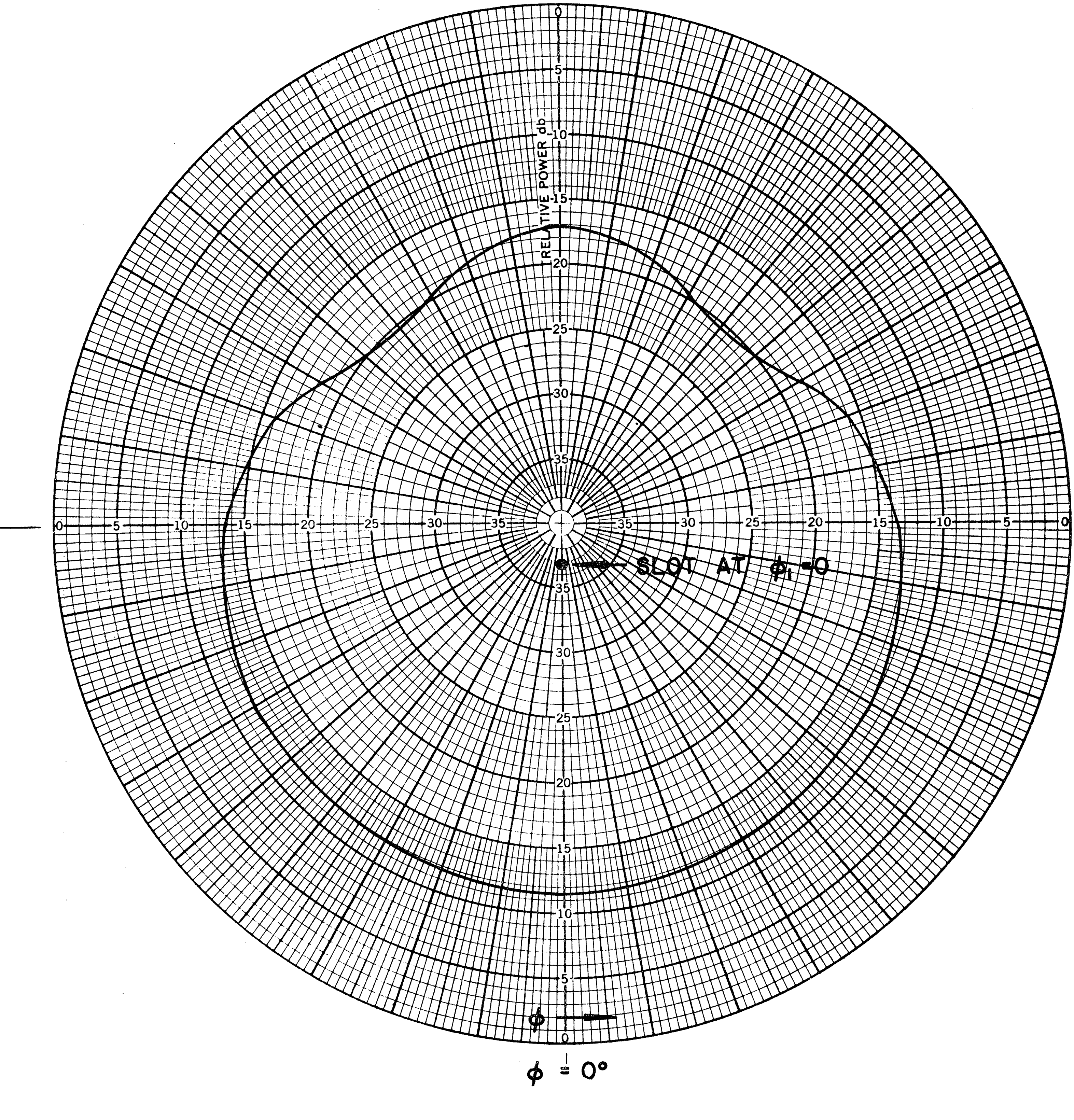


FIG. 3(b): Theoretical pattern of an axial slot on the surface of a conducting cylinder, ka = 0.4π.

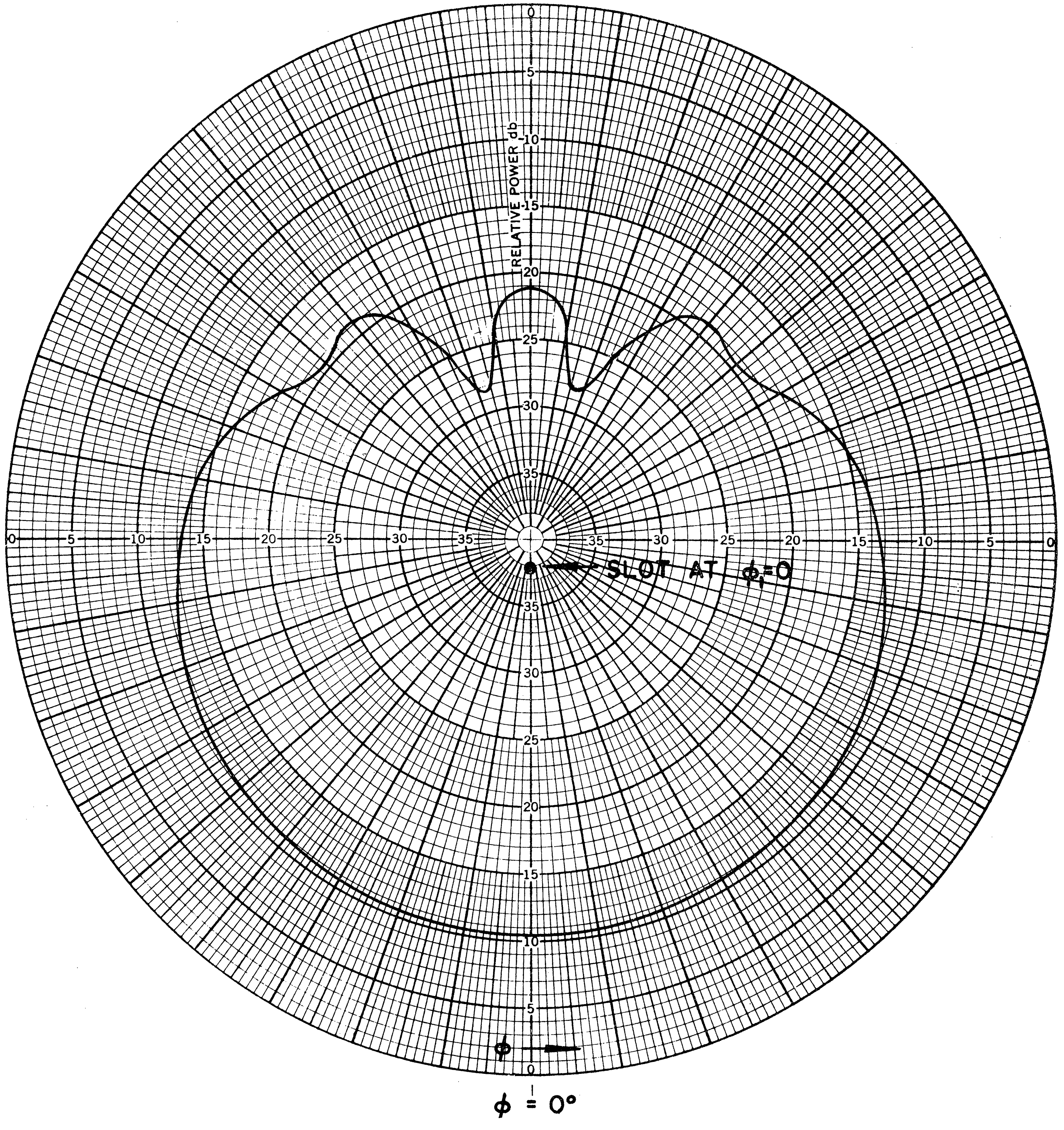


FIG. 3(c): Theoretical pattern of an axial slot on the surface of a conducting cylinder, ka = 1.33π.

such a system would also be quite simple. Figures 4(b) - 4(d) show the patterns of the 2-slot array, considered in Fig. 4(a), for three more selected values of ka. It is found that with increase of frequency, large lobes appear in the pattern indicating that such arrays may not be useful in the upper end of the frequency band.

Because of its possible application at the low frequency end, the 2-slot array has been studied further to ascertain whether it is possible to further reduce the field in the downward direction. Fig. 5(a) shows the pattern produced by a 2-slot array designed to have a large field in the region $\phi \sim \pi/2$ but small field in the region $\phi \sim 0$. As shown in Fig. 5(a) the field in the region $\pi/4 \lesssim \phi \lesssim \pi/2$ is about -6 dB and that in the region $\phi \sim 0$ is about -16 dB. The field in the region $\phi \sim -\pi/4$ is about -15 dB. This in this particular case, the discrimination between the fields in the desired and image directions is about 9 dB and the field in the downward direction is about 10 dB less than that in the desired direction. In this sense for ka = 0.4π, the pattern shown in Fig. 5(a) is better than that given in Fig. 4(a). However, as mentioned before, this pattern may not be satisfactory at higher frequencies. This can be seen from Fig. 5(b) which shows the pattern of the same antenna considered in Fig. 5(a) but for ka = 1.4π. This indicates that at higher frequencies more than two slots may be used with advantage.

2.4 Patterns of Arrays of Three Slots

Figures 6(a) - 6(c) show the patterns as functions of ka produced by a 3-slot array designed to produce maximum field in the direction of the horizon. Observe that for this design there exist large fields in the upper half space. It is found that the patterns may be acceptable at the upper end of the frequency band. However, in the lower end of the frequency band, it can be seen from Fig. 6(a) that the antenna produces a large field in the downward direction and almost no discrimination between the fields in the desired and image directions. In order to establish a low frequency limit for the acceptability of a 3-slot array, its patterns have been calculated for a number of ka's within the range $0.4\pi \leq ka \leq 1.4\pi$. The array has been designed to produce a maximum field in the direction $\phi = \pi/2$. The results are shown in Table 1.

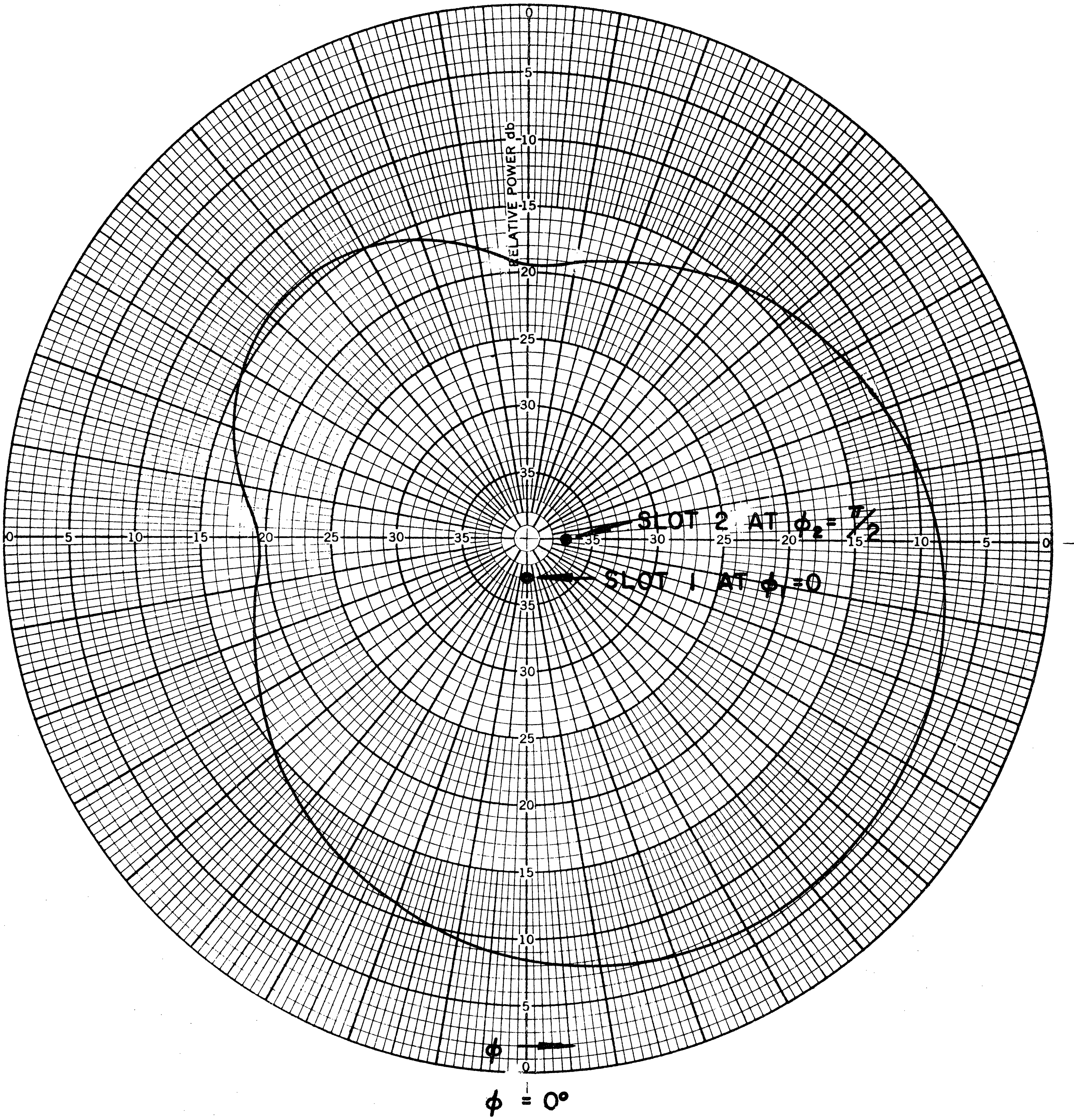


FIG. 4(a): Theoretical pattern of a pair of axial slots on the surface of a conducting cylinder, ka = 0.4π, $V_1 = V_2 = 1.0$, $\psi_1 = \psi_2 = 0^{\circ}$.

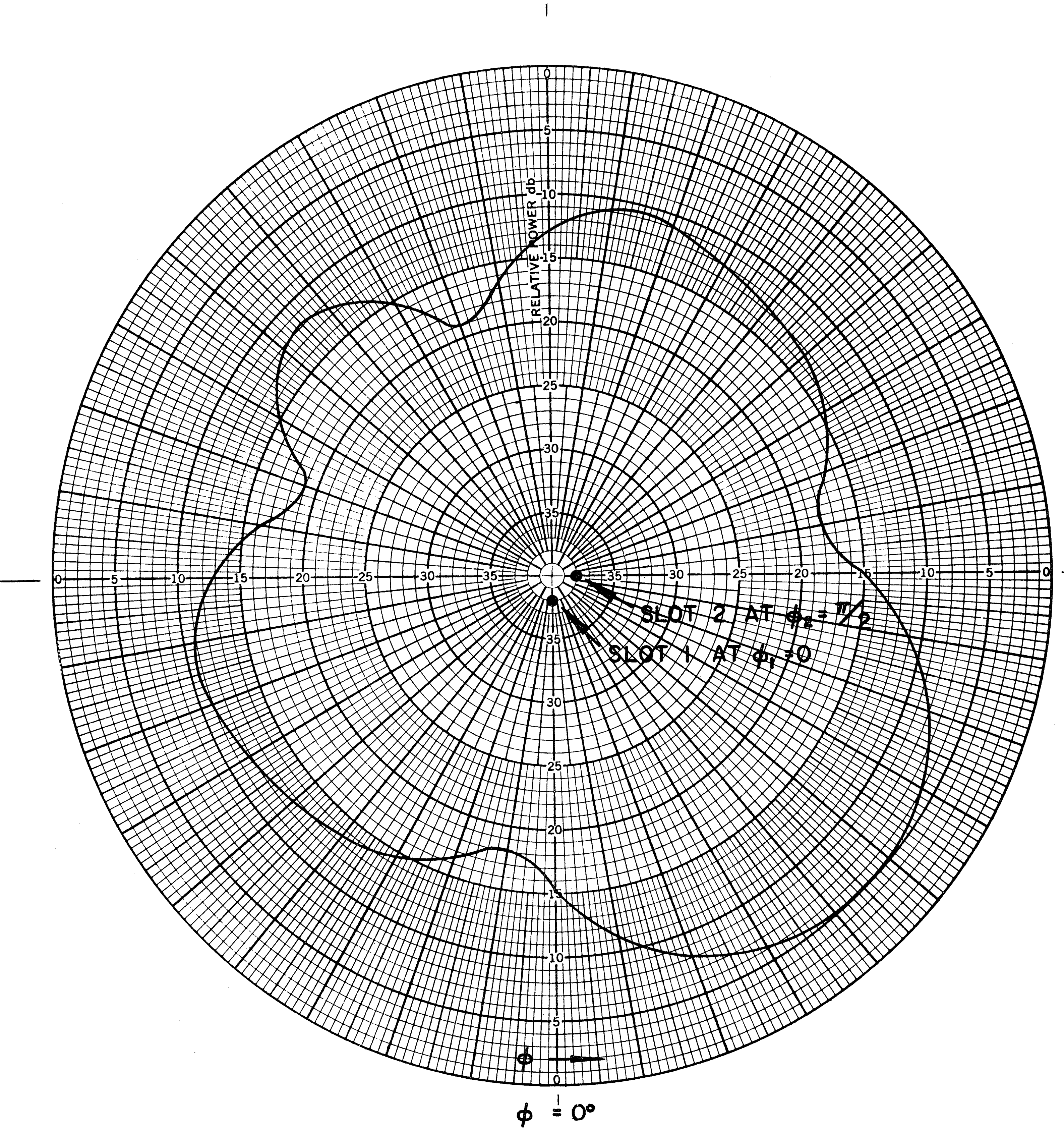


FIG. 4(b): Theoretical pattern for a pair of axial slots on the surface of a conducting cylinder, $ka = 0.8\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = \psi_2 = 0^o$.

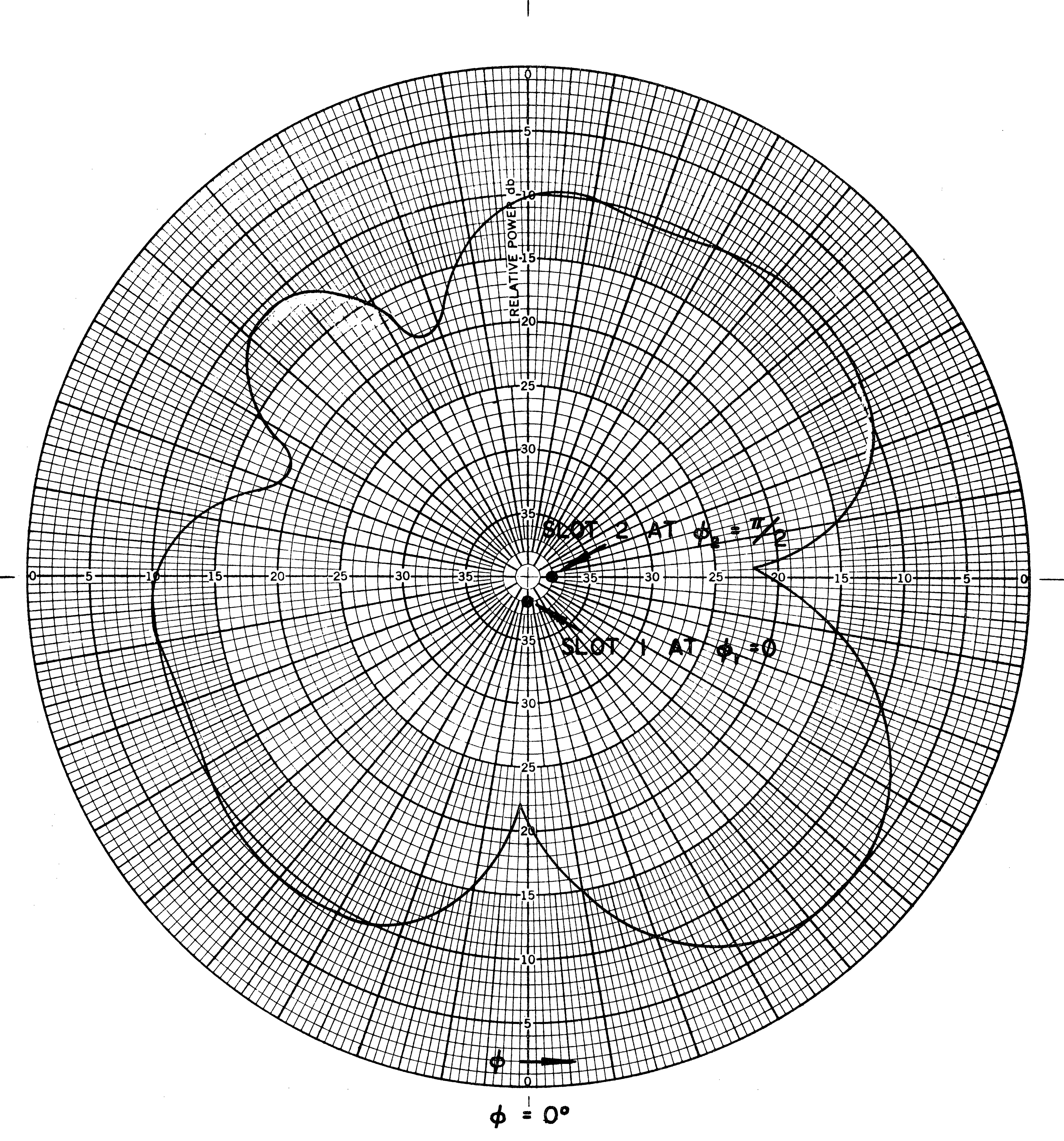


FIG. 4(c): Theoretical pattern of a pair of axial slots on the surface of a conducting cylinder, ka = 1.0π, $V_1 = V_2 = 1.0$, $\psi_1 = \psi_2 = 0^o$.

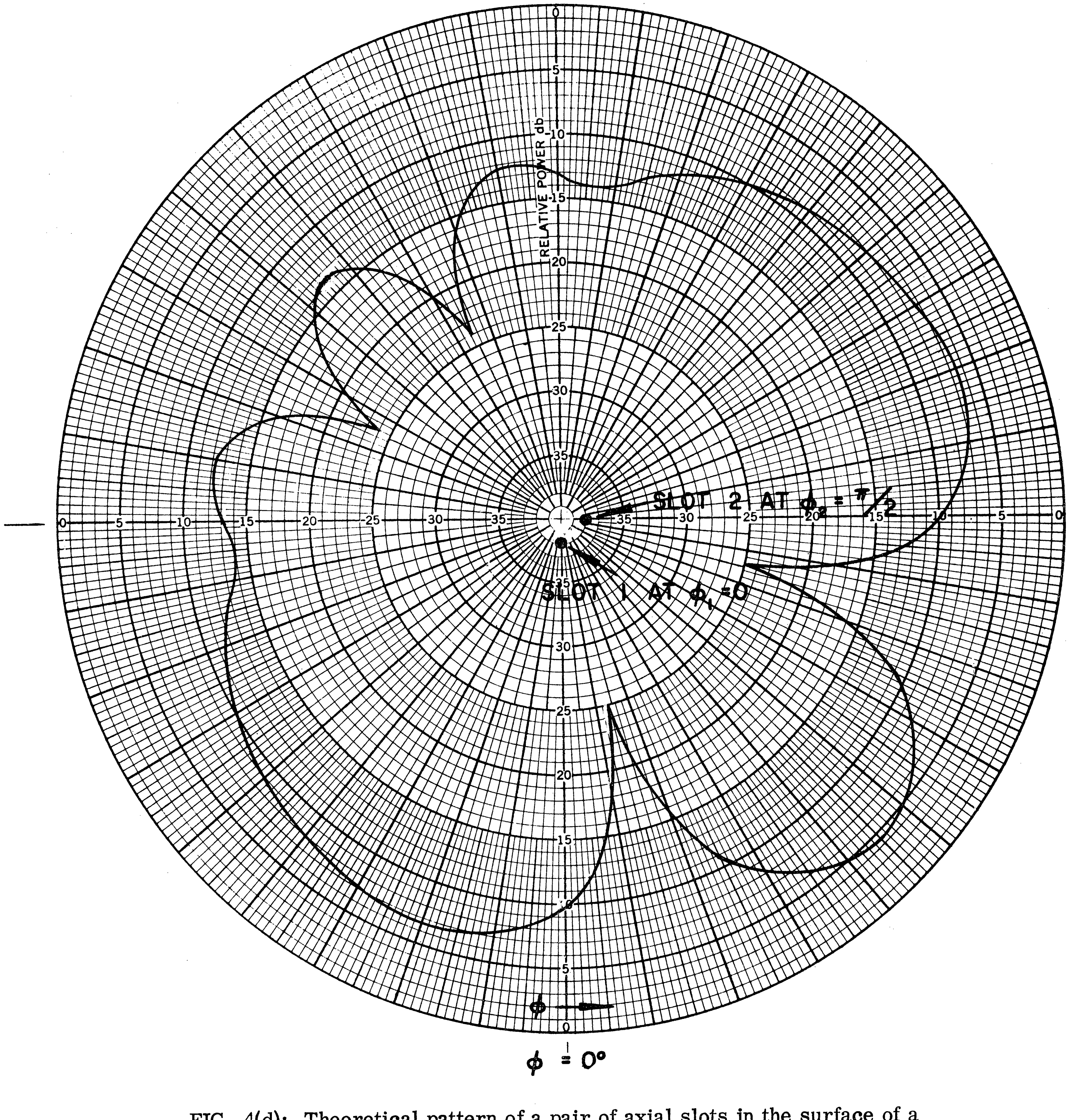
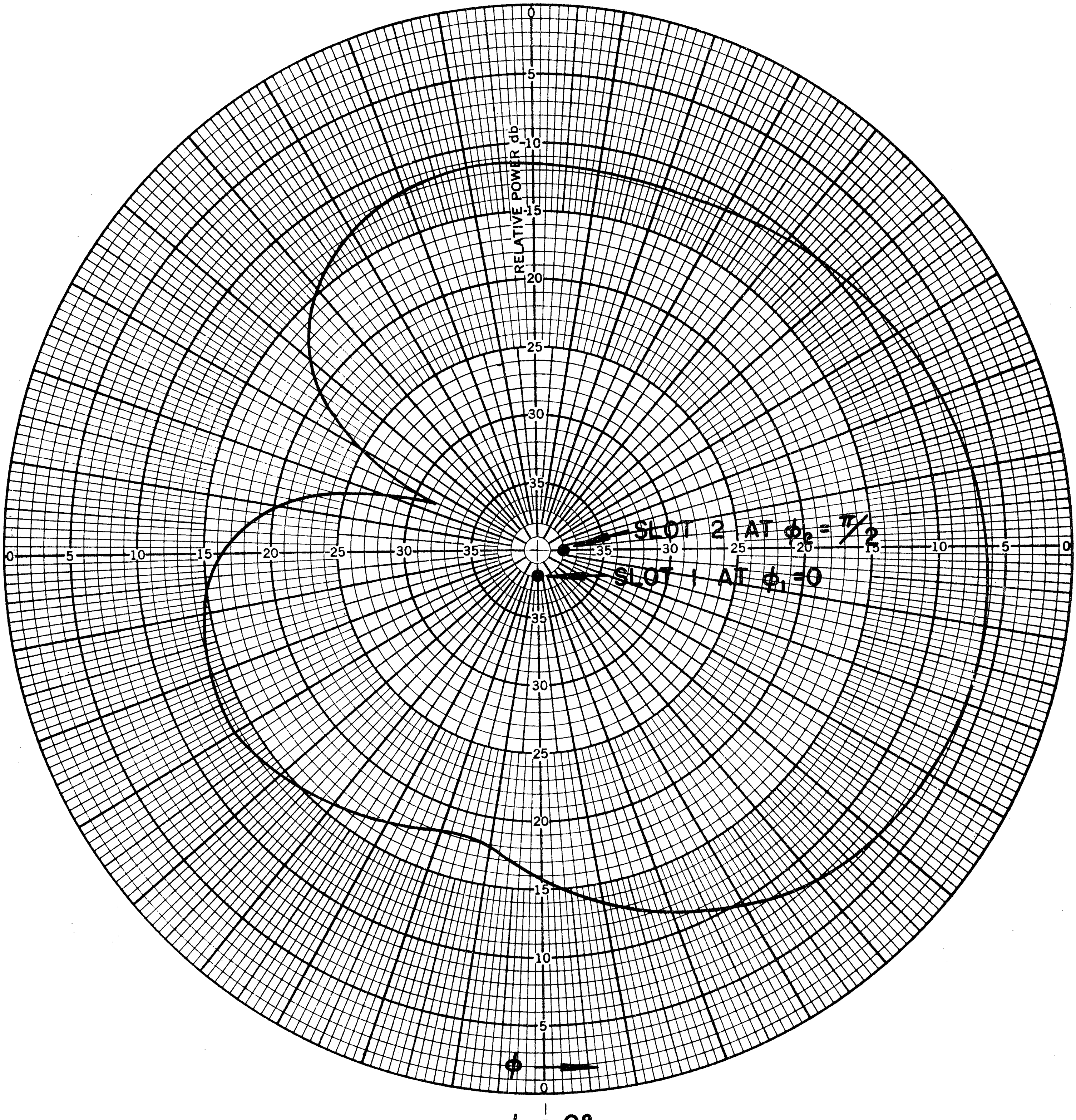


FIG. 4(d): Theoretical pattern of a pair of axial slots in the surface of a conducting cylinder, $ka = 1.4\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = \psi_2 = 0^o$.



$\phi = 0°$

FIG. 5(a): Theoretical pattern of a pair of axial slots on the surface of a conducting cylinder, $ka = 0.4\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka$.

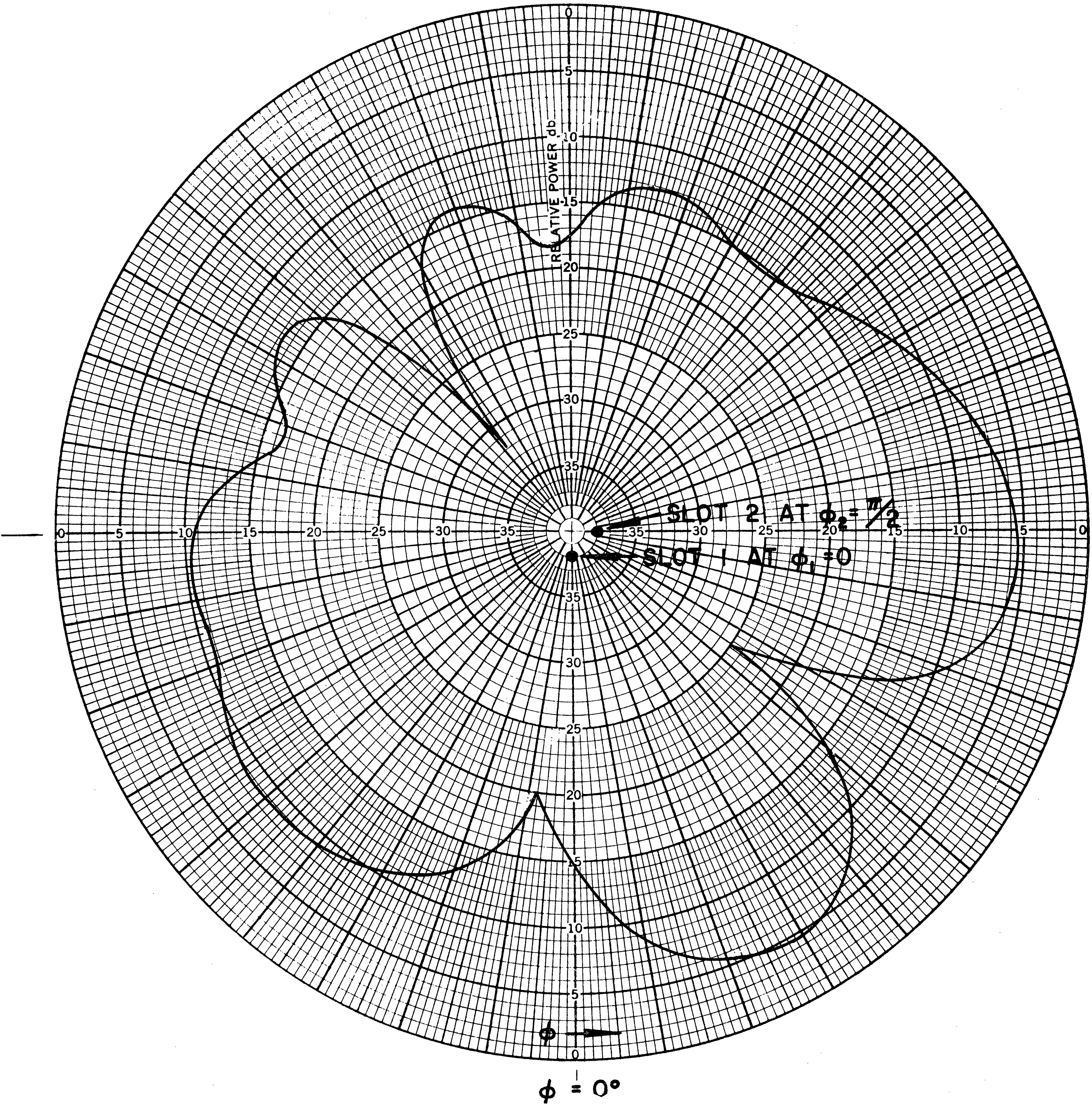


FIG. 5(b): Theoretical pattern of a pair of axial slots on the surface of a conducting cylinder, $ka = 1.4\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka$.

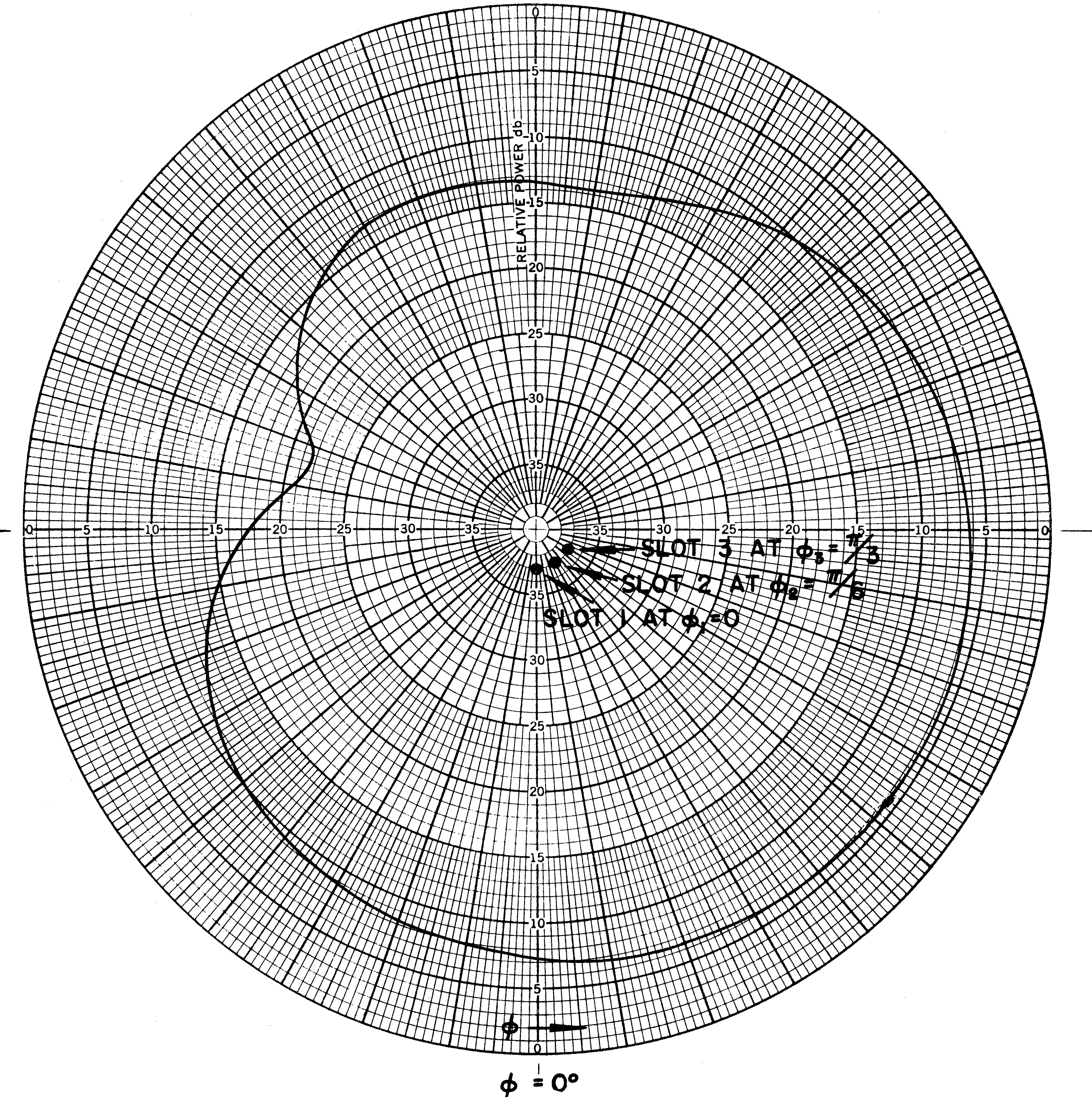


FIG. 6(a): Theoretical pattern of a 3-slot array on the surface of a conducting cylinder, $ka = 0.4\pi$, $V_1 = V_3 = 0.5$, $V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = \sqrt{3}/2\ ka$.

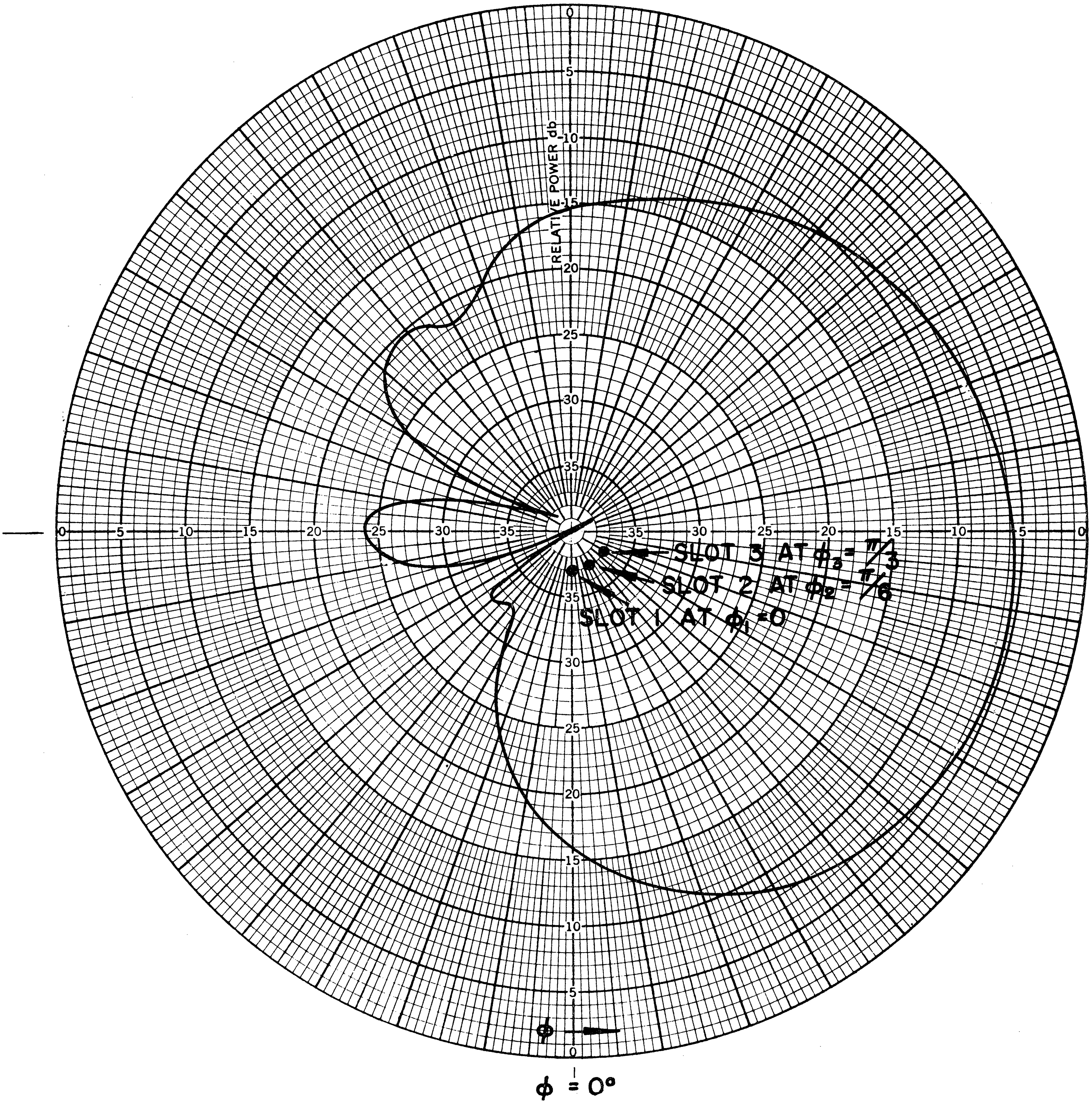


FIG. 6(b): Theoretical pattern of a 3-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_3 = 0.5$, $V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = \sqrt{3}/2\ ka$.

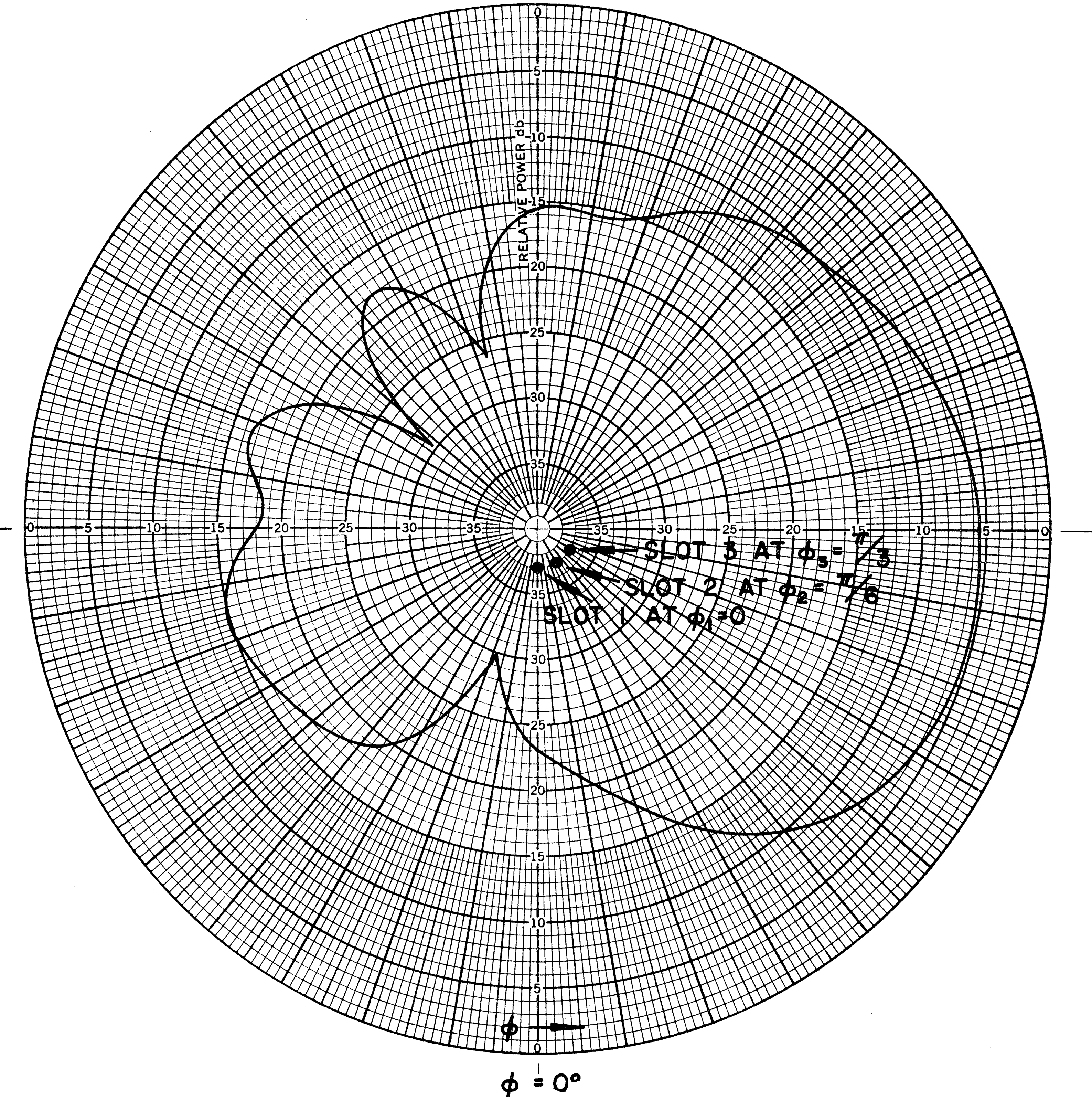


FIG. 6(c): Theoretical pattern of a 3-slot array on the surface of a conducting cylinder, $ka = 1.4\pi$, $V_1 = V_3 = 0.5$, $V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = \sqrt{3}/2\ ka$.

Table 1

Pattern characteristics of a 3-slot array designed to produce maximum field in the direction of the horizon.

ka	Field Discrimination $P_3(\pi/4) - P_3(-\pi/4)$ in dB	Downward Field Relative to the Maximum $P_3(0) - P_3(\pi/2)$ in dB
0.4π	3.99	-0.99
0.5π	6.17	-1.90
0.6π	9.76	-2.57
0.7π	13.17	-3.97
0.8π	15.57	-6.14
0.9π	19.16	-8.27
1.0π	25.45	-10.33
1.4π	8.83	-17.62

Thus if we set arbitrarily that the desired values of the discrimination between the fields in the $\pi/4$ and $-\pi/4$ directions be at least 10 dB and the field in the downward direction be about 5 dB below the maximum, then results shown in Table 1 indicate that the 3-slot array may produce an acceptable pattern at the lowest frequency such that $ka \simeq 0.75\pi$. The design parameters of the 3-slot array are: $V_1 = V_3 = 0.5$, $V_2 = 1.0$; $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = \sqrt{3}/2\ ka$; $\phi_1 = 0$, $\phi_2 = \pi/6$, $\phi_3 = \pi/3$.

Other 3-slot arrangements having different excitations were studied in [6], but the results shown above have been found to be most acceptable. In our previous final report [1] we considered 3-slot arrays where the array elements were located a at $\phi_1 = 0$, $\pi/4$ and $\pi/2$ and phased such that the beam maximum occurs in the direction $\phi = \pi/4$. Although this pattern has some desirable characteristics it produces a strong field in the downward direction. Here we consider a slight variation of the 3-slot array considered in [1]. Figure 7 shows the pattern produced by a uniformly spaced 3-slot array designed to produce a beam maximum in the direction $\phi = \pi/2$. Figure 7 results indicate that it may not be advantageous to use uniform amplitude excitation. Figure 8 shows the pattern of a uniformly spaced 3-slot array excited with nonuniform amplitude excitation and phased such that the beam maximum is in the direction $\phi = \pi/2$. This pattern is interesting in the sense that the field

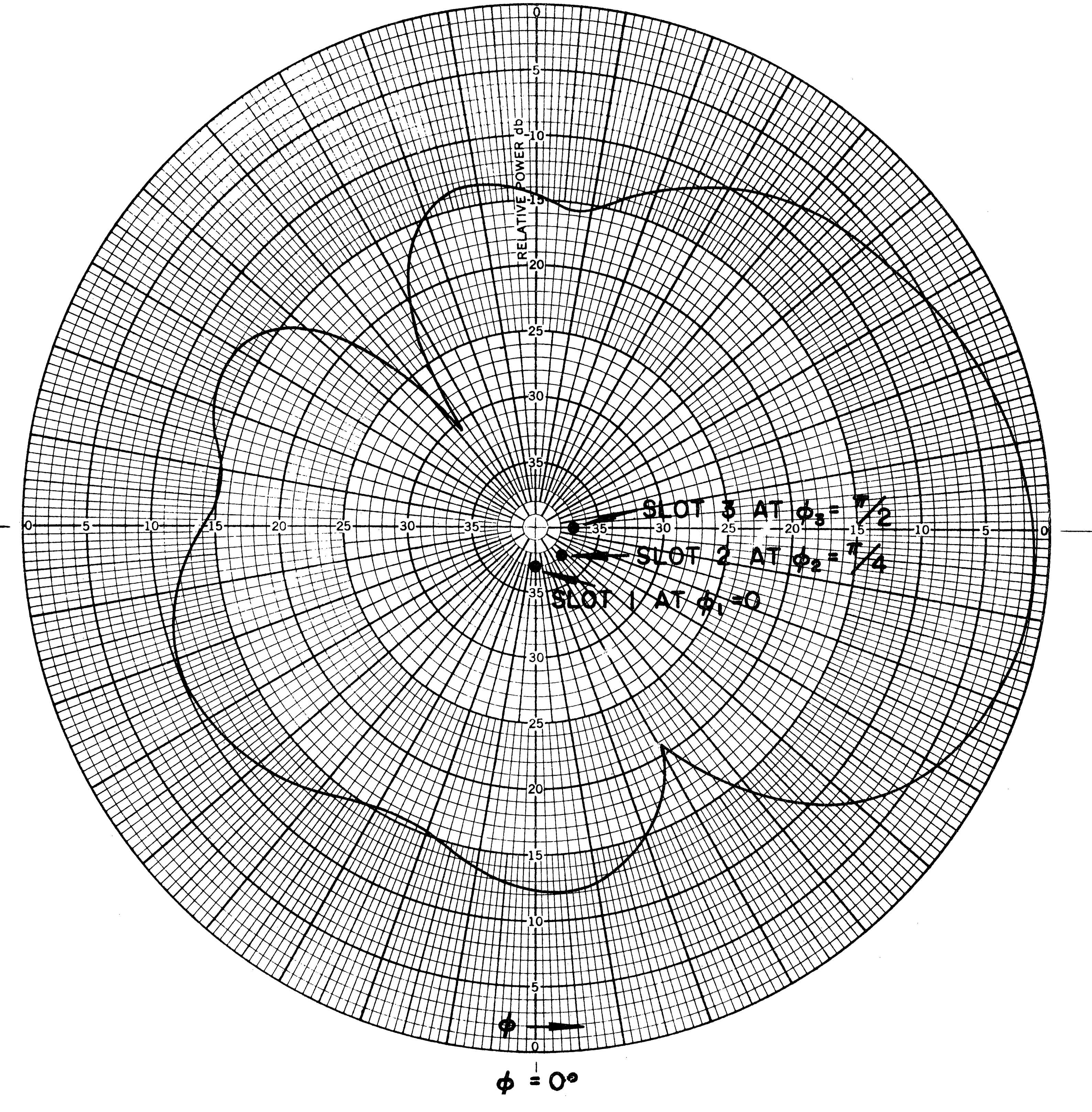


FIG. 7: Theoretical pattern of a 3-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_2 = V_3 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka/\sqrt{2}$, $\psi_3 = ka$.

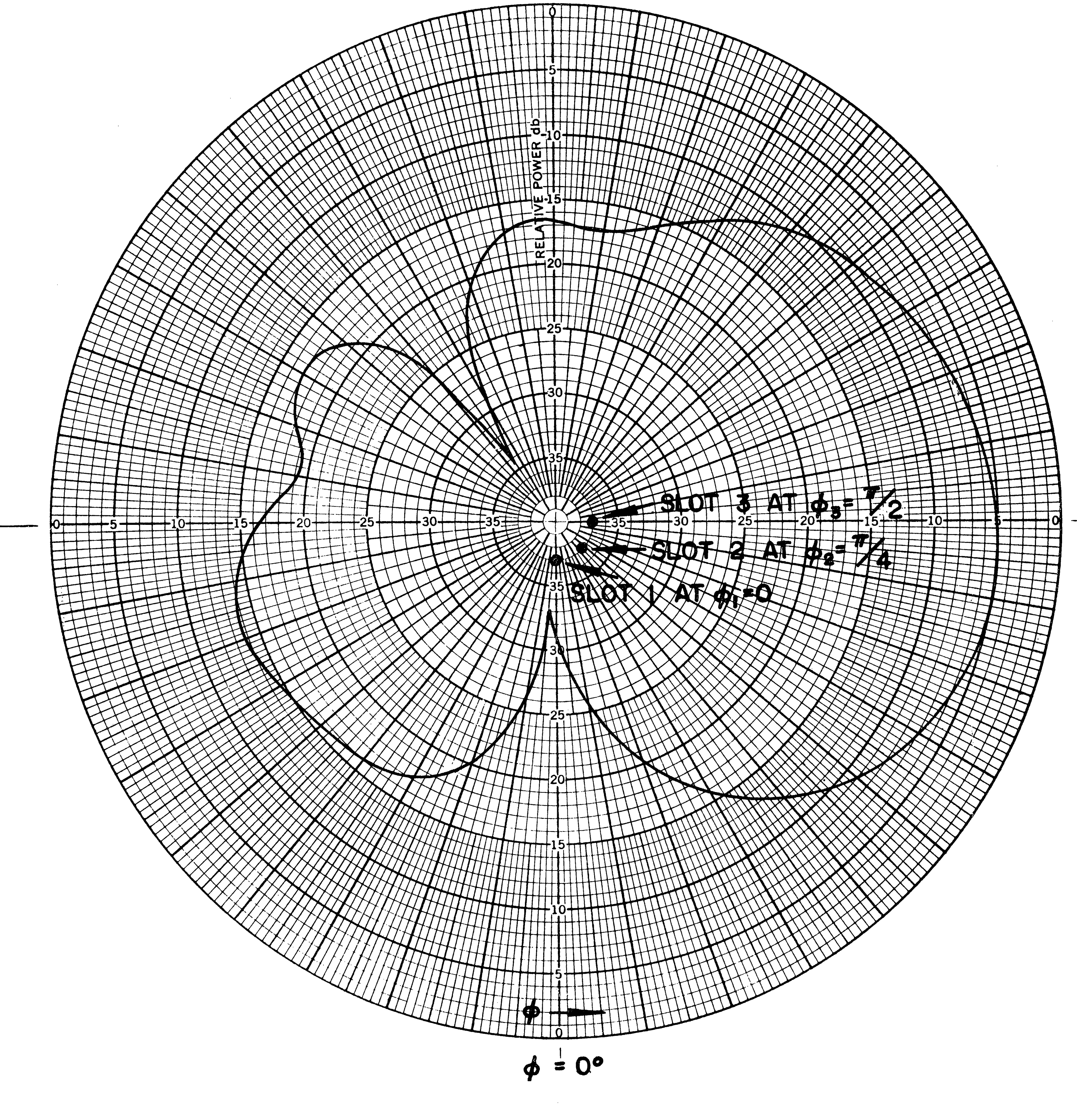


FIG. 8: Theoretical pattern of a 3-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_3 = 0.5$, $V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = ka/\sqrt{2}$, $\psi_3 = ka$.

discrimination between $\pm 70^{\circ}$ is about 10 dB and the downward field is about 27 dB less than that in the direction $\phi \sim 70^{\circ}$. However, compared to the 3-slot array considered in Table 1, the performance of this larger 3-slot array is poor over other regions of space.

2.5 Patterns of Arrays of Four Slots

Theoretical and experimental investigations of patterns of 4-slot arrays have been discussed in [1]. Among the array configurations considered in [1], of particular interest are the patterns of a uniformly spaced 4-slot array designed to have a beam maximum in the direction $\phi_0 = \pi/4$. These patterns are reproduced in Figs. 9(a) - 9(c). Note that, as expected, the pattern becomes quite broad in the low frequency end but at the high frequency end the patterns appear to be satisfactory although they have rather high field in the downward direction. This can be improved by physically rotating the positions of the slots by $\pi/4$ (i.e., $\phi_1 = \pi/4$, $\phi_2 = \pi/2$, $\phi_3 = 3\pi/4$, $\phi_4 = 0$ in Figs. 9(a) - 9(c)) so that the beam maximum appears in the direction of the horizon.

Figures 10(a) - 19(c) show the patterns of a nonuniformly spaced 4-slot array designed to produce a maximum in the direction $\phi_0 = \pi/2$. This array configuration has a fairly good pattern in the lower frequency range, but the patterns develop large lobes in the high frequency end.

Figures 11(a) - 11(c) show the patterns of a different nonuniformly spaced 4-sl 4-slot array designed to produce a beam maximum in the direction $\phi_0 = \pi/2$. As can be seen from Fig. 11, the patterns may be acceptable for the range of ka $0.4\pi \leq ka \lesssim 1.0\pi$; At ka $\simeq 1.4\pi$ the fields in the directions $\pm\pi/2$ are of the same order and hence may be undesirable.

The relevant pattern characteristics of the 4-slot arrays considered in Figs. 9 - 11 are summarized in Table 2.

It appears from the results discussed in this section that uniformly spaced arrays have better performance than the nonuniformly spaced arrays. The results also indicate that a single 4-slot array may not be useful over the entire band of

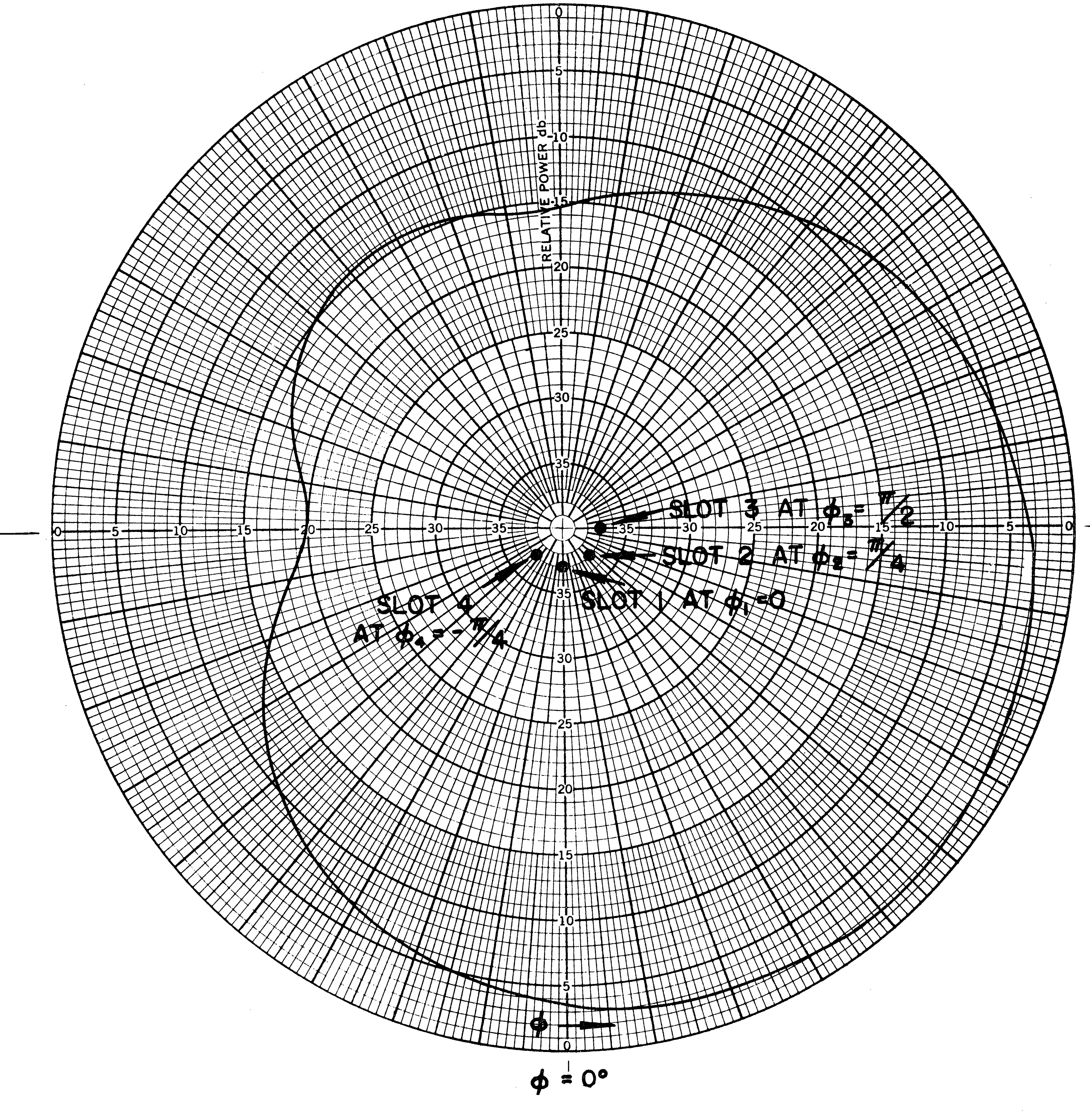


FIG. 9(a): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 0.4\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = \psi_3 = ka/\sqrt{2}$, $\psi_2 = ka$, $\psi_4 = 0$.

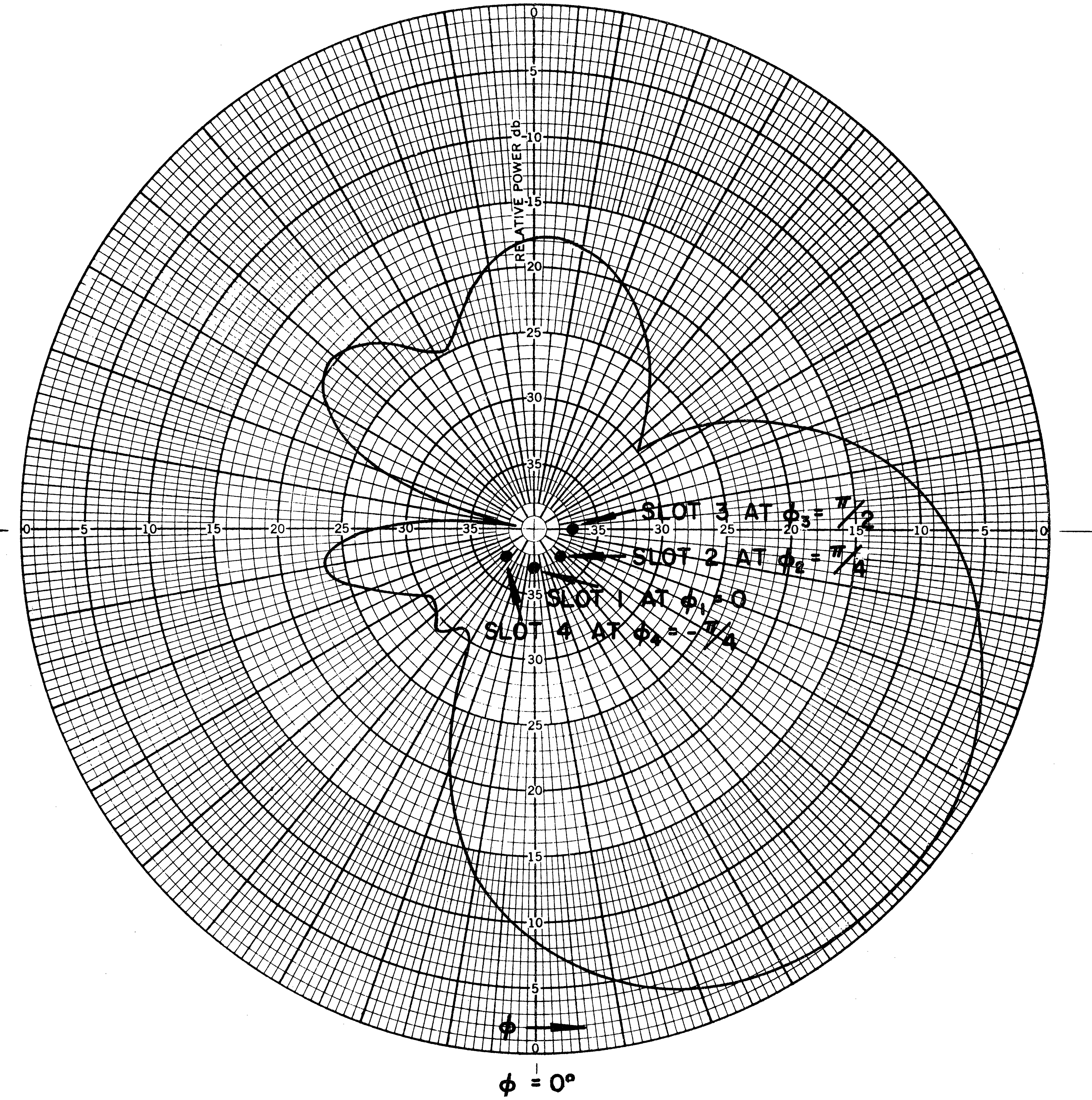


FIG. 9(b): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 0.8\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = \psi_3 = ka/\sqrt{2}$, $\psi_2 = ka$, $\psi_4 = 0$.

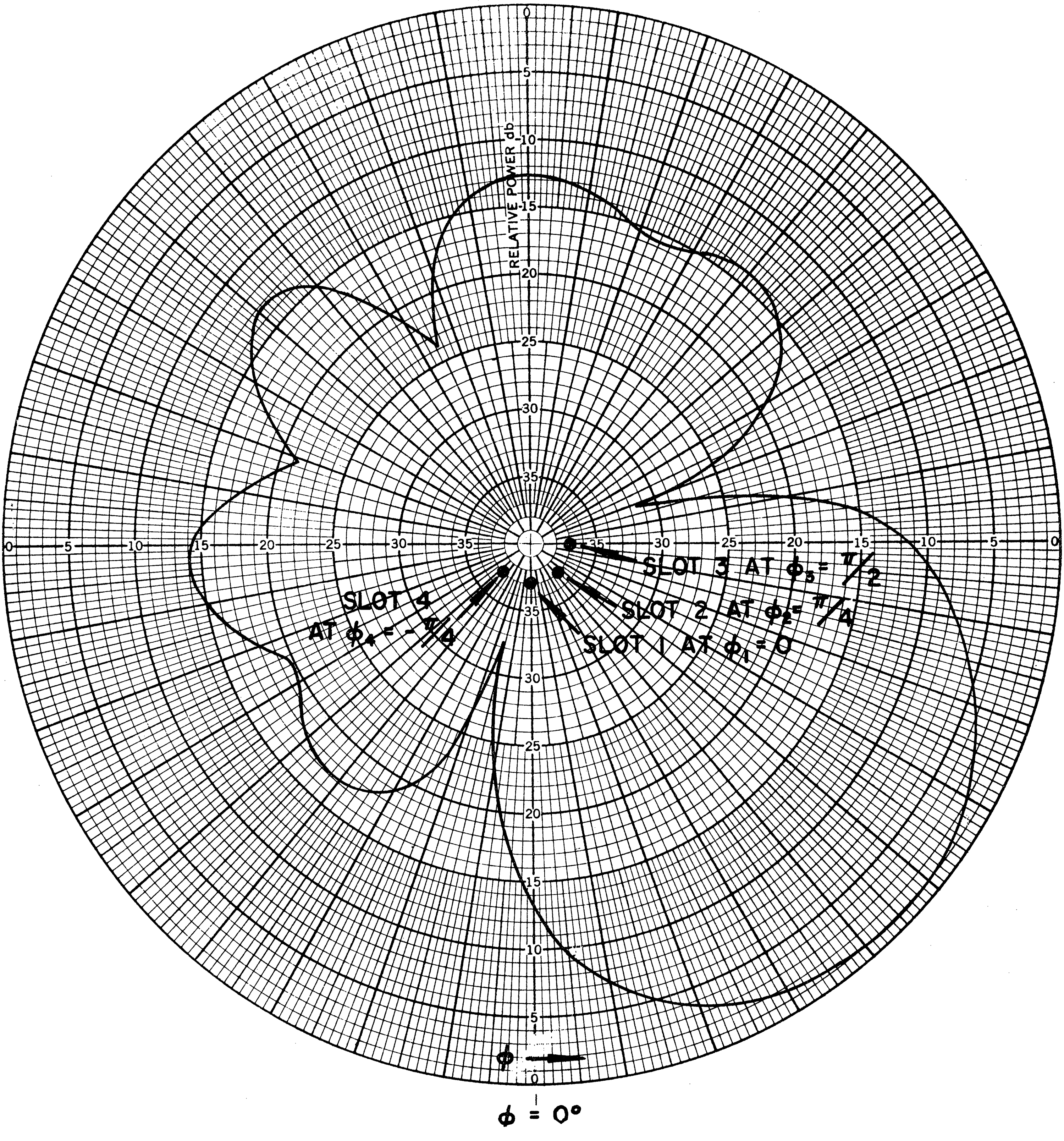


FIG. 9(c): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = \psi_3 = ka/\sqrt{2}$, $\psi_4 = 0$.

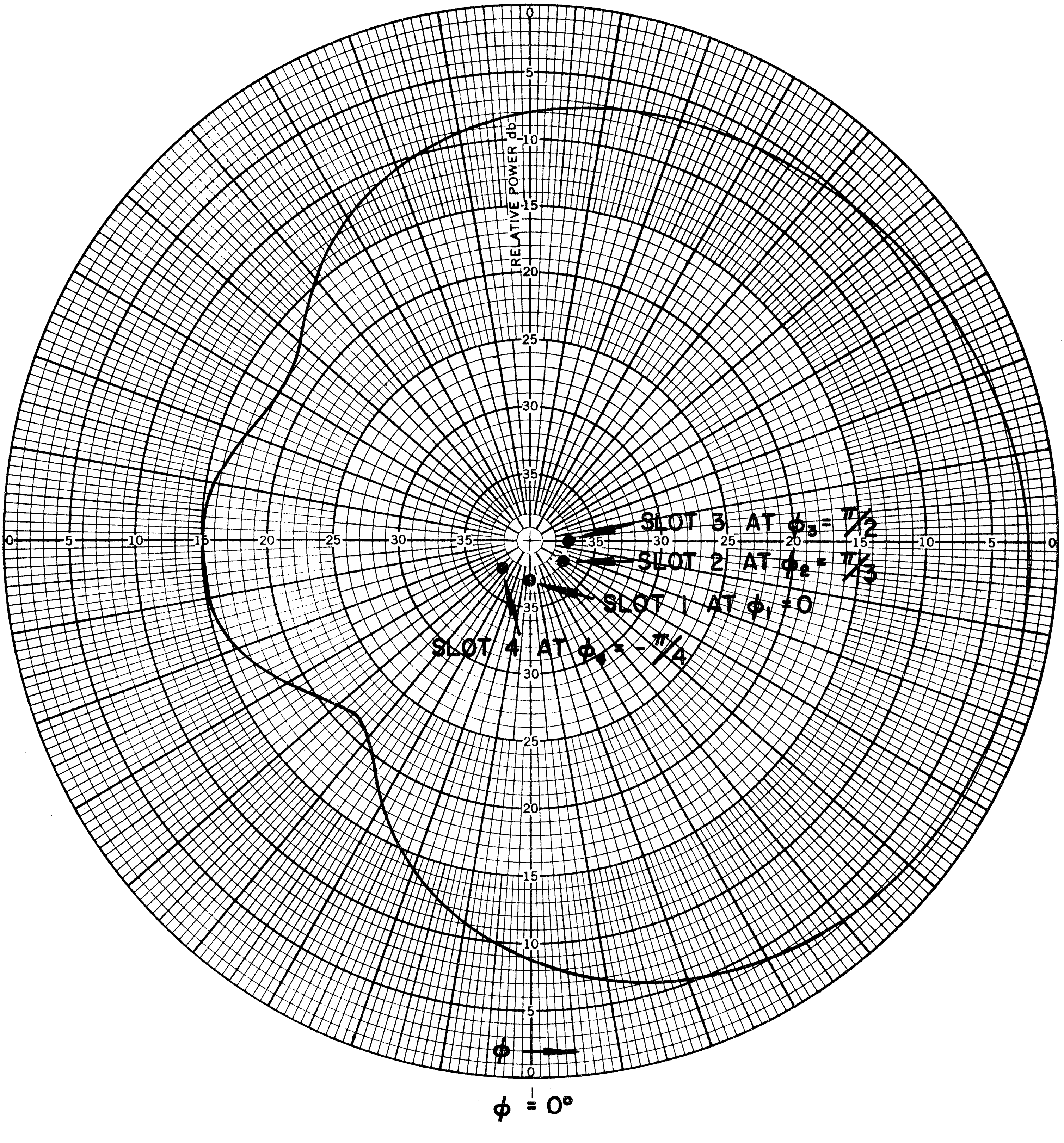


FIG. 10(a): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 0.4\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka\sin(\pi/3)$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

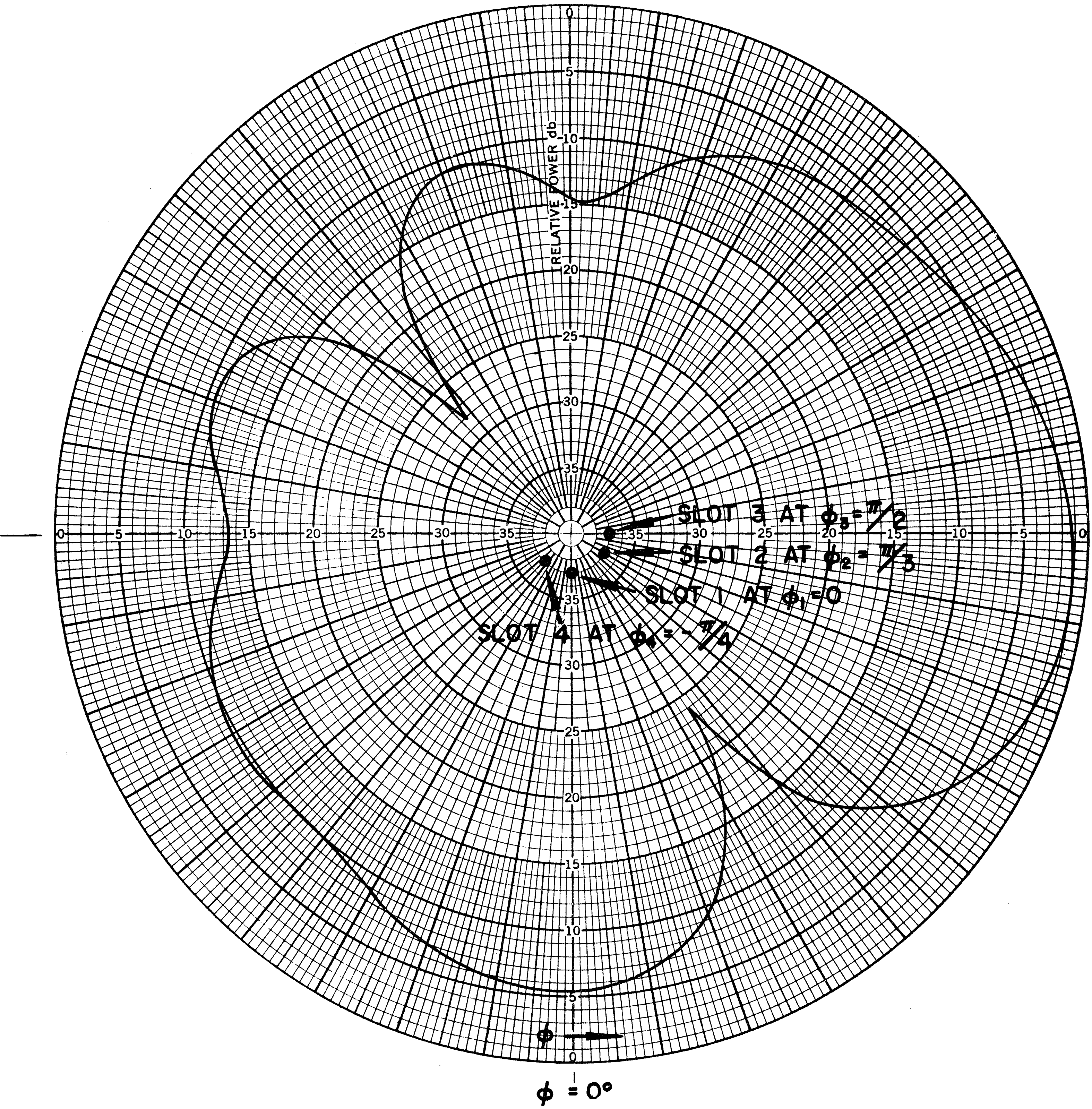


FIG. 10(b): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka \sin(\pi/3)$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

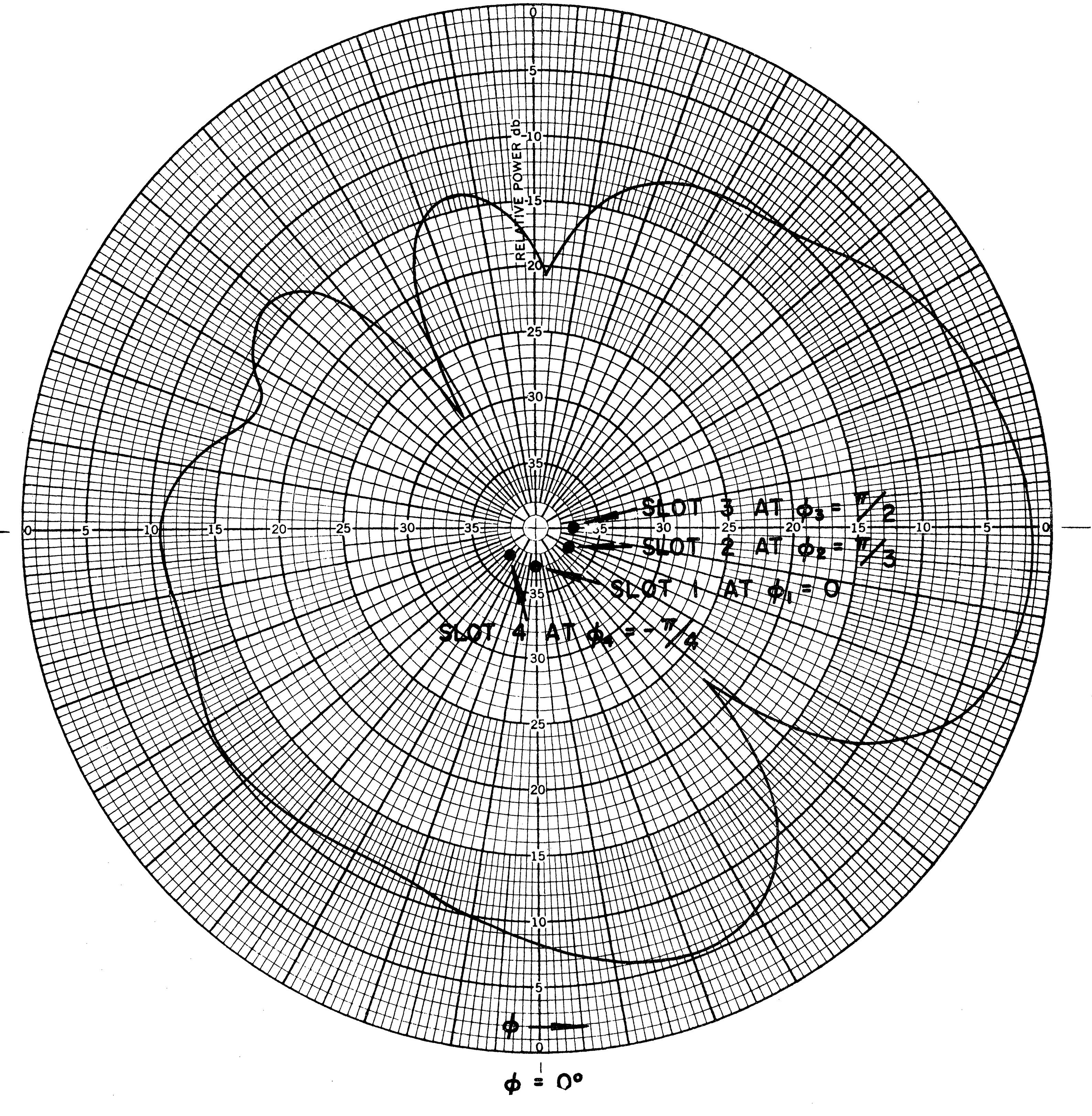


FIG. 10(c): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 1.4\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka\sin(\pi/3)$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

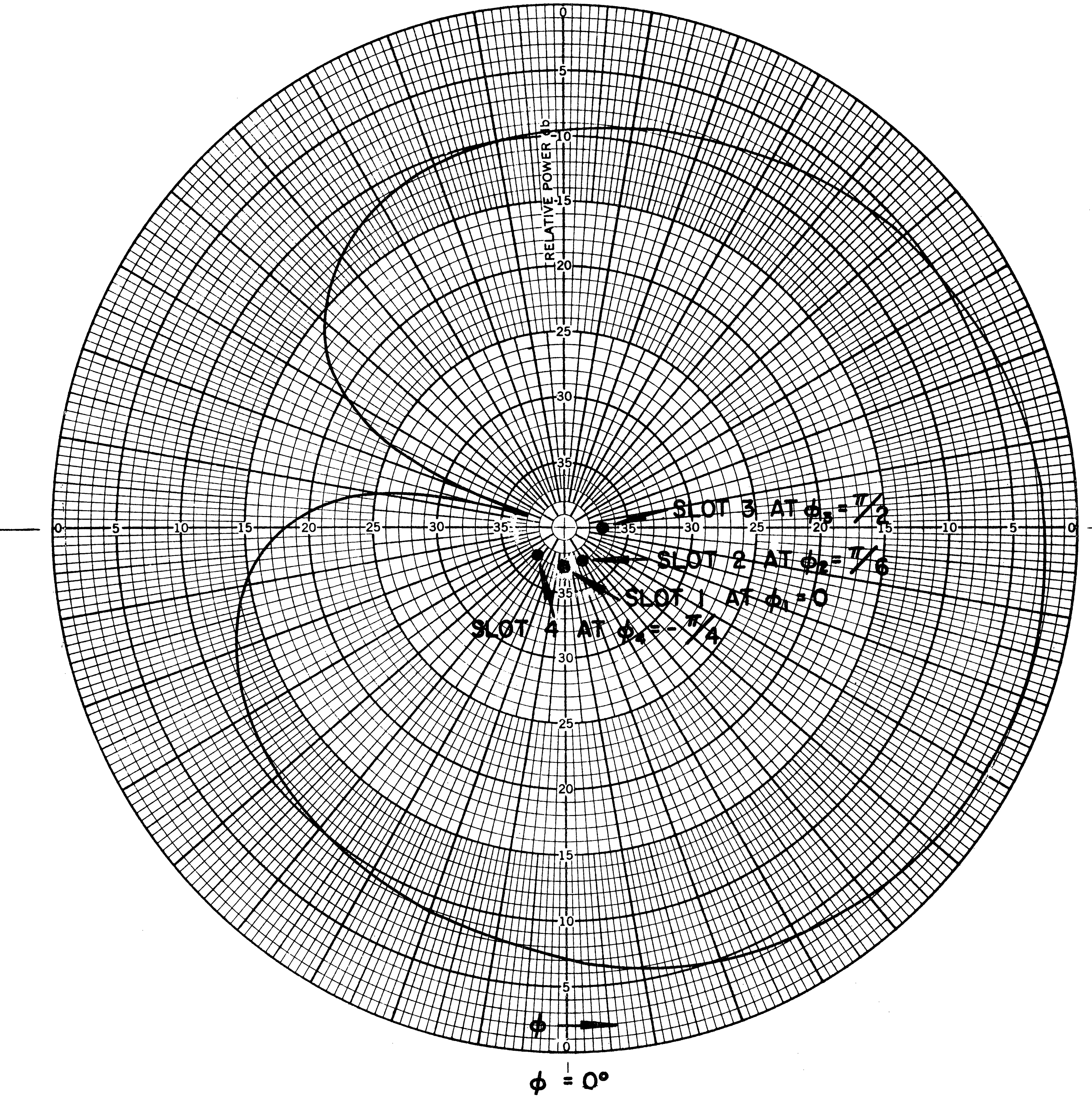


FIG. 11(a): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 0.4\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

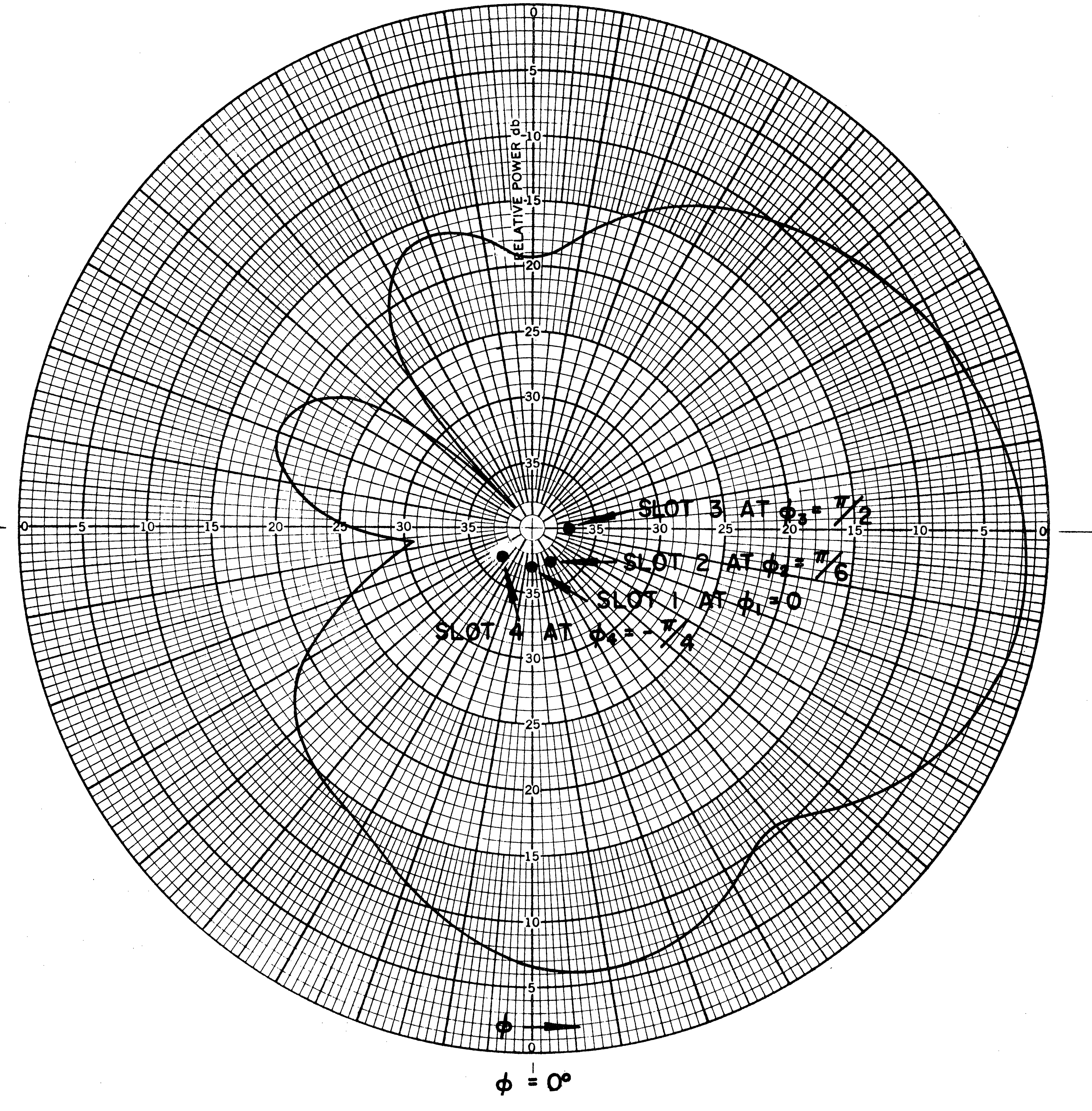


FIG. 11(b): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 1.0\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

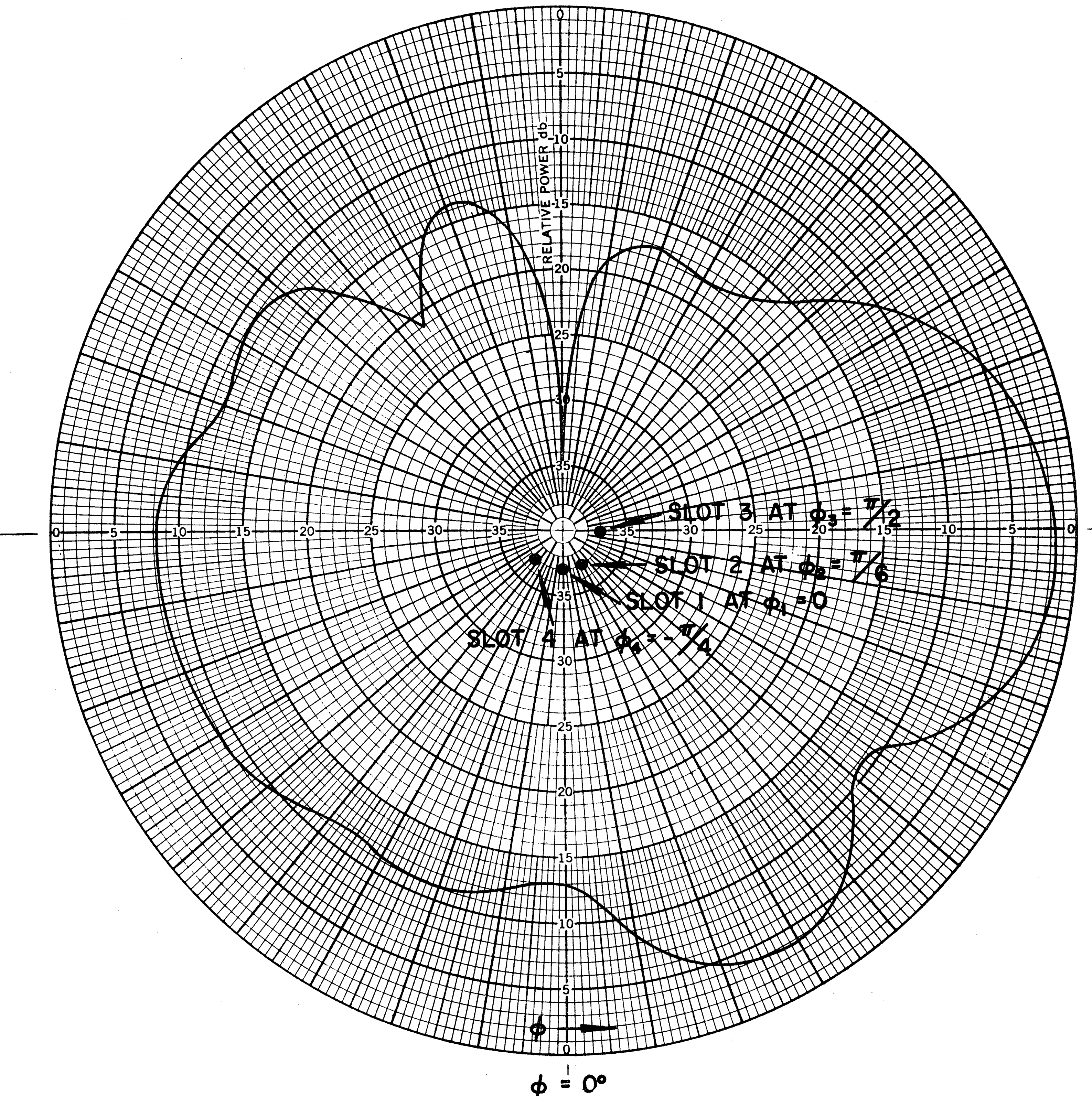


FIG. 11(c): Theoretical pattern of a 4-slot array on the surface of a conducting cylinder, $ka = 1.4\pi$, $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$, $\psi_1 = 0$, $\psi_2 = ka/2$, $\psi_3 = ka$, $\psi_4 = -ka/\sqrt{2}$.

Table 2

Pattern characteristics of 4-slot arrays designed to have beam maximum in the directions $\phi_0 = \pi/2$. $V_1 = V_2 = V_3 = 1.0$, $V_4 = 0.25$.

Array No.	Slot locations	ka	Field Discrimination $P_4(75^o) - P_4(-75^o)$ in dB	Downward Field Relative to Max (db)
1	$\phi_1 = \pi/4$, $\phi_2 = \pi/2$	0.4π	13.2	-7.3
	$\phi_3 = 3\pi/4$, $\phi_4 = 0$	0.8π	19.5	-27.5
		1.0π	14.2	-15.2
2	$\phi_1 = 0$, $\phi_2 = \pi/3$	0.4π	13.5	-6.46
	$\phi_3 = \pi/2$, $\phi_4 = -\pi/4$	1.0π	10.5	-4.19
		1.4π	10	-6.86
3	$\phi_1 = 0$, $\phi_2 = \pi/6$	0.4π	11.5	-4.47
	$\phi_2 = \pi/2$, $\phi_4 = -\pi/4$	1.0π	25.7	-4.74
		1.4π	6	-10.84

frequencies. A field discrimination of 10 dB between $\pm 75^o$ and a downward field of -5 dB may be achieved over the range $0.4\pi \leq ka \leq 1.4\pi$ with the help of the 4-slot array number 1.

III. EXPERIMENTAL STUDIES

In this chapter we discuss the results of an experimental investigation of radiating slots on the walls of reduced height waveguide sections. The objective of the experimental studies have been to ascertain the best way of employing resonant slots in the walls of reduced height waveguide sections. Measured radiation patterns produced by single and double slot arrangements are also discussed. The feasibility of arraying 3 and 4 slots on the cylinder surface and their patterns have been studied experimentally in [1] and hence have not been further studied during the present phase of the research. The experimental studies discussed below have been conducted at the nominal frequency of 3.0 GHz so that all the relevant physical dimensions correspond to a 100:1 scale model.

3.1 Slot on a Reduced-Height Waveguide Cavity

Previous work [1] has shown that a relatively small slot antenna can be obtained by employing a strip-line design. A strip-line S-band slot radiator was fabricated that has the overall dimensions 3.6" x 2.0" x 0.186", the slot itself having the dimensions 3.25" x 0.25". It has been found that for such a slot of length approximately equal to a wavelength, the input VSWR stays within 1:3 in the frequency range of 2.8 - 3.4 GHz. Further results about the strip-line design may be found in [1].

In an attempt to reduce the physical size of the slot radiator, it was fabricated in the broad wall of a conventional S-band waveguide section (3.00" x 1.50"). Initially the slot was excited by a cavity having outside dimensions approximately 3.0" x 3.0" x 1.5", as shown in Fig. 12. The cavity was excited by a voltage probe located on the center line of the cavity and approximately $\lambda_g/4$ from the short noted in Fig. 12. Initial efforts were devoted to reduce the width (w) of the slot. This work showed that for a given cavity and short position (s) the slot impedance as a function of frequency depends on the slot width (w). This also showed that it is feasible to fabricate a slot 0.125" wide in the cavity wall of Fig. 12. Figures 13(a) - 13(c) illustrate how the slot impedance varies with frequency for selected values of slot width when the waveguide height and the short position are held constant. The

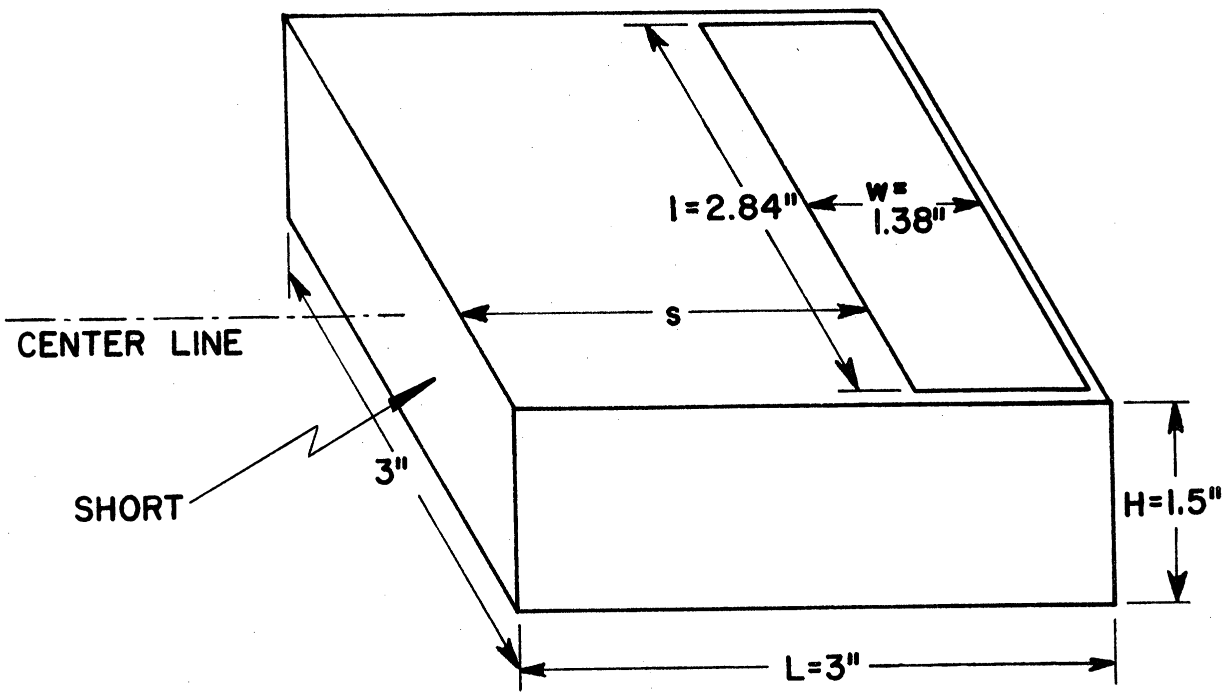


FIG. 12: Sketch of a radiating slot on the broad wall of a reduced-height waveguide cavity.

impedances are referred to a plane that coincides with the inside surface of the reduced-height waveguide to which the coaxial connector is attached. All the impedances are normalized to 50 ohms. Similar impedance plots with different waveguide heights and short positions are discussed in [6] and will not be repeated here. From these results it has been found that as the waveguide height increases from 0.125" to 0.5", the slot impedance as well as its bandwidth increases. At the same time it is found that the increase of waveguide height tends to rotate the frequency band in a clockwise direction on the Smith chart. The increase of the short position (s) tends to reduce the impedance as well as the bandwidth of the antenna. The outoome of this part of the investigation is that it has been found feasible to fabricate a slot element 0.125" wide in a waveguide cavity whose external height is 0.125". However, for such a slot it would be necessary to employ some external impedance

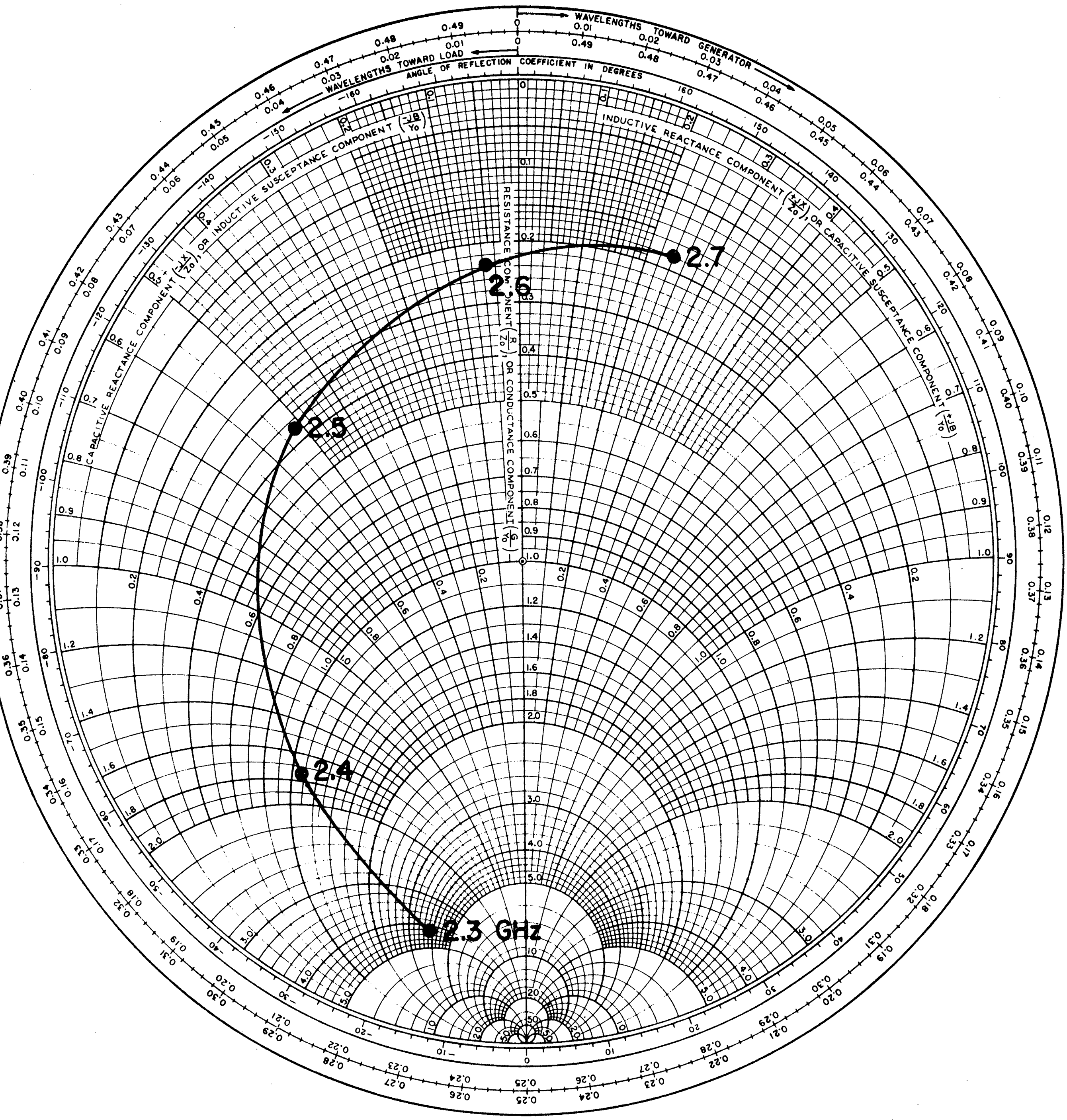


Fig. 13(a): Input impedance as a function of frequency for the reduced-height waveguide slot. w = 0.5", h = 0.125", s = 1.36".

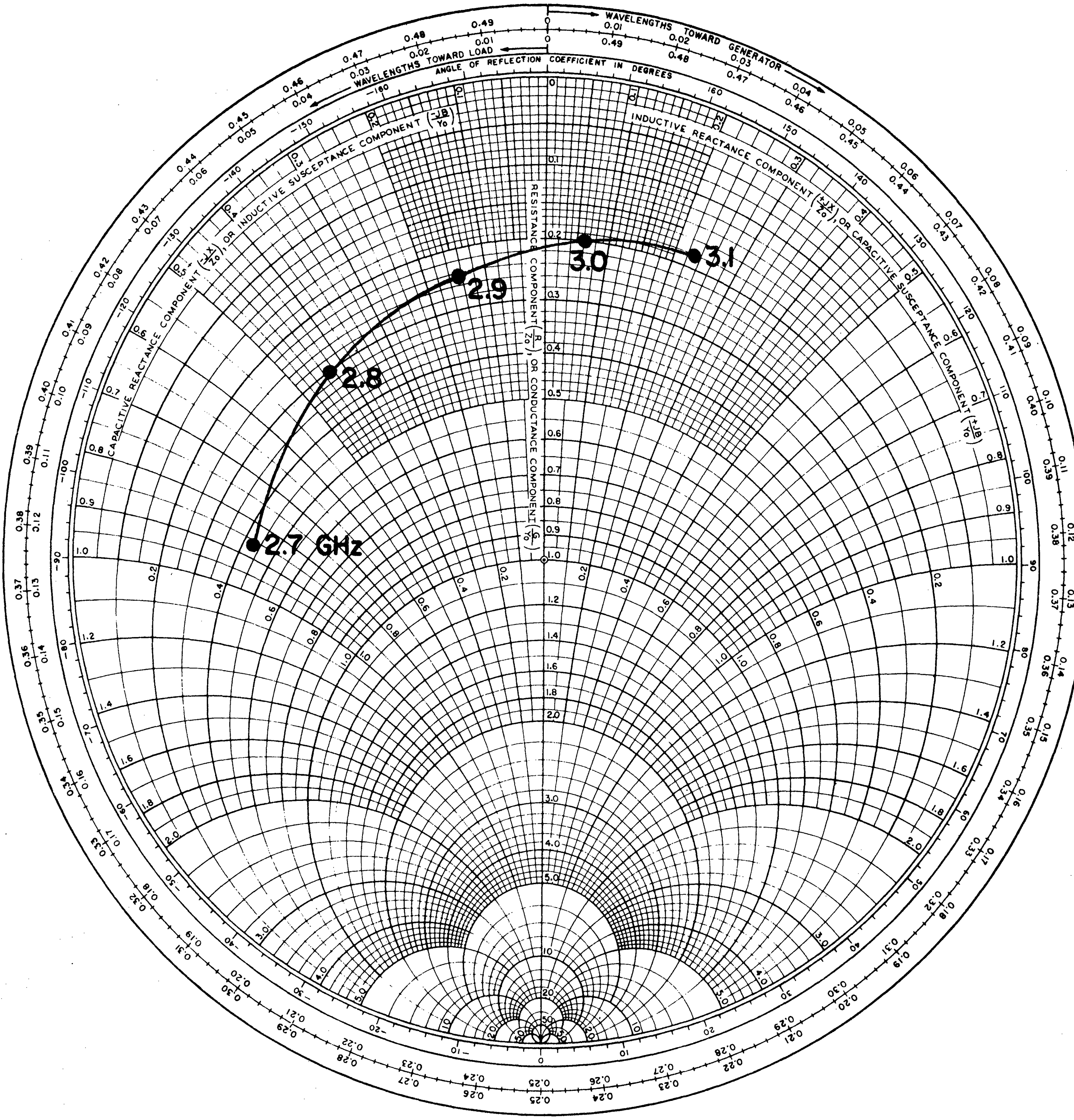


FIG. 13(b): Imput impedance as a function of frequency for the reduced-height waveguide slot. w = 1.0", h = 0.125", s = 1.36".

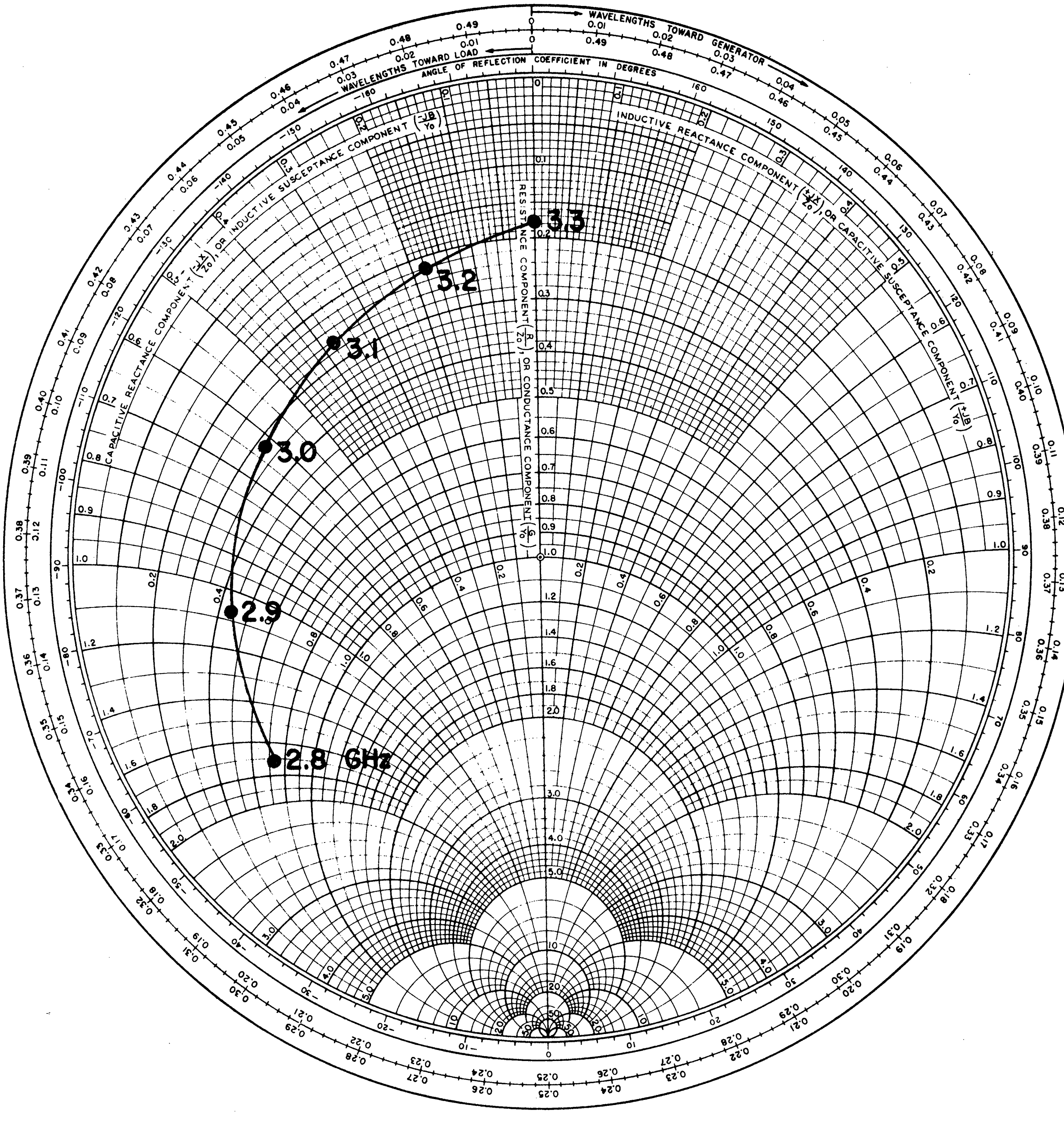


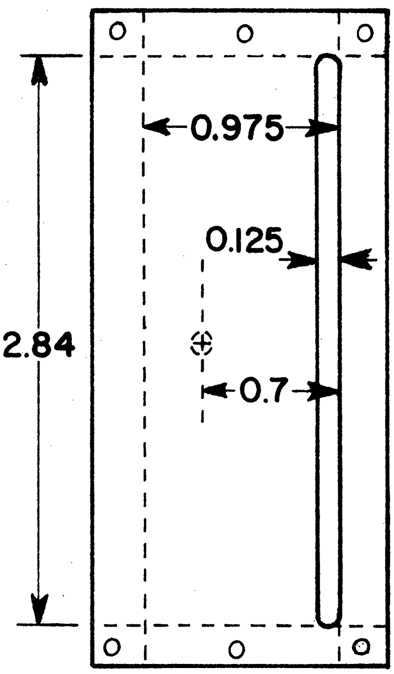
FIG. 13(c): Input impedance as a function of frequency for the reduced-height waveguide slot. w = 1.34", h = 0.125", s = 1.36".

matching circuitry to achieve an antenna whose impedance characteristics would match within 1:3 of the transmission line impedance over a 10 percent frequency.

The next phase of the study was conductdd to determine the feasibility of reducing the length L of the cavity shown in Fig. 12. For this purpose the excitation of the cavity was obtained by a magnetic probe instead of a voltage probe. Physically, the magnetic probe was identical to the voltage probe. However, since the waveguide height was reduced to 0.125", it was reasoned that the voltage probe could be used to excite the magnetic field of the cavity if it were moved closer to the cavity short (Fig. 12). It was determined experimentally that the magnetic field in the cavity could effectively be excited with the voltage probe located 0.250" from the cavity short. During the investigation it was observed that the distance from the probe to the radiating slot had considerable effects on the impedance characteristics of the antenna, i.e., the slot tended to resonant at higher frequencies as the distance from the probe to the short was reduced. It was found that a cavity-backed slot radiator having satisfactory impedance characteristics could be fabricated employing a probe-to-short distance approximately equal to $\lambda_g/4$. The final slot configuration obtained from the study is shown in Fig. 14. Figures 15(a) - 15(b) illustrate the input impedance variation of the cavity-backed slot radiator over the frequency range of 2 - 8 GHz. The results show that the antenna element has a very low impedance in the 2-3 GHz range. It has a resonance in the range 3-4 GHz and then again the impedance returns to low values in the range 4 - 6.9 GHz. A second resonance occurs in the range 6.9 - 7.1 GHz. Efforts to reduce the dimension L of the cavity resulting in the shifting of the resonance in Fig. 15.

3.2 Radiation Patterns

In this section we discuss the radiation patterns produced by a single and double cavity-backed slots, discussed in the previous section, mounted on the surface of a conducting cylinder of diameter 5.5" and length 36". The two slots were angularly separated by 90° as shown in Fig. 16. Figures 17 and 18 show the E- and H-plane patterns of a single cavity-backed slot mounted on the cylinder.



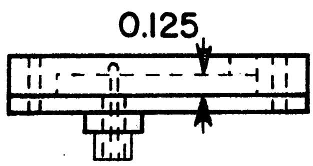


FIG. 14: Reduced-size slot radiator on broad face of a reduced-height waveguide cavity.

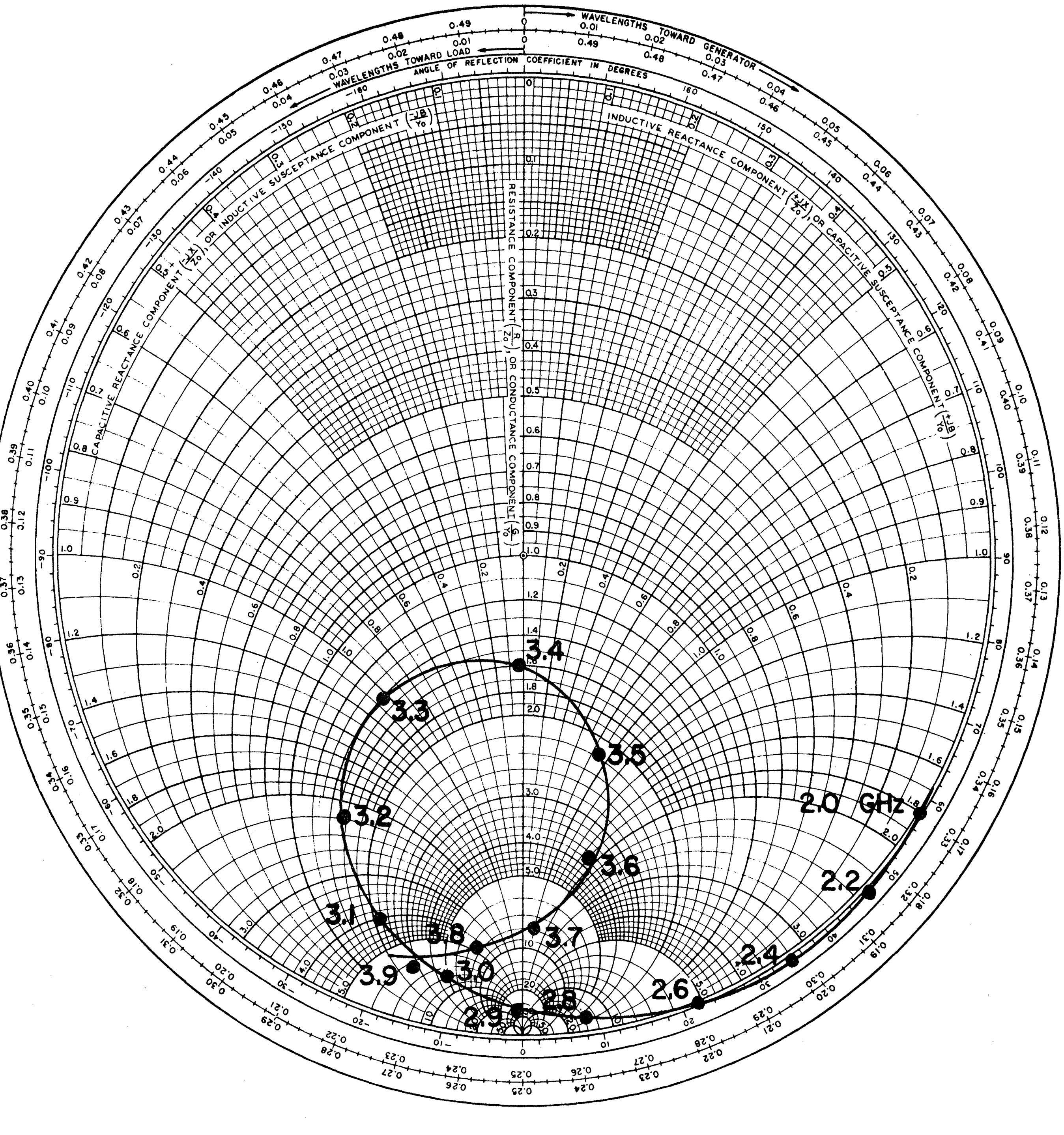


FIG. 15(a): Impedance characteristics of reduced-size waveguide slot element.

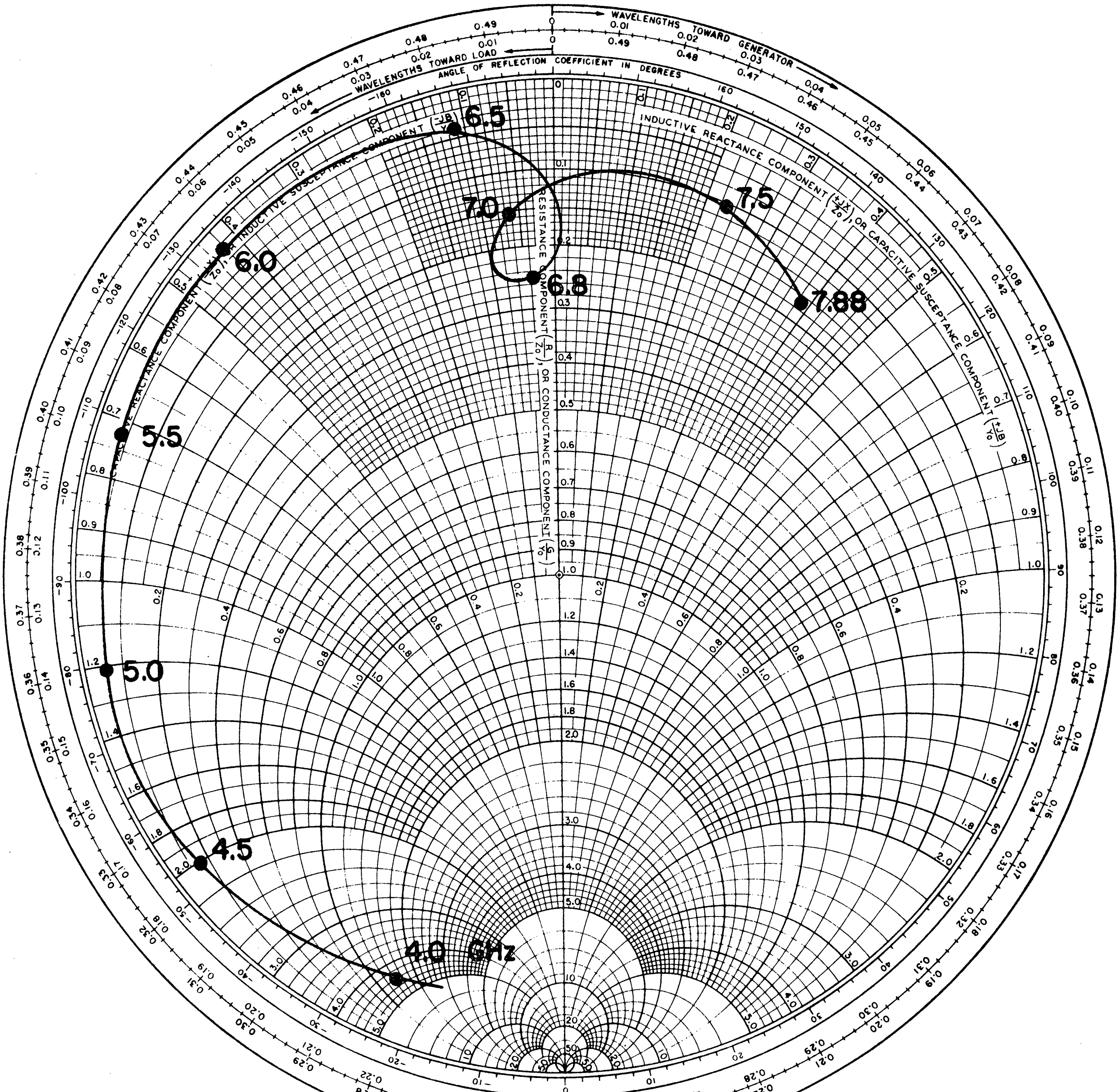


FIG. 15(b): Impedance characteristics of reduced-size waveguide slot element.

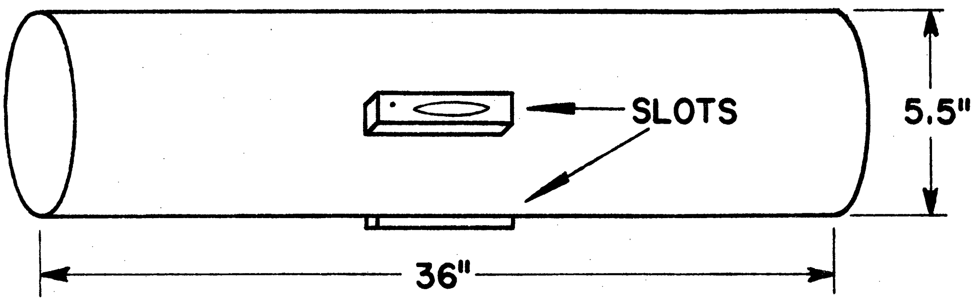


FIG. 16: Sketch of 2-slot array on the surface of a conducting cylinder.

In order to study the proximity effects of the slots, the pattern of one of the slots of the 2-slot array was measured when the other slot was terminated by 50 ohms. Figures 19 and 20 show the E-plane patterns of the two slots. It is found that over most of the range of ϕ, the mutual coupling effects may be neglected.

Figures 21(a) - 21(f) show the measured patterns of a 2-slot antenna array at a number of frequencies. The excitation of the array was such that the phase of the slot located at $\phi_2 = -\pi/2$ lagged that of the slot located at $\phi_1 = 0$ by an amount 86^o (i.e., by ka at 3.0 GHz). The amplitude of excitation was equal for the two slots.

Figures 22(a) - 22(f) show the patterns of the same 2-slot array at a number of frequencies under the condition that the phase difference between the two slots was maintained at ka at each frequency.

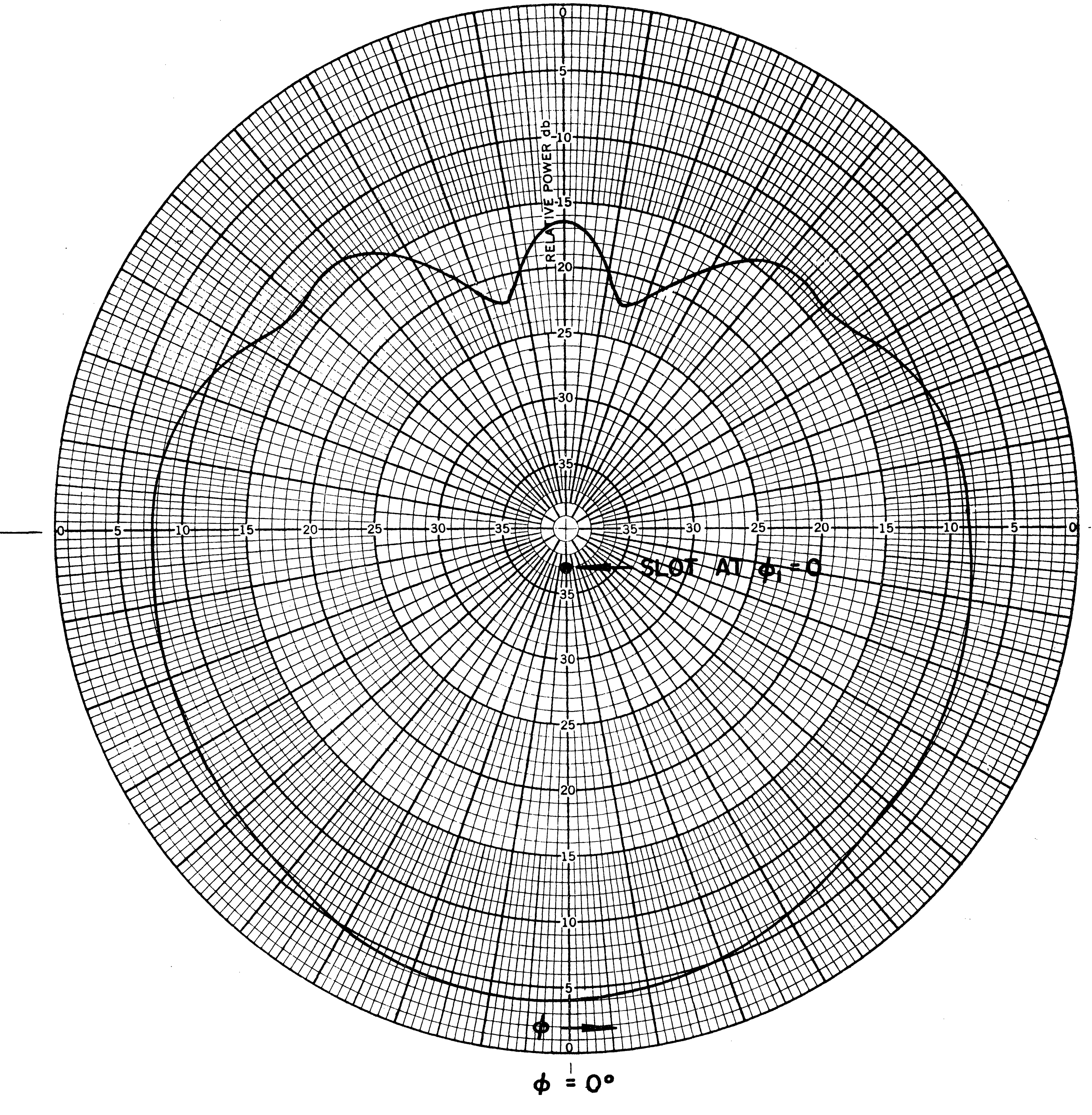


FIG. 17: Measured E-plane pattern of a slot on the surface of a conducting cylinder of diameter 5.5". ka = 1.397π, f = 3.0 GHz.

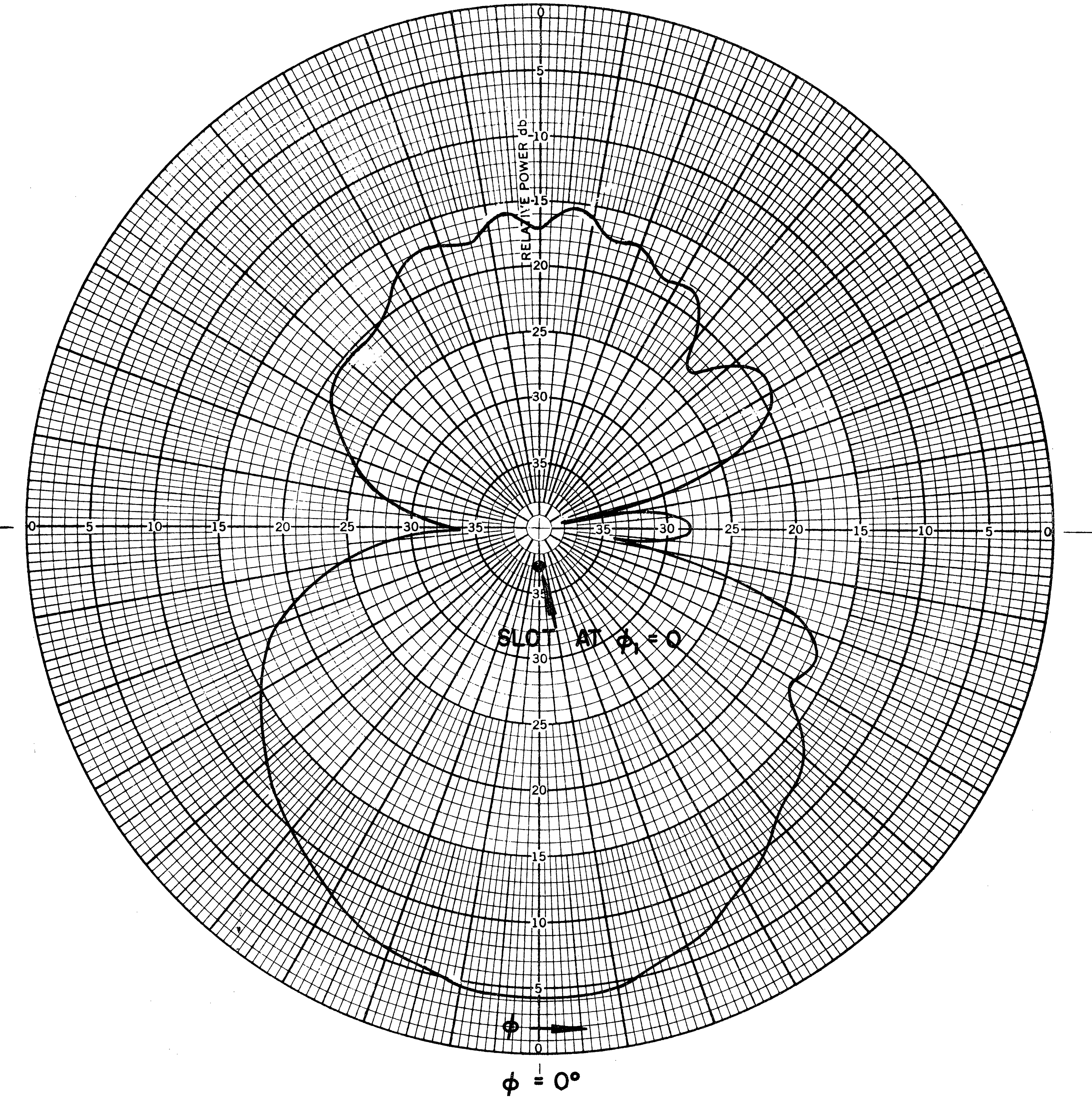


FIG. 18: Measured H-plane pattern of a slot on the surface of a conducting cylinder of diameter 5.5", ka = 1.397π.

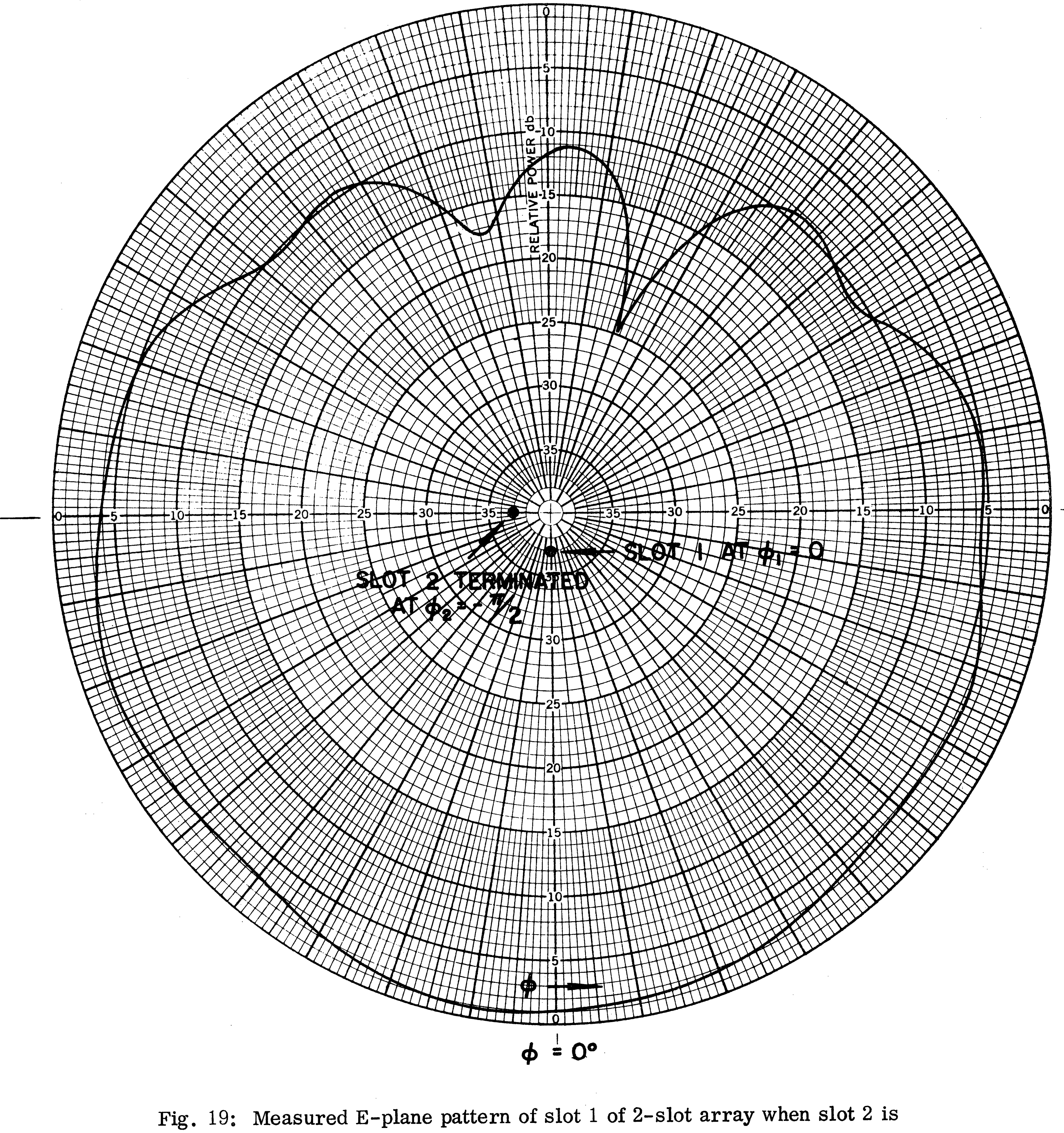


Fig. 19: Measured E-plane pattern of slot 1 of 2-slot array when slot 2 is terminated. ka = 1.397π, f = 3.0 GHz.

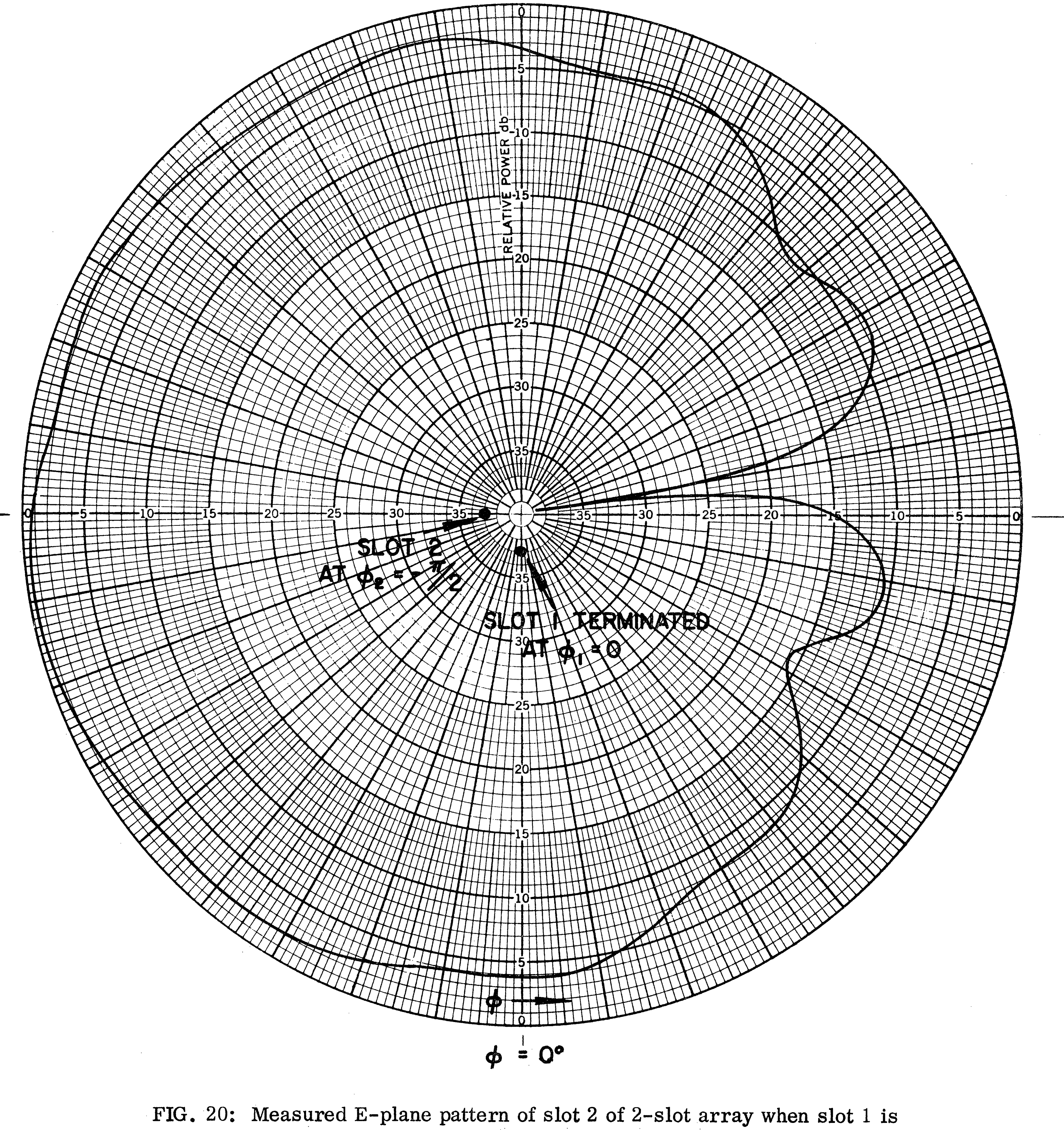


FIG. 20: Measured E-plane pattern of slot 2 of 2-slot array when slot 1 is terminated. $ka = 1.397\pi$, $f = 3.0$ GHz.

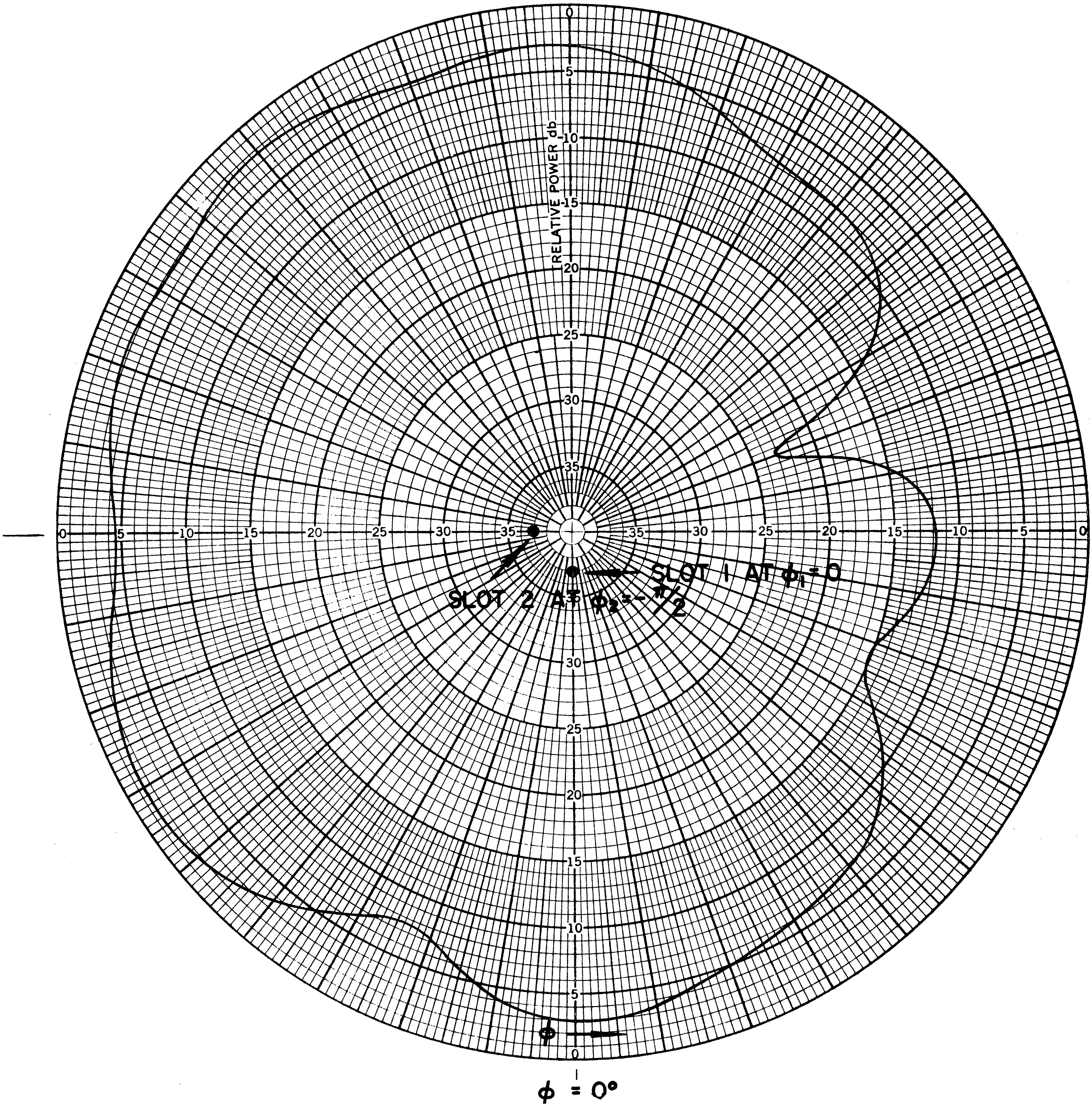


FIG. 21(a): Measured E-plane pattern of 2-slot array on the surface of a conducting cylinder. $ka = 1.118\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^o$, f = 2.4 GHz.

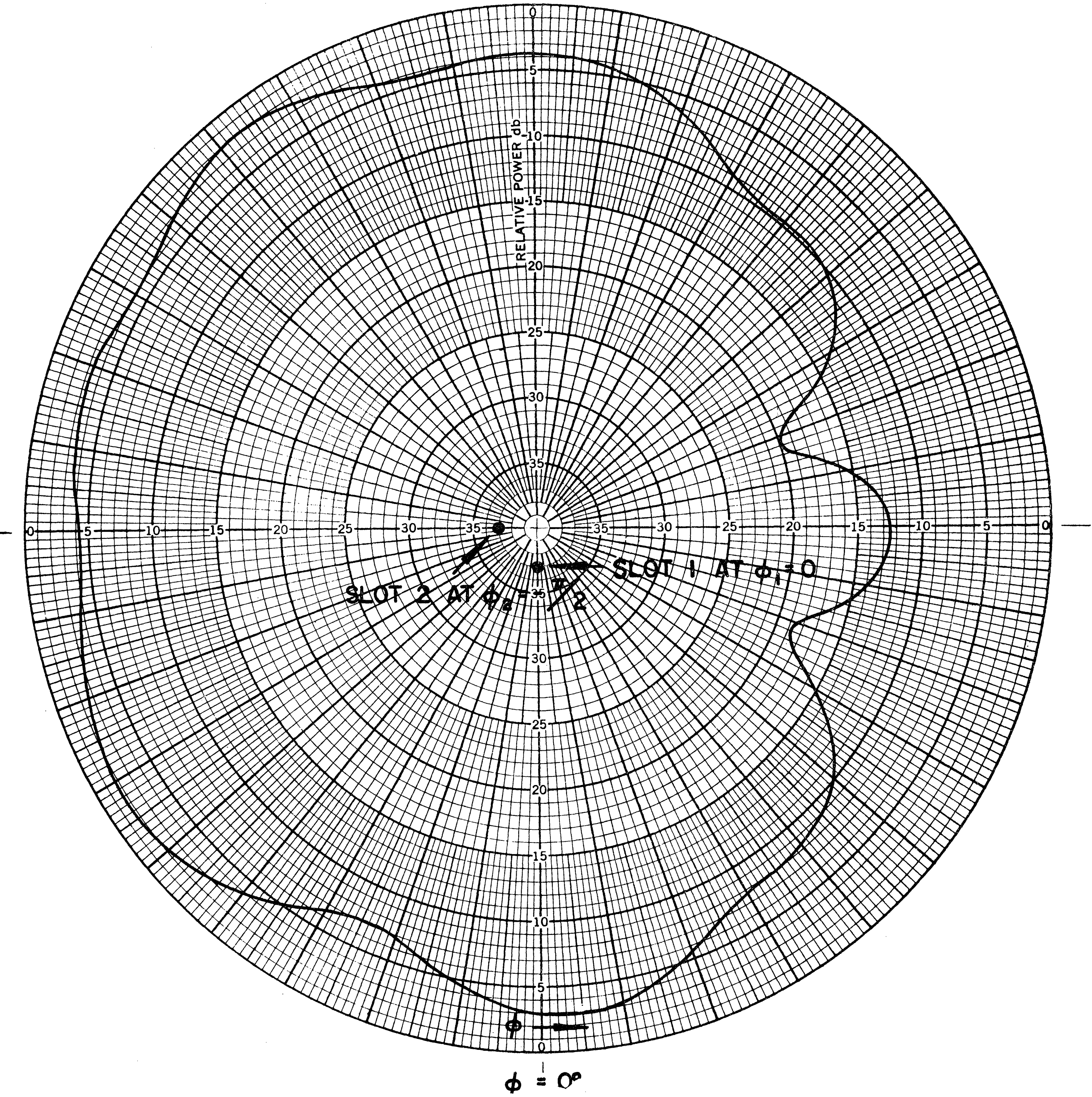


FIG. 21(b): Measured H-plane pattern of 2-slot array on the surface of a conducting cylinder. $ka = 1.215\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^o$, $f = 2.6$ GHz.

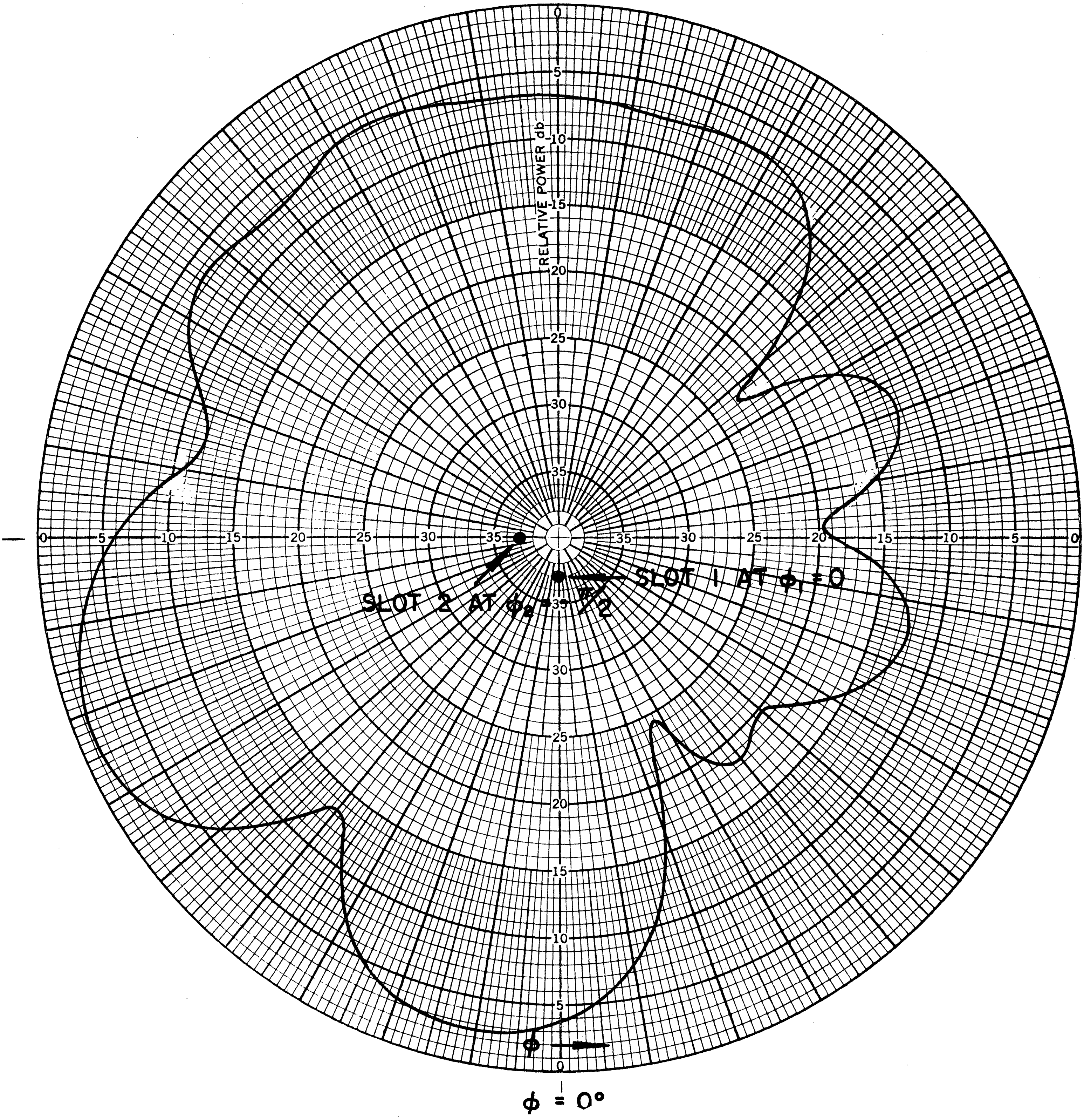


FIG. 21(c): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.299\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$ $\psi_2 = -86^o$, $f = 2.8$ GHz.

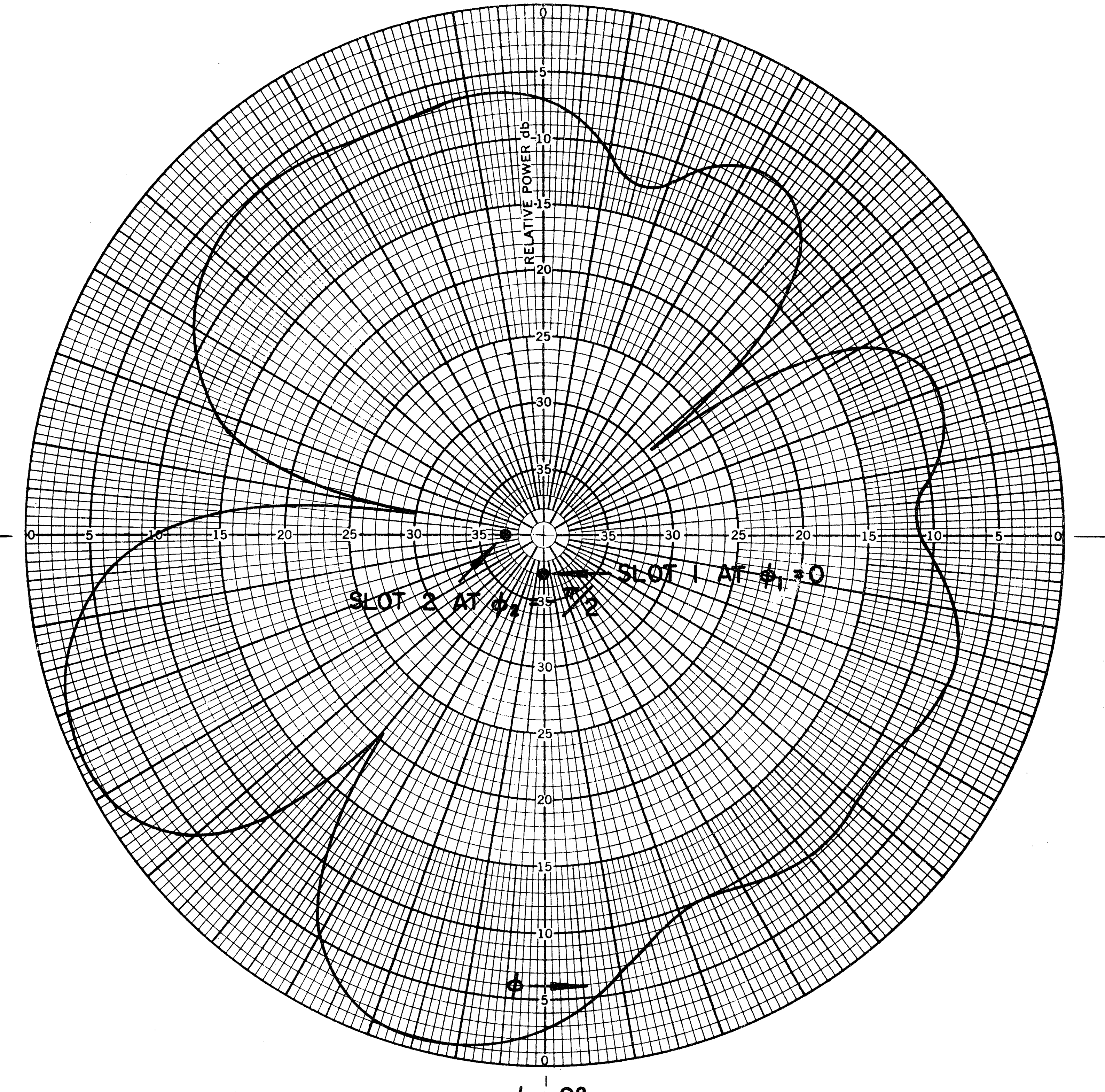


FIG. 21(d): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. ka = 1.397π, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^o$, f = 3.0 GHz.

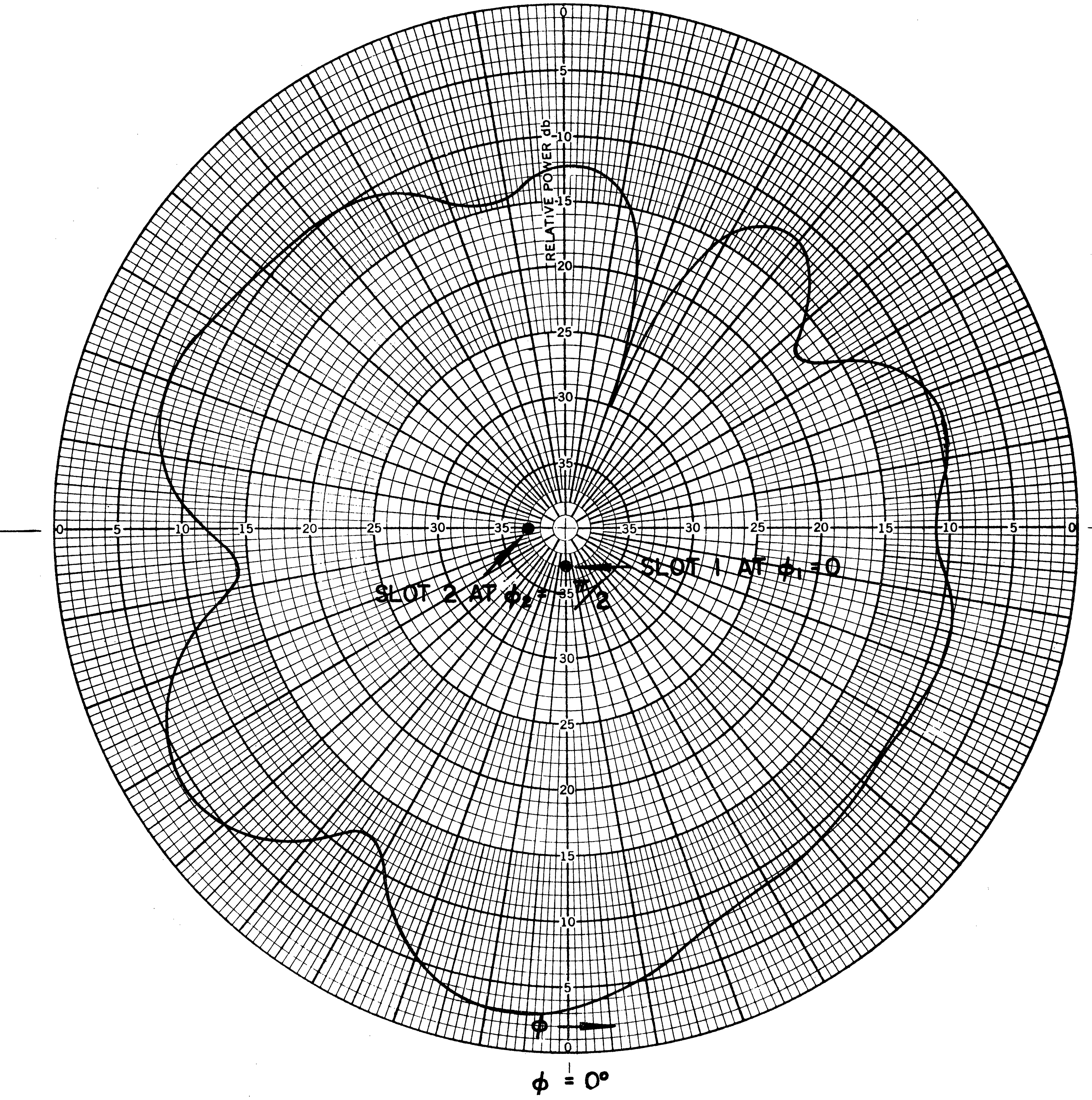


FIG. 21(e): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.495\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^o$, f = 3.2 GHz.

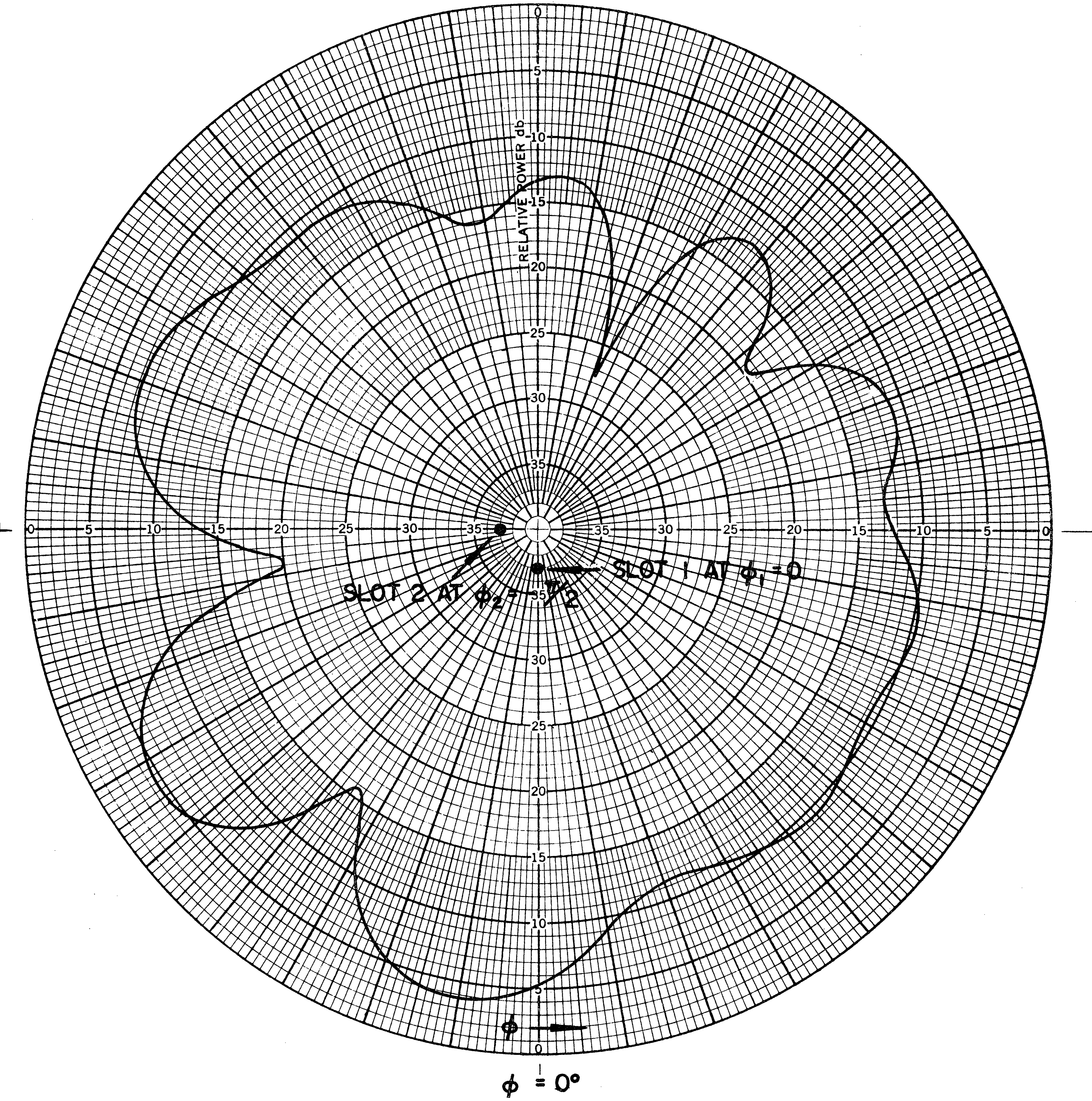


FIG. 21(f): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.579\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^{\circ}$, f = 3.4 GHz.

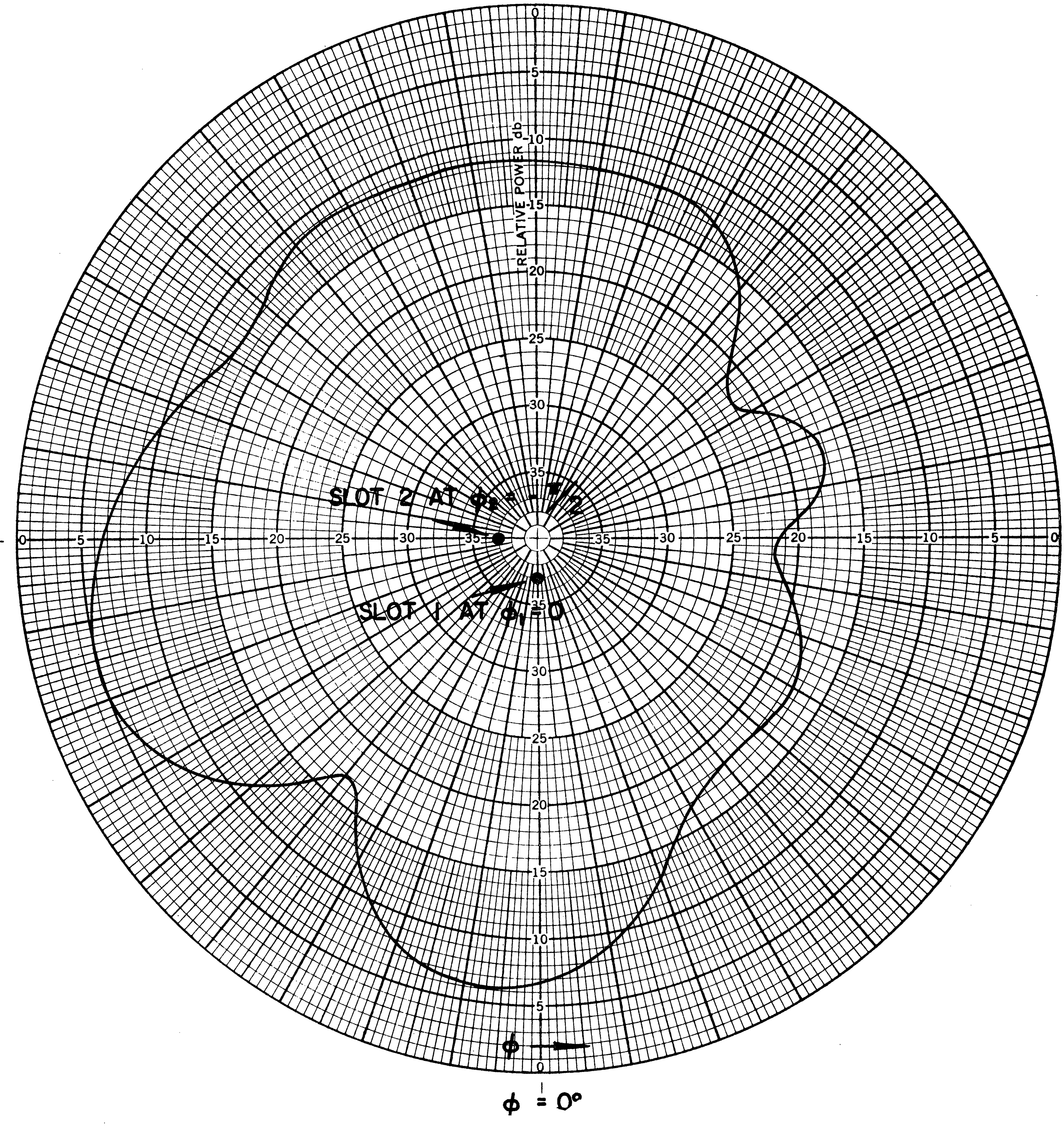


FIG. 22(a): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.118\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -161.2^{o}$, $f = 2.4$ GHz.

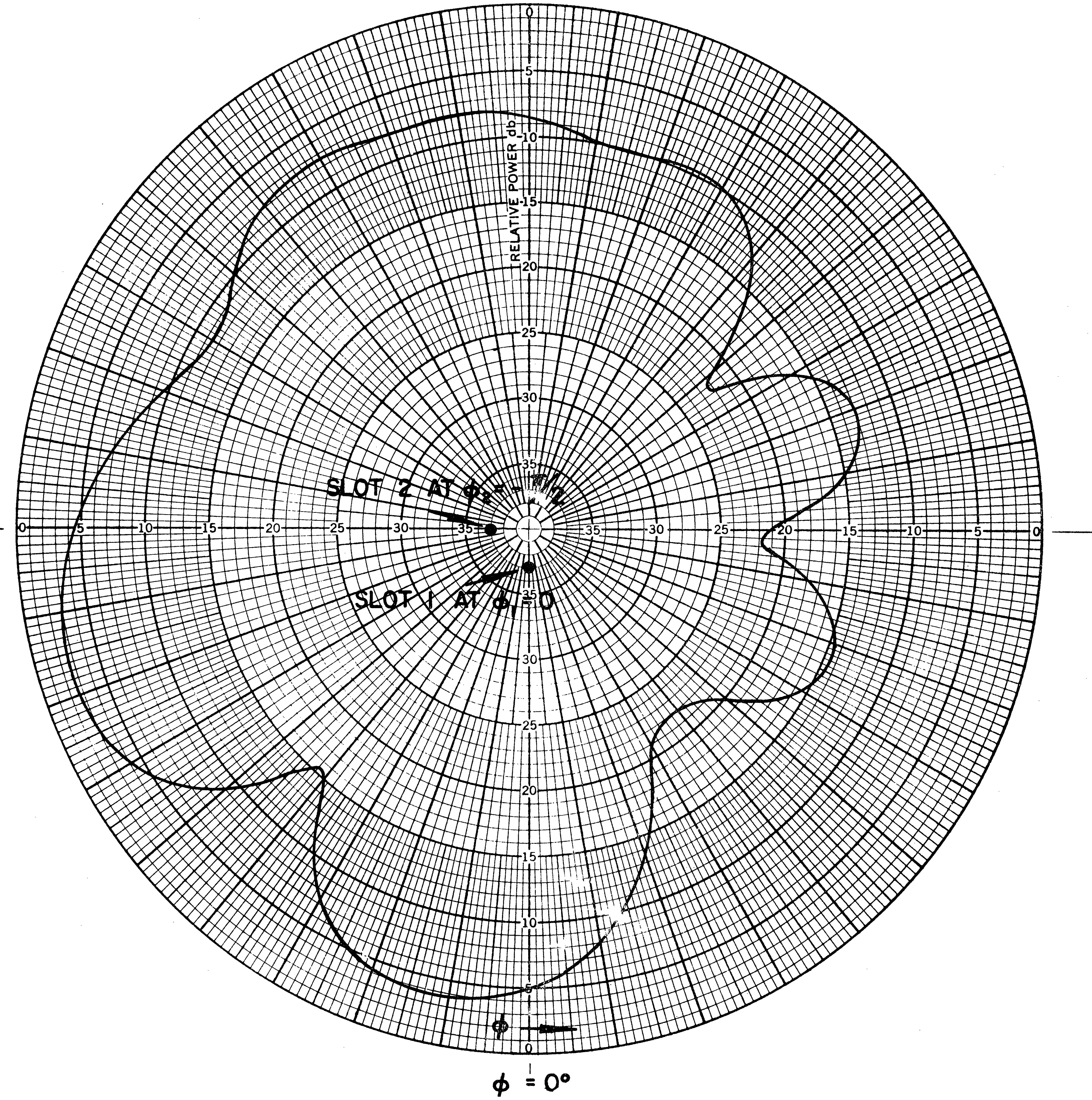


FIG. 22(b): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. ka = 1.215π, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -123^o$, f = 7.6 GHz.

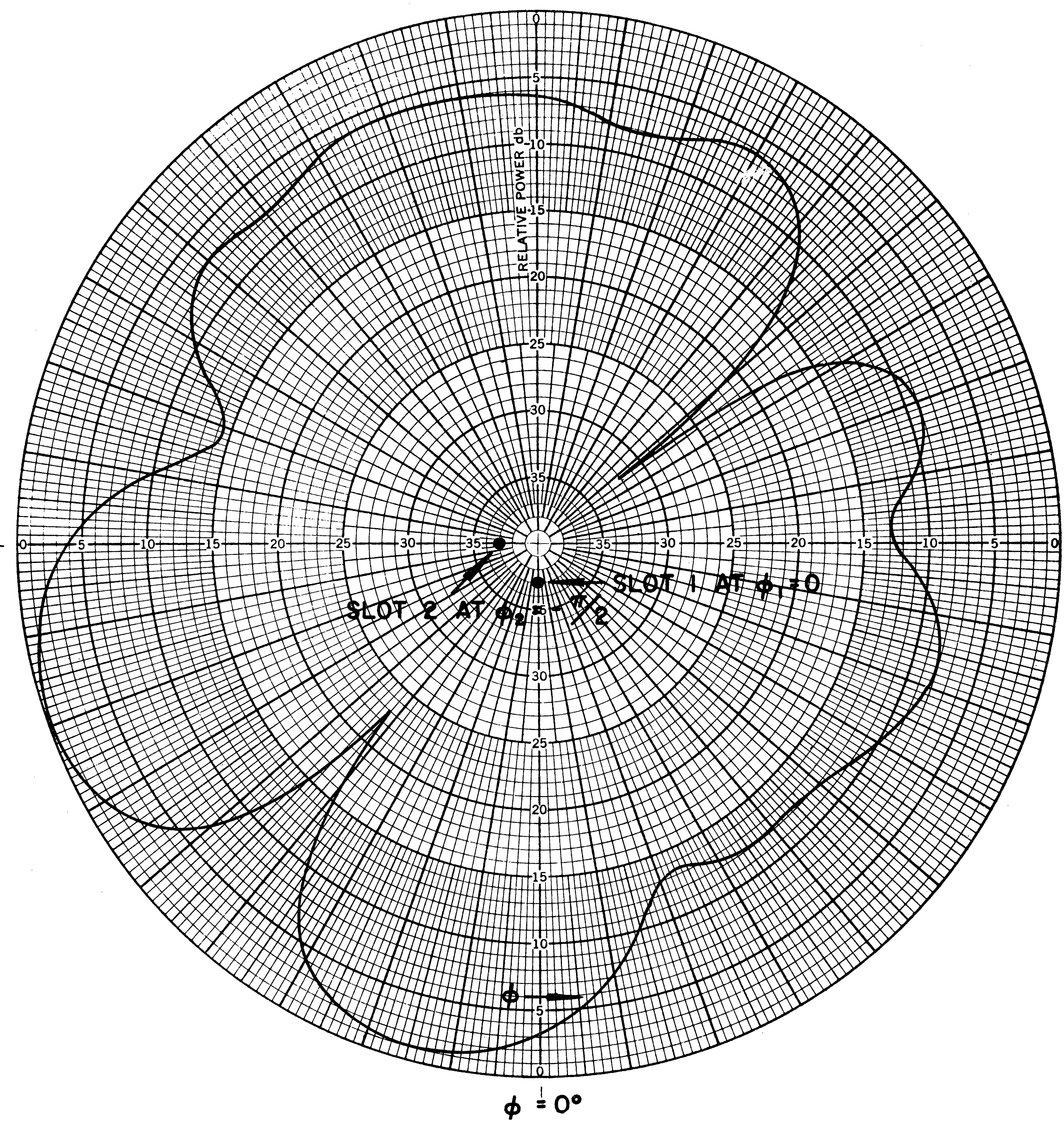


FIG. 22(c): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.299\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -108^{o}$, f = 2.8 GHz.

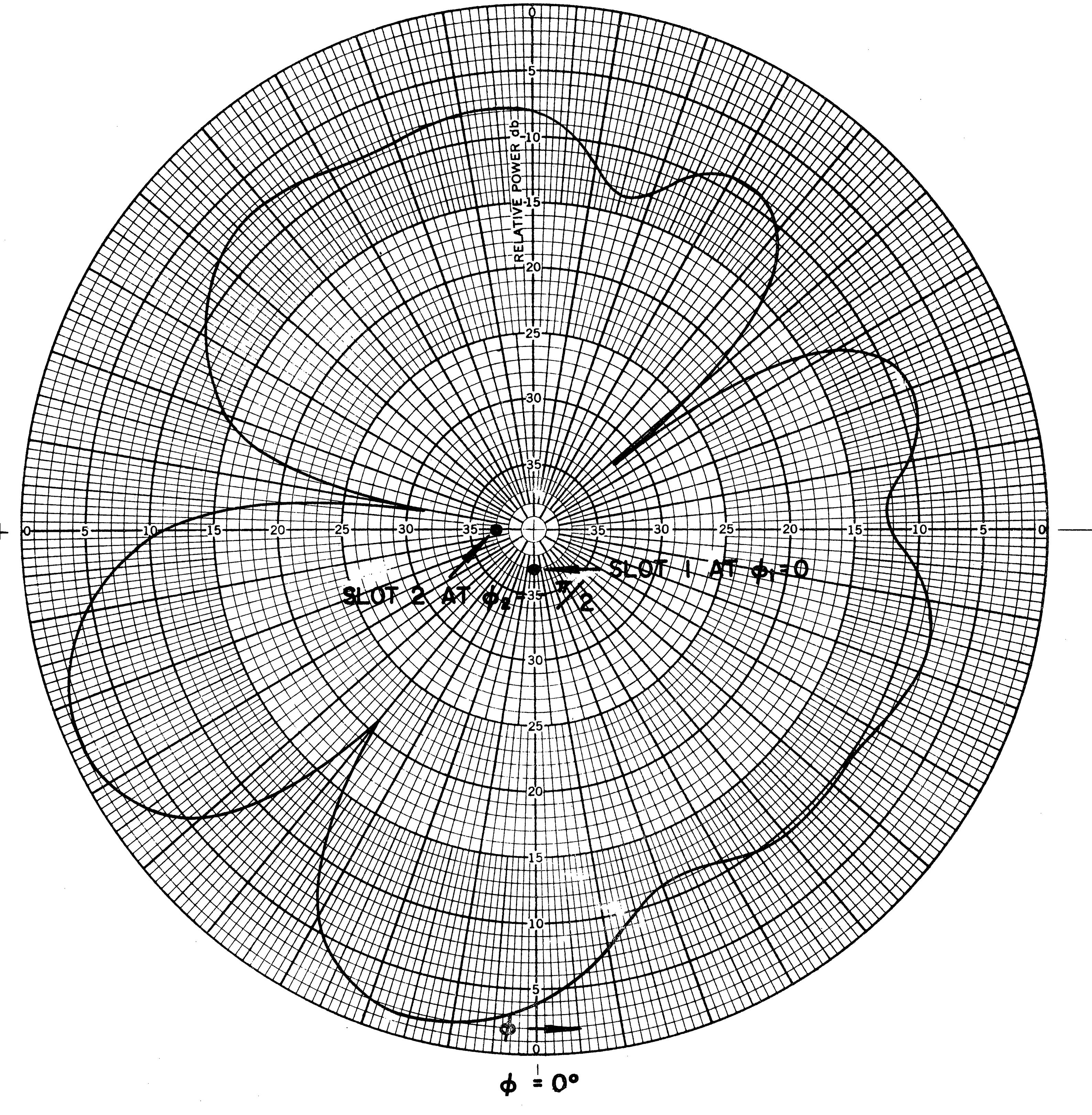


FIG. 22(d): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. $ka = 1.397\pi$, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -86^o$, f = 3.0 GHz.

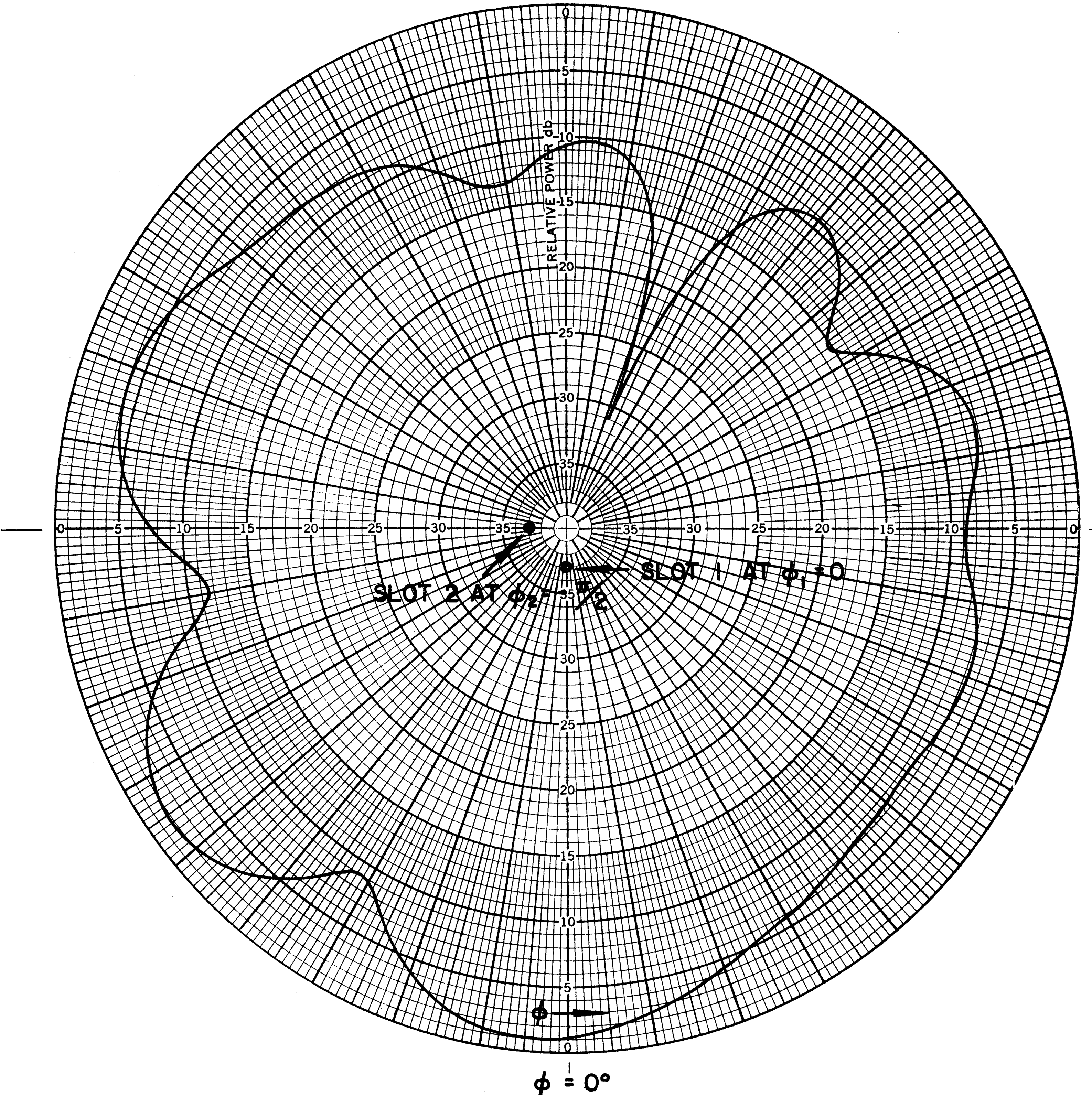


FIG. 22(e): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. ka = 1.495π, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -67.4^o$, f = 3.2 GHz.

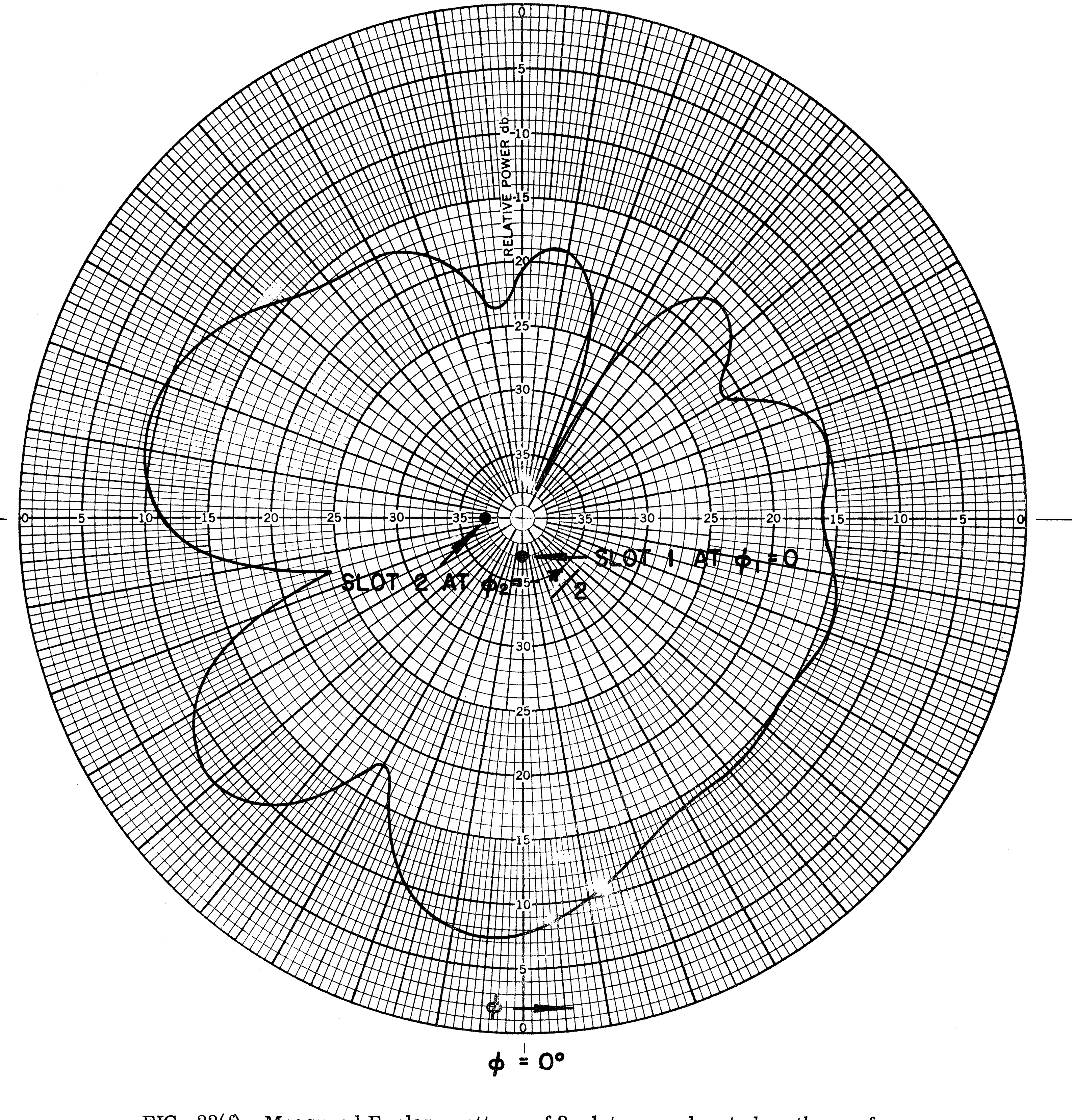


FIG. 22(f): Measured E-plane pattern of 2-slot array located on the surface of a conducting cylinder. ka = 1.579π, $V_1 = V_2 = 1.0$, $\psi_1 = 0$, $\psi_2 = -48^o$, f = 3.4 GHz.

IV. DISCUSSION

On the basis of the results given in the previous sections, it may be concluded that the goals of the present research outlined in Section 1.3 have been accomplished. A method has been developed for the design of a reduced-height waveguide cavity-backed slot element which can be used in the design of antenna arrays for use on electrically small vehicles. Extensive experimental studies indicate that the size of such a waveguide slot assembly can be reduced significantly. At 3.0 GHz, a 100:1 model of such an element has been fabricated using a waveguide cavity section 3" wide, 0.5" long and 0.125" high, i.e., 0.76λ wide, $0.13\ \lambda$ long and 0.03λ high. The radiating slot element is 2.84" long and 0.125" wide, i.e., 0.72λ long and 0.03λ wide. The antenna element can be impedance matched with acceptable VSWR to operate over a 10 percent bandwidth and over the band of frequencies of interest.

For the given size of the cylinder, desired vertical plane patterns may be obtained by using arrays of the above mentioned waveguide cavity-backed slots mou mounted on the conducting cylinder. It is recommended that arrays of 3 or 4 slots be used for the range $0.4\pi \lesssim ka \lesssim 1.14\pi$. For the range $0.2\pi \lesssim ka \lesssim 0.4\pi$ satisfactory patterns may be obtained with arrays of 2 slots. The physical arrangements and excitation of the individual slot elements for a given case are obtained from the considerations of field discrimination in desired directions.

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