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A VHF DIRECTION FINDING SYSTEM

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FOREWORD

This is a special technical report on a study conducted by the Electrical Engineering Department under the auspices of the Auburn Research Foundation toward the fulfillment of the requirements prescribed in NASA Contract NAS8-11251. An electronic direction finding system for use at VHF frequencies is presented.

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I. INTRODUCTION

H. P. Neff, R. J. Coleman and E. R. Graf

A need exists for a direction finding device to be used at VHF frequencies. Conventional direction finders employ such devices as loop antennas. These loops are rotated until a null in the antenna pattern is aligned with the signal direction. This method requires a mechanical rotation of the antenna which may be a disadvantage if the system is to be used in an unmanned application. A receiving antenna with a very narrow beam width may be used as a direction finder with the direction information being taken again from the pointing of the antenna. This also requires mechanical movement of the antenna and presents the problem of forming narrow beams at VHF frequencies. This method requires large physical structures for the antenna.

The direction of an incoming signal may be obtained from an appropriate antenna array. The array under consideration consists of four elements arranged in a square. The elements are each composed of two orthogonal dipoles. This particular configuration is necessary since the antenna must respond to a signal of any polarization throughout a hemisphere of coverage. The array may be thought of as an array of four vertical dipoles and a similar array of horizontal dipoles.

In this configuration the direction information may be extracted from the antennas which respond to vertical polarization with no coupled signal due to the array which is affected by horizontal polarization.

The array allows the extraction of direction information in the form of a direction cosine analog. Information in this form is usable by the electronic equipment which follows the antenna array.

A matrix system of phase lines and associated equipment follow the antenna array. This allows voltages with phase angles proportional to direction cosine analogs and a reference signal to be obtained from the array. Conventional phase measuring equipment may be used on a signal of this type to obtain the direction of the received signal.

II. THEORETICAL DISCUSSION

A plane wave from some point in space will exhibit in general both θ and ϕ polarization. Therefore a direction finding antenna must be capable of receiving both types of polarization. It would be highly desirable for the antenna to possess a hemispherical radiation characteristic for both types of polarization. It will later be demonstrated that this requirement cannot be completely satisfied in practice. In order to demonstrate the basic principles of the direction finding system, first consider a four element array of identical sources as shown in Figure 2.

It is helpful in determining the performance of an antenna as a receiving antenna to determine first its performance as a transmitting antenna and then invoke reciprocity. The far-zone radiation field of an antenna is composed of two parts in general,

$$E_\theta = - j\omega\mu A_\theta,$$

$$E_\theta = - j\omega\mu \left[A_x \cos\theta\cos\phi + A_y \cos\theta\sin\phi - A_z \sin\theta \right] \tag{1}$$

and

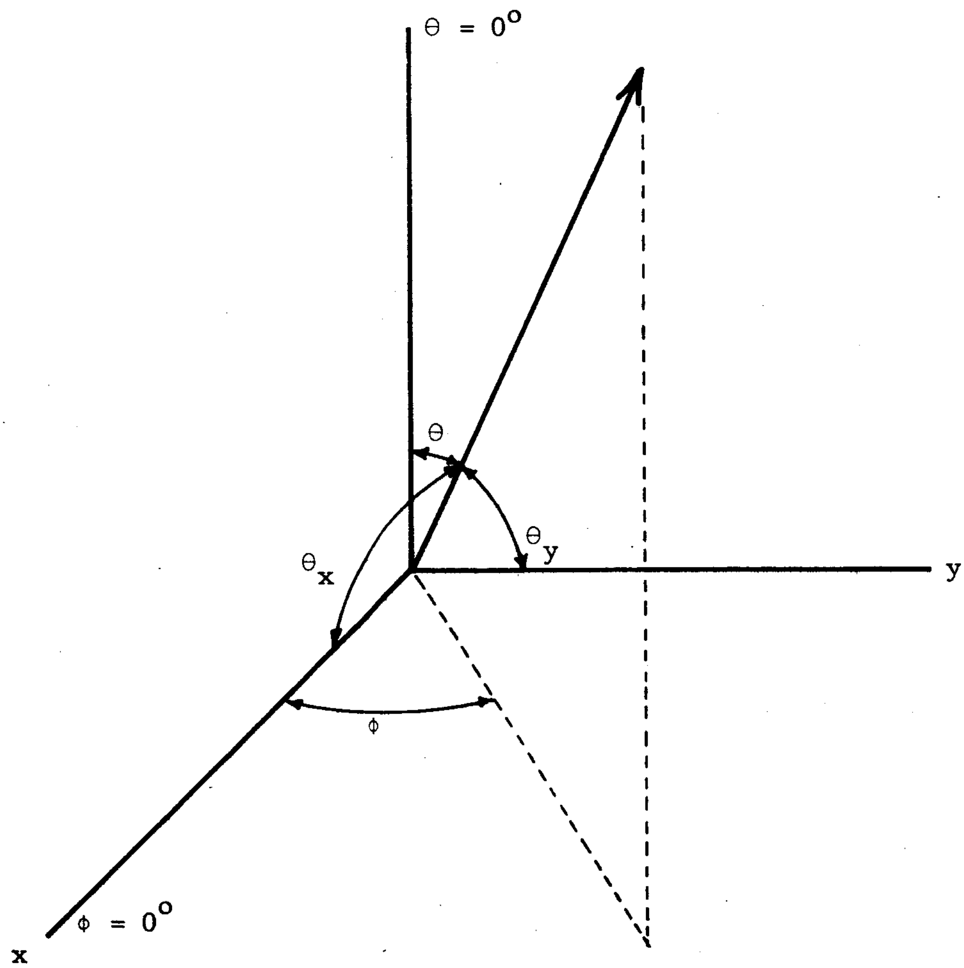

Fig. 1--The coordinate system.

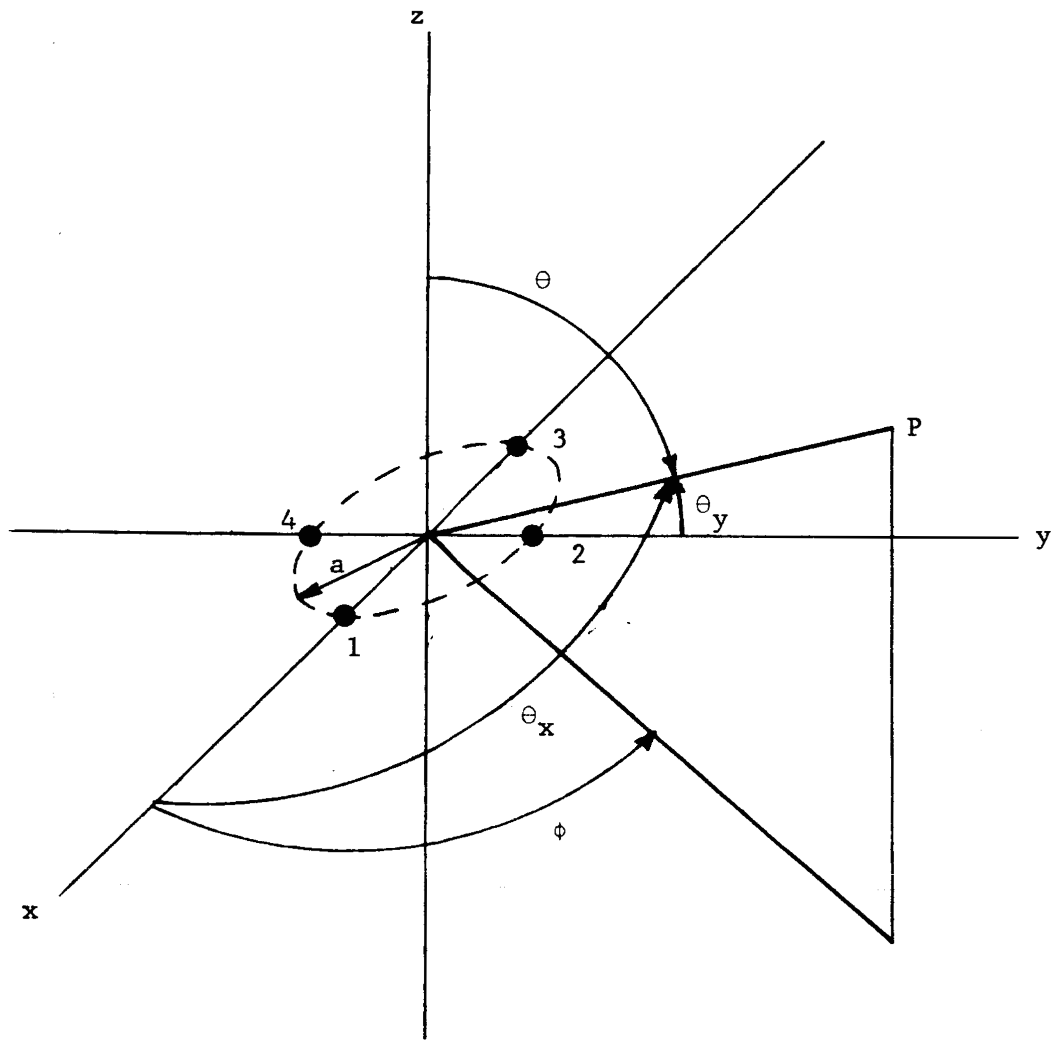

Fig. 2--A four element array of isotropic antennas.

$$E_\phi = -j\omega\mu A_\phi$$

$$E_\phi = -j\omega\mu \left[-A_x \sin\phi + A_y \cos\phi\right] \tag{2}$$

The receiving characteristics of an array will depend on the polarization of the received signal as shown in equations (1) and (2), and also on the magnetic vector potential components A_x, A_y and A_z.

For the hypothetical radiators a system of simultaneous equations describing the behavior of the array may be written:

$$\begin{aligned}
V_1 &= f_1(\theta,\phi)e^{jka\cos\theta_x} = I_1Z_{11} + I_2Z_{12} + I_3Z_{13} + I_4Z_{12} \\
V_2 &= f_2(\theta,\phi)e^{jka\cos\theta_y} = I_1Z_{12} + I_2Z_{11} + I_3Z_{12} + I_4Z_{13} \\
V_3 &= f_3(\theta,\phi)e^{-jka\cos\theta_x} = I_1Z_{13} + I_2Z_{12} + I_3Z_{11} + I_4Z_{12} \\
V_4 &= f_4(\theta,\phi)e^{-jka\cos\theta_y} = I_1Z_{12} + I_2Z_{13} + I_3Z_{12} + I_4Z_{11}.
\end{aligned} \tag{3}$$

In these equations Z_{11} is the self impedance of each element plus the input impedance to the connected transmission line, Z_{12} is the mutual impedance between one element and its nearest adjacent antenna, and Z_{13} is the mutual impedance between one element and the element diametrically opposite. It is extremely important to recognize that these equations hold if, and only if, each element of the four element array is in the same environment as each of the other elements. This condition is satisfied if, given $f_1(\Theta,\Phi)$,

$$f_2(\Theta,\Phi) = f_1(\Theta,\Phi + \pi/2) \tag{4}$$

$$f_3(\Theta,\Phi) = f_1(\Theta,\Phi + \pi) \tag{5}$$

$$f_4(\Theta,\Phi) = f_1(\Theta,\Phi + \frac{3\pi}{2}). \tag{6}$$

With these requirements established and given the dimensions of the S-band tracking antenna and the equations governing its beam pointing the following equations apply:

$$\cos\Theta_x = \sin\Theta\cos\Phi = \frac{-\ell\delta_o}{kd}$$

$$\cos\Theta_y = \sin\Theta\sin\Phi = \frac{-m\delta_o}{kd}, \tag{7}$$

where

$$k = \frac{2\pi}{\lambda}, \quad a = \lambda/4$$

and d is the element spacing in the S-band array.

Therefore,

$$ka \cos \theta_x = - \frac{a}{d} \ell \delta_o = - c\ell \tag{8}$$

$$ka \cos \theta_y = - \frac{a}{d} m\delta_o = - cm, \tag{9}$$

where

$$c = \frac{a\delta_o}{d} = \frac{0.25\lambda}{0.44\lambda} (22.5^o),$$

$$c = 12.8^o \tag{10}$$

The integers ℓ and m are the quantities which actually determine the beam pointing of the S-band antenna. For each integral step in ℓ the diode phase shifters introduce an additional phase shift of δ_o=22.5^o in the x direction. Likewise each integral step in m introduces an additional phase shift of δ_o = 22.5^o in the y direction. Thus, for each possible combination of ℓ and m the beam will co-phase in a different direction in space. The possible values of ℓ,m are

$$|c\ell| = | ka\cos \theta_x| \leqq |ka|, \text{ or}$$

$$|\ell| \leqq \left|\frac{kd}{\delta_o}\right| = 7.04.$$

The same considerations hold for m with cos θ_x replaced by cos θ_y Thus, the values are,

$$-7 \leq \ell, m \leq +7 \ . \tag{11}$$

By use of equations (8) and (9), the system equation (3), may be simplified as follows:

$$\begin{aligned}
V_1 &= f_1 e^{-jc\ell} = I_1 Z_{11} + I_2 Z_{12} + I_3 Z_{13} + I_4 Z_{12} \\
V_2 &= f_2 e^{-jcm} = I_1 Z_{12} + I_2 Z_{11} + I_3 Z_{12} + I_4 Z_{13} \\
V_3 &= f_3 e^{jc\ell} = I_1 Z_{13} + I_2 Z_{12} + I_3 Z_{11} + I_4 Z_{12} \\
V_4 &= f_4 e^{jcm} = I_1 Z_{12} + I_2 Z_{13} + I_3 Z_{12} + I_4 Z_{11} \ .
\end{aligned} \tag{12}$$

The equations (12) reveal the quantities which the direction finding system must measure. That is, ℓ and m, appear as phase angles (with a scale factor c) on the antenna terminal voltages. Any scheme for measuring these phase angles (and hence ℓ and m) at this point must account for the mutual impedance. This antenna is actually a four element circular array, and it is well known that if each element is identical, then the system equations may be uncoupled. The scheme for accomplishing this depends on forming the sequence voltages $V_R^{(0)}$, $V_R^{(1)}$, $V_R^{(2)}$, and $V_R^{(3)}$. In this notation the superscript indicates the sequence number.

The zero sequence, $V_R^{(0)}$, is formed by summing all the terminal voltages across a common load, R, through equal length transmission lines. This would lead to the following equations.

$$V_R^{(0)} = \left[I_1 + I_2 + I_3 + I_4 \right] R, \text{ and}$$

$$V \left[f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm} \right] = \left[I_1 + I_2 + I_3 + I_4 \right] \times$$

$$\left[Z_{11} + 2Z_{12} + Z_{13} \right] .$$

This set of equations may be solved to yield

$$V_R^{(0)} = \frac{VR}{Z_{11} + 2Z_{12} + Z_{13}} \left[f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm} \right].$$

The zero sequence impedance, $Z^{(0)}$, is defined as:

$$Z^{(0)} = Z_{11} + 2Z_{12} + Z_{13} = \left| Z^{(0)} \right| e^{j\phi_o} . \tag{13}$$

Accordingly, $V_R^{(0)}$ may be written as

$$V_R^{(0)} = \frac{VR}{\left| Z^{(0)} \right|} e^{-j\phi_o} \left[f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm} \right] . \tag{14}$$

The sequence voltage, $V_R^{(1)}$, is formed by combining the antenna voltage V_1, the antenna voltage V_2 through a $3\lambda/4$ line, the antenna voltage V_3 through a $\lambda/2$ line and the antenna voltage V_4 through a $\lambda/4$ line. This gives

$$V_R^{(1)} = V_1 + jV_2 - V_3 - jV_4.$$

Similarily, the expression for $V_R^{(2)}$ and $V_R^{(3)}$ are

$$V_R^{(2)} = V_1 - V_2 + V_3 - V_4, \text{ and}$$

$$V_R^{(3)} = V_1 - jV_2 - V_3 + jV_4.$$

When the indicated operations are performed, it follows that

$$V_R^{(0)} = \frac{VR}{|Z^{(0)}|} e^{-j\phi_o} \left[f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm} \right]$$

$$V_R^{(1)} = \frac{VR}{|Z^{(1)}|} e^{-j\phi_1} \left[f_1 e^{-jc\ell} + jf_2 e^{-jcm} - f_3 e^{jc\ell} - jf_4 e^{jcm} \right]$$

$$V_R^{(2)} = \frac{VR}{|Z^{(2)}|} e^{-j\phi_2} \left[f_1 e^{-jc\ell} - f_2 e^{-jcm} + f_3 e^{jc\ell} - f_4 e^{jcm} \right] \tag{15}$$

$$V_R^{(3)} = \frac{VR}{|Z^{(3)}|} e^{-j\phi_3} \left[f_1 e^{-jc\ell} - jf_2 e^{-jcm} - f_3 e^{jc\ell} + jf_4 e^{jcm} \right]$$

where

$$Z^{(0)} = Z_{11} + 2Z_{12} + Z_{13} = |Z^{(0)}| e^{j\phi_o}, \tag{16}$$

$$Z^{(1)} = Z_{11} - Z_{13} = \left|Z^{(1)}\right| e^{-j\phi_1}, \tag{17}$$

$$Z^{(2)} = Z_{11} - 2Z_{12} + Z_{13} = \left|Z^{(2)}\right| e^{-j\phi_2}, \text{ and} \tag{18}$$

$$Z^{(3)} = Z^{(1)}. \tag{19}$$

Thus, by using phased transmission lines and simple passive combiners it is possible to form the sequence voltages and uncouple the system equations. There is one step remaining before the sequence voltages may be utilized to obtain ℓ and m. The presence of the sequence impedance in each of the sequence voltages makes the coefficient, $\frac{V_R}{\left|Z^{(n)}\right|} e^{-j\phi_n}$ unequal for n = 0,1,2 and 3. This difficulty may be removed by a simple normalization process. This process requires the use of an attenuator for each sequence voltage to equalize the amplitudes, and a phase shift (additional line length) to equalize the phases, ϕ_n. The use of an attenuator is not desirable, but since the attenuation introduced will be small in general, it was felt attenuators would cause less difficulty than amplifiers in practice.

The normalized sequence voltages may now be written:

$$V_{RN}^{(0)} = f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm}$$

$$V_{RN}^{(1)} = f_1 e^{-jc\ell} + jf_2 e^{-jcm} - f_3 e^{jc\ell} - jf_4 e^{jcm}$$

$$V_{RN}^{(2)} = f_1 e^{-jc\ell} - f_2 e^{-jcm} + f_3 e^{jc\ell} - j_4 e^{jcm}$$
$$V_{RN}^{(3)} = f_1 e^{-jc\ell} - jf_2 e^{-jcm} - f_3 e^{jc\ell} + jf_4 e^{jcm} \ . \tag{20}$$

The voltages for determining ℓ and m are now formed in a manner similar to that used in forming the sequence voltages, that is,

$$V_\ell = \left[V_{RN}^{(0)} - V_{RN}^{(1)} + V_{RN}^{(2)} - V_{RN}^{(3)} \right] \text{, or} \tag{21}$$

$$V_\ell = 4f_3(\Theta,\phi)e^{jc\ell} \text{, and} \tag{22}$$

$$V_m = \left[V_{RN}^{(0)} + j\ V_{RN}^{(1)} - V_{RN}^{(2)} - j\ V_{RN}^{(3)} \right] \text{, or} \tag{23}$$

$$V_m = 4f_4(\Theta,\phi)e^{jcm} . \tag{24}$$

A reference signal for phase measurements is needed, and in this case $V_{RN}^{(0)}$ would serve as a reference, therefore,

$$V_{ref} = V_{RN}^{(0)} = f_1 e^{-jc\ell} + f_2 e^{-jcm} + f_3 e^{jc\ell} + f_4 e^{jcm} \ . \tag{25}$$

The three terminal voltages are

$$V_{ref} = V_{RN}^{(0)},$$

$$V_{\ell} = 4f_3 e^{jc\ell}, \text{ and} \tag{26}$$

$$V_m = 4f_4 e^{jcm}.$$

A phase measuring device will now measure $c\ell$ and cm. From these ℓ and m may easily be determined. One obvious requirement for measuring phase accurately is that the three functions $V_{RN}^{(0)}$, $f_3(\Theta,\Phi)$ and $f_4(\Theta,\Phi)$ either have no phase angle dependence on Θ and Φ, or that they have the same phase angle dependence. This is the basic method of direction finding by a phase measurement scheme.

The problem now becomes one of determining a suitable antenna element which will satisfy equations (4), (5) and (6). The hypothetical isotropic source will obviously meet the requirements. A turnstile antenna is an interesting possibility, but the spiral phase characteristics introduce difficulties in the phase measuring techniques. Another possibility (for Φ polarization only) is the small horizontal loop, but the difficulty in obtaining the required uniform current and the resulting small radiation resistance are undesirable features. A good possibility (for Θ polarization only) is the vertical dipole. It has two undesirable features:

1. It will not respond to Φ polarization.
2. Since the element factor is

$$f_1(\Theta,\phi) = \frac{\cos(\pi/2 \cos\Theta)}{\sin \Theta} ,$$

it will not respond to any polarization at $\Theta = 0$.

The first of these deficiencies may be partially remedied by adding horizontal elements whose phase center is coincident with the hypothetical sources used in the derivation. These elements must be incorporated in such a way that they do not interfere with the uncoupling feature of the impedances upon which the phase measurement depends. That is to say, equations (4), (5) and (6) must be satisfied. Satisfying these equations, and recognizing that only A_x and A_y components of vector potential exist for horizontal elements, requires that the field be zero along the polar axis ($\Theta = 0^o$). Thus, the second deficiency may not be overcome in any case, and the system will not respond to signals from $\Theta = 0^o$. This is not an unsurmountable difficulty as will later be demonstrated.

An arrangement which appears to incorporate the best features of this type system is shown in Figure 3. The horizontal part is a four element array of dipoles with their feed points at the same locations as those of the vertical elements.

The theoretical performance of such an array will now be investigated. All of the previously developed equations hold symbolically, with the exception that the angular dependence of each element (element factor) should be examined separately for the two types of polarization.

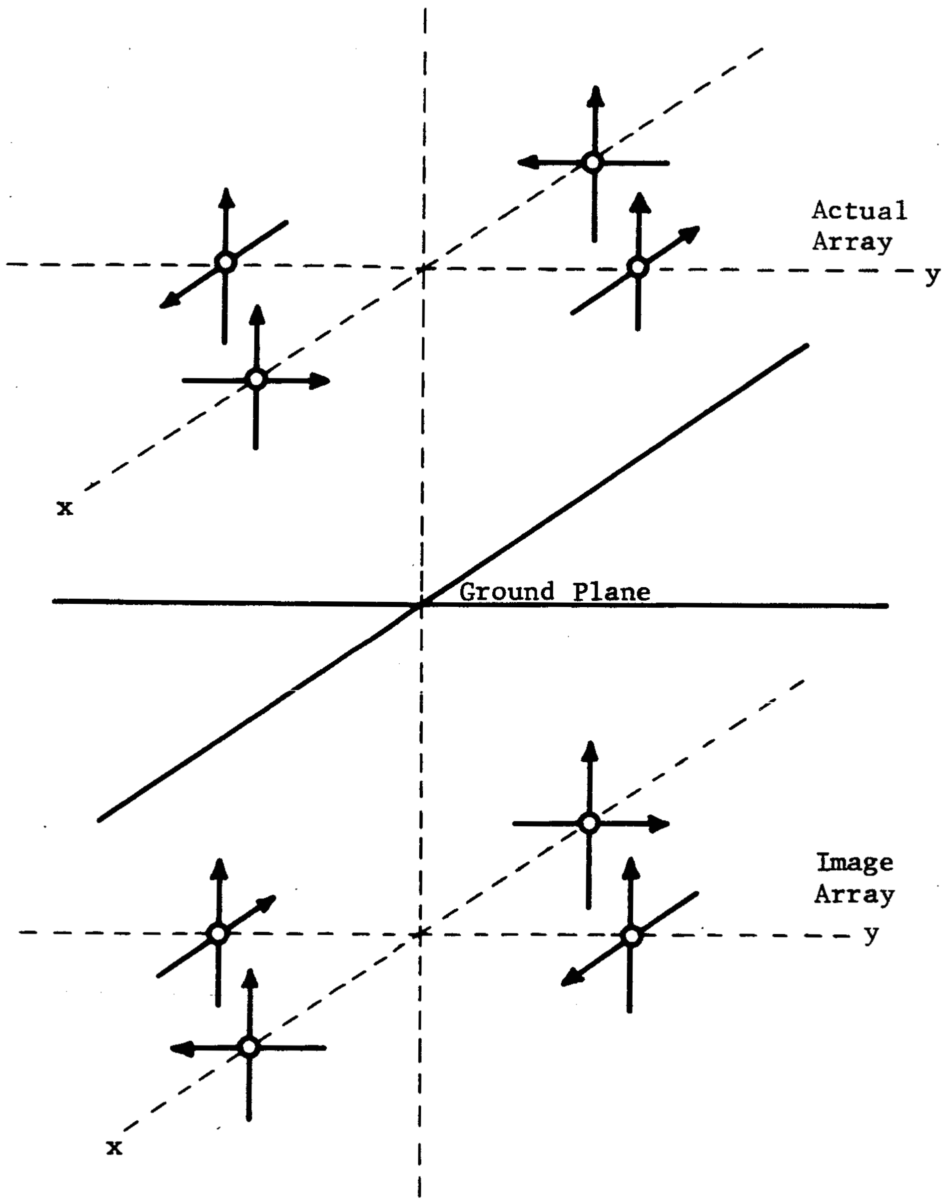

Fig. 3--The direction finding antenna and its image.

Case I. Θ Polarization

$$V_{1v} = \frac{\cos(\pi/2\cos\Theta)}{\sin\Theta} e^{-jc\ell}$$

$$V_{2v} = \frac{\cos(\pi/2\cos\Theta)}{\sin\Theta} e^{-jcm}$$

$$V_{3v} = \frac{\cos(\pi/2\cos\Theta)}{\sin\Theta} e^{jc\ell} \tag{27}$$

$$V_{4v} = \frac{\cos(\pi/2\cos\Theta)}{\sin\Theta} e^{jcm}$$

$$V_{1h} = \frac{-\cos\Theta\sin\phi\cos(\pi/2\sin\Theta\sin\phi)}{1-\sin^2\Theta\sin^2\phi} e^{-jc\ell}$$

$$V_{2h} = \frac{\cos\Theta\cos\phi\cos(\pi/2\sin\Theta\cos\phi)}{1-\sin^2\Theta\cos^2\phi} e^{-jcm}$$

$$V_{3h} = \frac{\cos\Theta\sin\phi\cos(\pi/2\sin\Theta\sin\phi)}{1-\sin^2\Theta\sin^2\phi} e^{jc\ell} \tag{28}$$

$$V_{4h} = \frac{-\cos\Theta\cos\phi\cos(\pi/2\sin\Theta\cos\phi)}{1-\sin^2\Theta\cos^2\phi} e^{jcm}$$

Case II. ϕ Polarization

$$V_{1v} = V_{2v} = V_{3v} = V_{4v} = 0 \tag{29}$$

$$V_{1h} = \frac{-\cos\Phi \cos(\pi/2 \sin\Theta \sin\Phi)}{1 - \sin^2\Theta \sin^2\Phi} e^{-jc\ell}$$

$$V_{2h} = \frac{-\sin\Phi \cos(\pi/2 \sin\Theta \cos\Phi)}{1 - \sin^2\Theta \cos^2\Phi} e^{-jcm}$$

$$V_{3h} = \frac{\cos\Phi \cos(\pi/2 \sin\Theta \sin\Phi)}{1 - \sin^2\Theta \sin^2\Phi} e^{jc\ell} \tag{30}$$

$$V_{4h} = \frac{\sin\Phi \cos(\pi/2 \sin\Theta \cos\Phi)}{1 - \sin^2\Theta \cos^2\Phi} e^{jcm}$$

In these equations the numbered subscripts refer to the element location and the lettered subscripts refer to the horizontal or vertical element. The sequence voltages are formed, normalized and recombined to yield the following results.

Case I. Θ Polarization

$$V_{ref,v} = \frac{2\cos(\pi/2\cos\Theta)}{\sin\Theta}\left[\cos(\pi/2\sin\Theta\cos\Phi) + \cos(\pi/2\sin\Theta\sin\Phi)\right]$$

$$V_{\ell,v} = 4\,\frac{\cos(\pi/2\cos\Theta)}{\sin\Theta}\, e^{jc\ell} \tag{31}$$

$$V_{m,v} = 4\,\frac{\cos(\pi/2\cos\Theta)}{\sin\Theta}\, e^{jcm}$$

$$V'_{ref,h} = 2j \left[\frac{\cos\Theta \sin\phi \cos(\pi/2 \sin\Theta \sin\phi) \sin(\pi/2 \sin\Theta \cos\phi)}{1 - \sin^2\Theta \sin^2\phi} \right.$$

$$\left. - \frac{\cos\Theta \cos\phi \cos(\pi/2 \sin\Theta \cos\phi) \sin\pi/2 (\sin\Theta \sin\phi)}{1 - \sin^2\Theta \cos^2\phi} \right]$$

$$V'_{\ell,h} = \frac{4 \cos\Theta \sin\phi \cos(\pi/2 \sin\Theta \sin\phi)}{1 - \sin^2\Theta \sin^2\phi} e^{jc\ell}$$

$$V'_{m,h} = \frac{-4\cos\Theta \cos\phi \cos(\pi/2 \sin\Theta \cos\phi)}{1 - \sin^2\Theta \cos^2\phi} e^{jcm} \tag{32}$$

Case II. ϕ Polarization

$$V_{ref,h} = 2j \left[\frac{\cos\phi \cos(\pi/2 \sin\Theta \sin\phi) \sin(\pi/2 \sin\Theta \cos\phi)}{1 - \sin^2\Theta \sin^2\phi} \right.$$

$$\left. + \frac{\sin\phi \cos(\pi/2 \sin\Theta \cos\phi) \sin(\pi/2 \sin\Theta \sin\phi)}{1 - \sin^2\Theta \cos^2\phi} \right] \tag{33}$$

$$V_{\ell,h} = \frac{4\cos\phi \cos(\pi/2 \sin\Theta \sin\phi)}{1 - \sin^2\Theta \sin^2\phi} e^{jc\ell}$$

$$V_{m,h} = \frac{4\sin\phi \cos(\pi/2 \sin\Theta \cos\phi)}{1 - \sin^2\Theta \cos^2\phi} e^{jcm}$$

These equations, less the phase factors, have been programmed and calculated by computer in five degree increments of Θ and ϕ for ranges of 0 to 90 degrees in Θ and 0 to 180^{o} in Φ. The data may be extended for Φ ranging from 0 to 180^{o} through negative values by taking note that, neglecting the phase terms

$$
\begin{aligned}
V_{ref,v}(\Theta,\Phi) &= + V_{ref,v}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V_{\ell.v}(\Theta,\Phi) &= + V_{\ell,v}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V_{m,v}(\Theta,\Phi) &= + V_{m,v}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V'_{ref,h}(\Theta,\Phi) &= - V'_{ref,h}(\Theta, -\Phi) && \text{(odd function of } \Phi) \\
V'_{\ell,h}(\Theta,\Phi) &= - V'_{\ell,h}(\Theta, -\Phi) && \text{(odd function of } \Phi) \\
V'_{m,h}(\Theta,\Phi) &= V'_{m,h}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V_{ref,h}(\Theta,\Phi) &= + V_{ref,h}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V_{\ell,h}(\Theta,\Phi) &= + V_{ref,h}(\Theta, -\Phi) && \text{(even function of } \Phi) \\
V_{m,h}(\Theta,\Phi) &= - V_{m,h}(\Theta, -\Phi) && \text{(odd function of } \Phi)
\end{aligned}
\tag{34}
$$

The functions $V_{\ell,v}$ and $V_{m,v}$ are the ordinary dipole pattern factor and are shown in Figure 4 . The function $V'_{ref,h}$ is less than 0.02 in magnitude (normalized) and is not plotted. The other functions are shown in Figures A-1 through A-37. On these plots Φ is the independent variable and Θ is the parameter.

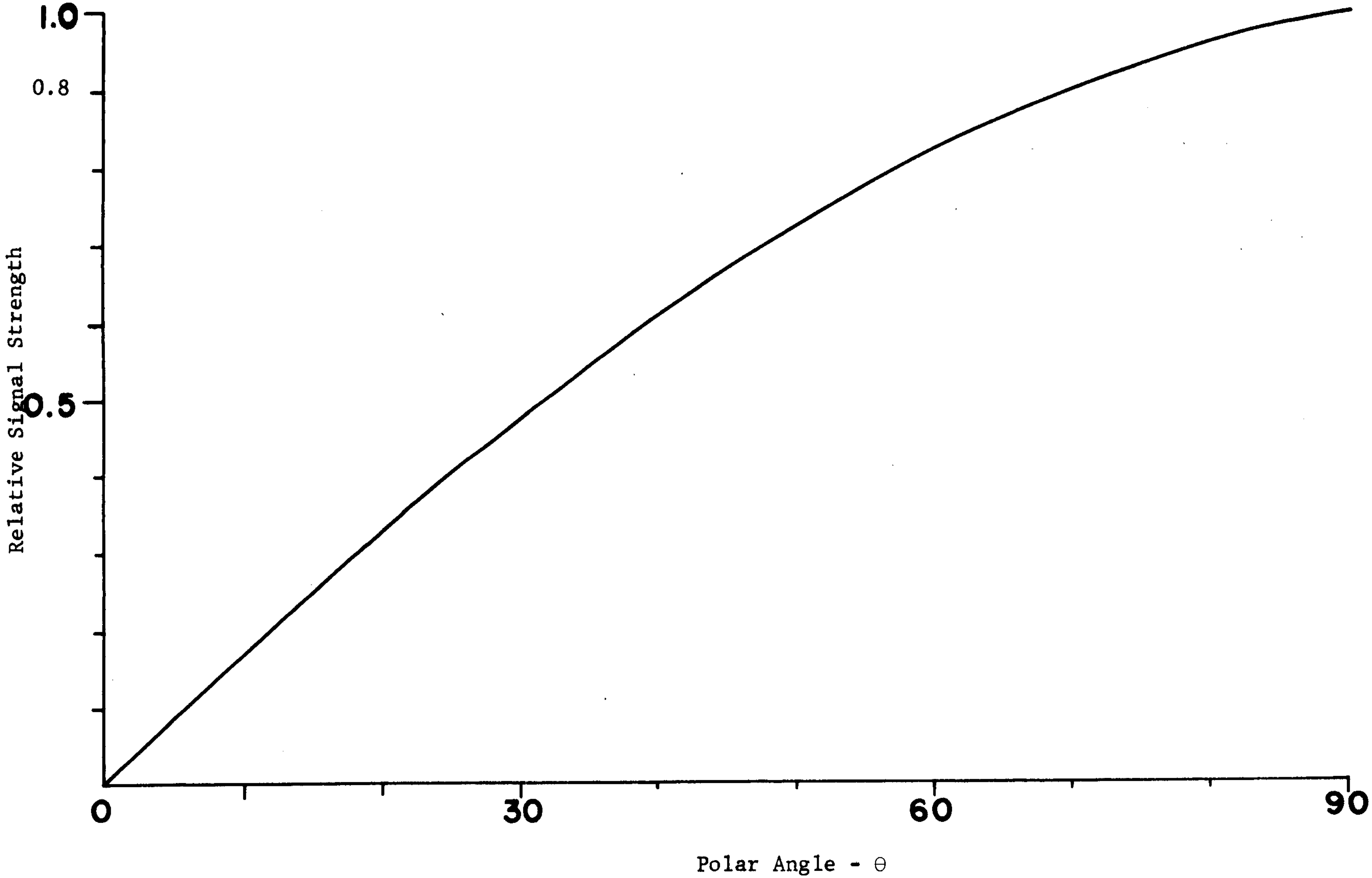

Fig. 4--Half-wave dipole pattern factor

In order to fully understand the system, one must take into account the effects of multipath. Any antenna system is subject to degradation of performance by multipath signals. This is especially true of a direction finding system in which a phase measurement determines the direction of arrival of the signal. An inspection of Figure 5 shows that a multipath signal down by only thirteen db could introduce a phase shift of thirteen degrees. From equation (10) it may be seen this is sufficient to cause the system to misread ℓ or m by one integer, causing the beam in the S-band antenna to point in an incorrect direction.

The most likely source of multipath signals is a reflection from the ground surrounding the antenna. It could be anticipated that the system would be subjected to a wide range of reflection coefficients, depending on the exact geographical location. The value of reflection coefficient usually lies between 0.3 and 0.7 in magnitude. A series of experimental tests were performed to determine how the reflection coefficient could be reduced by placing absorbing material under an antenna similar to the one previously described. These tests show the reflection coefficient was reduced for some polar angles, but nulls in the radiation patterns occured at other angles which were not present without the absorbing material. These tests indicate when the material was used, energy was being scattered. From the results of these tests, it was felt the only way to resolve the difficulty with multipath signals due to ground reflections in a predictable manner was to build the direction finding system above a metallic ground plane. In this case the coefficient of reflection will be unity for all practical purposes.

The use of a ground plane would ordinarily create many problems due to the image effects. If all the vertical elements of the array have phase centers in the same horizontal plane, and all the horizontal elements of the array lie in the same horizontal plane, then all the previously developed equations are valid symbolically. That is to say, the system of simultaneous equations will be uncoupled and the desired parameters ℓ and m may be measured. Each term involving a horizontal element must be multiplied by

$$F_{ih} = 1 - e^{-j2kh\cos\theta} \tag{35}$$

to account for the image array. In this equation h is the height of the antenna phase center above the ground plane. In the same manner every term in the vertical array must be multiplied by

$$F_{iv} = 1 + e^{-j2kh\cos\theta} \tag{36}$$

to account for its image array. Since these "image array factors" introduce the same phase angle variation into each term, the magnitudes of these terms are sufficient as a multiplying coefficient for pattern calculation. This is not true if the signals from the vertical elements are combined with those from the horizontal array. In this case the factors F_{iv} and F_{ih} must be used as they appear above. These array factors may be written:

$$F_{ih} = 2j\sin(kh\cos\theta)\ e^{-jkh\cos\theta} \tag{37}$$

$$F_{iv} = 2\cos(kh\cos\theta)\ e^{-jkh\cos\theta}. \tag{38}$$

In order to determine the performance of the direction finding system above the ground system, equations (37) and (38) are introduced into equations (31), (32) and (33). In addition, an angle α is introduced to distinguish the cases of θ - polarization and ϕ - polarization; such that $\alpha = 0$ for θ - polarization only, and $\alpha = \pi/2$ for ϕ - polarization only. The resulting equations for a height of $\lambda/4$ are:

$$V''_{ref,v} = 4\cos\alpha\cos(\pi/2\cos\theta)e^{-j\frac{\pi}{2}\cos\theta}V_{ref,v}$$

$$V''_{\ell,v} = 8\cos\alpha\cos(\pi/2\cos\theta)e^{-j\frac{\pi}{2}\cos\theta}V_{\ell,v}e^{jc\ell} \tag{39}$$

$$V''_{m,v} = 8\cos\alpha\cos(\pi/2\cos\theta)e^{-j\frac{\pi}{2}\cos\theta}V_{m,v}e^{jcm}$$

$$V''_{ref,h} = -4\sin(\pi/2\cos\Theta)e^{-j\frac{\pi}{2}\cos\Theta}\left[\cos\alpha V'_{ref,h} + \sin\alpha V_{ref,h}\right]$$

$$V''_{\ell,h} = 8j\sin(\pi/2\cos\Theta)e^{-j\frac{\pi}{2}\cos\Theta}\left[\cos\alpha V'_{\ell,h} + \sin\alpha V_{\ell,h}\right]e^{jc\ell} \qquad (40)$$

$$V''_{m,h} = 8j\sin(\pi/2\cos\Theta)e^{-j\frac{\pi}{2}\cos\Theta}\left[\cos\alpha V'_{m,h} + \sin\alpha V_{m,h}\right]e^{jcm}$$

where (39) applies to the ring of vertical elements and (40) applies to the ring of horizontal elements.

An inspection of equations (39) shows that the vertical ring performs as desired. This result obviously occurs due to the fact that the radiation functions are independent of Φ. Equations (40) are more complicated, requiring the use of a computer. In order to determine the performance of the horizontal ring the equations were calculated with Φ as the independent variable and with Θ and α as parameters.

The direction finding system is also required to furnish a signal for the station control receiver. This signal should be derived from the particular antenna radiation functions which are independent of direction. In this manner the signal will have a hemispherical characteristic insofar as direction is concerned. Of course, as in any antenna system mounted above a ground plane, there will be a null in the received signal at $\Theta = \pi/2$ for Φ polarization. The other polarization (Θ) will provide a signal at this angle. A combination of the voltages already derived in the system will serve as the station control receiver signal. This is a linear combination of the zero-sequence voltage from the vertical ring and the one-sequence voltage from the horizontal ring. The resulting signal will approximate that described above.

A block diagram of the direction finding system is shown in Figure 9. The signal from each antenna element is amplified in an r.f. amplifier and divided into phase lines and combiners. This is the matrix system which forms the sequence voltages. The sequence voltages are normalized, as mentioned earlier, and then recombined in another matrix system to form the signals whose phase is to be measured. In each case the phase lines are coaxial transmission lines whose lengths differ by one quarter wavelength at the operating frequency (138mc). The combiners and dividers are actually the same device, constructed from passive elements. Transmission line type diode switches are employed to switch the desired signals into the phase measuring equipment. To insure proper operation of the phase measuring equipment amplifier-limiters are used ahead of the converter. In order to operate at frequencies within the bandwidth of the phase meter, a two-channel converter-local oscillator is employed at this point in the system. The phase meter produces the desired analog output.

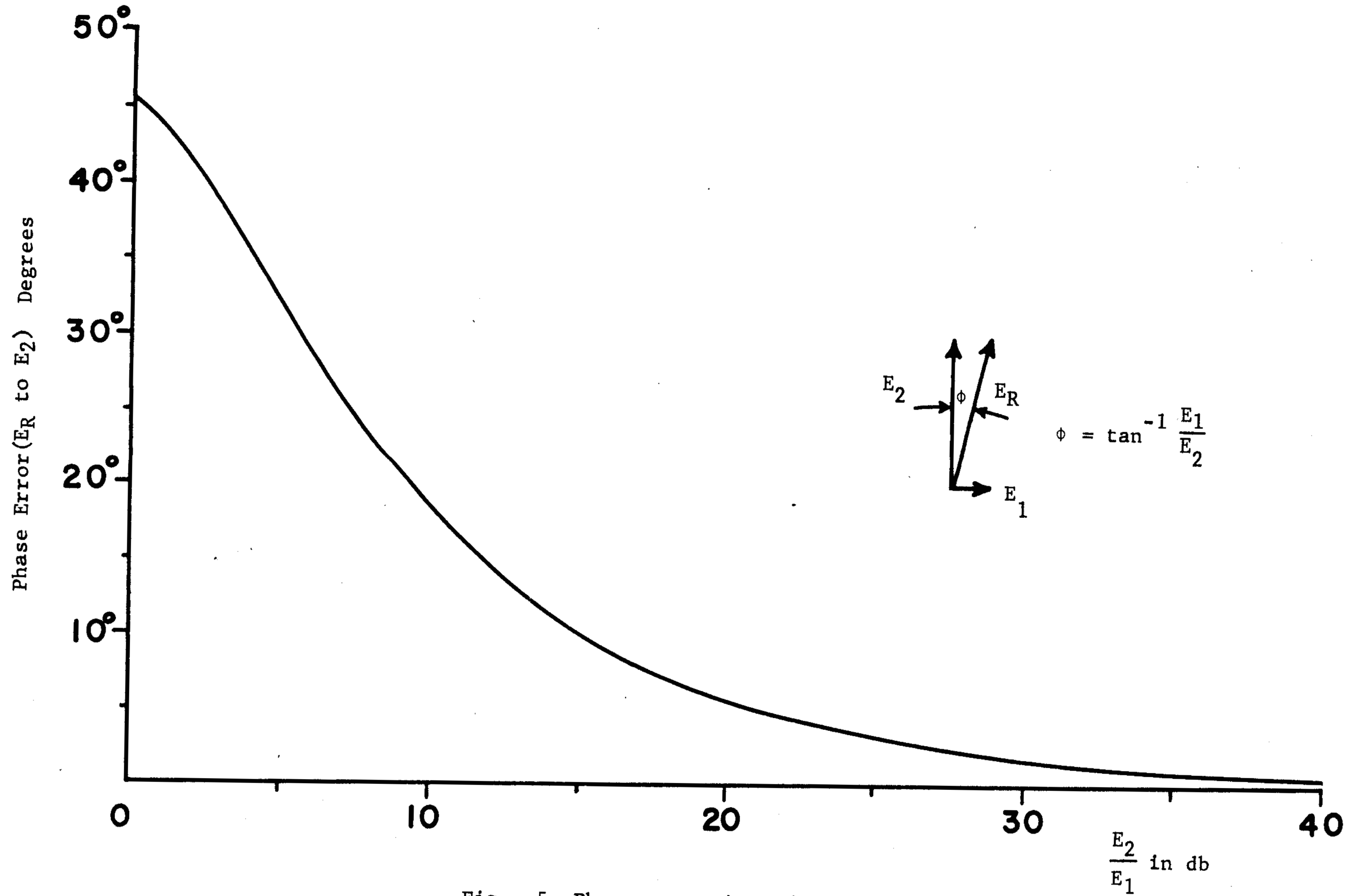

Fig. 5--Phase error introduced by interfering signal.

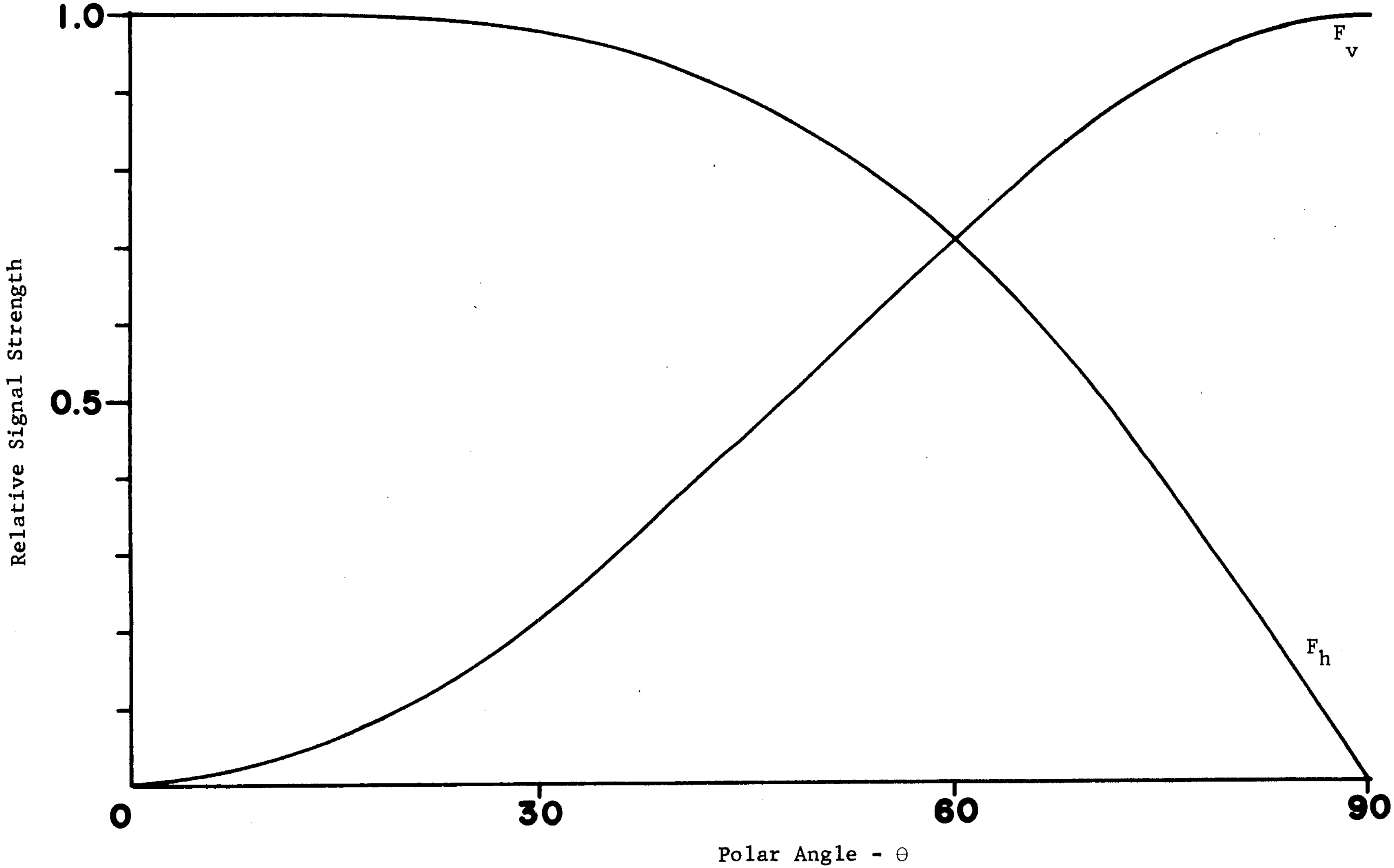

Fig. 6--Horizontal and vertical image array factors, $h = \lambda/4$.

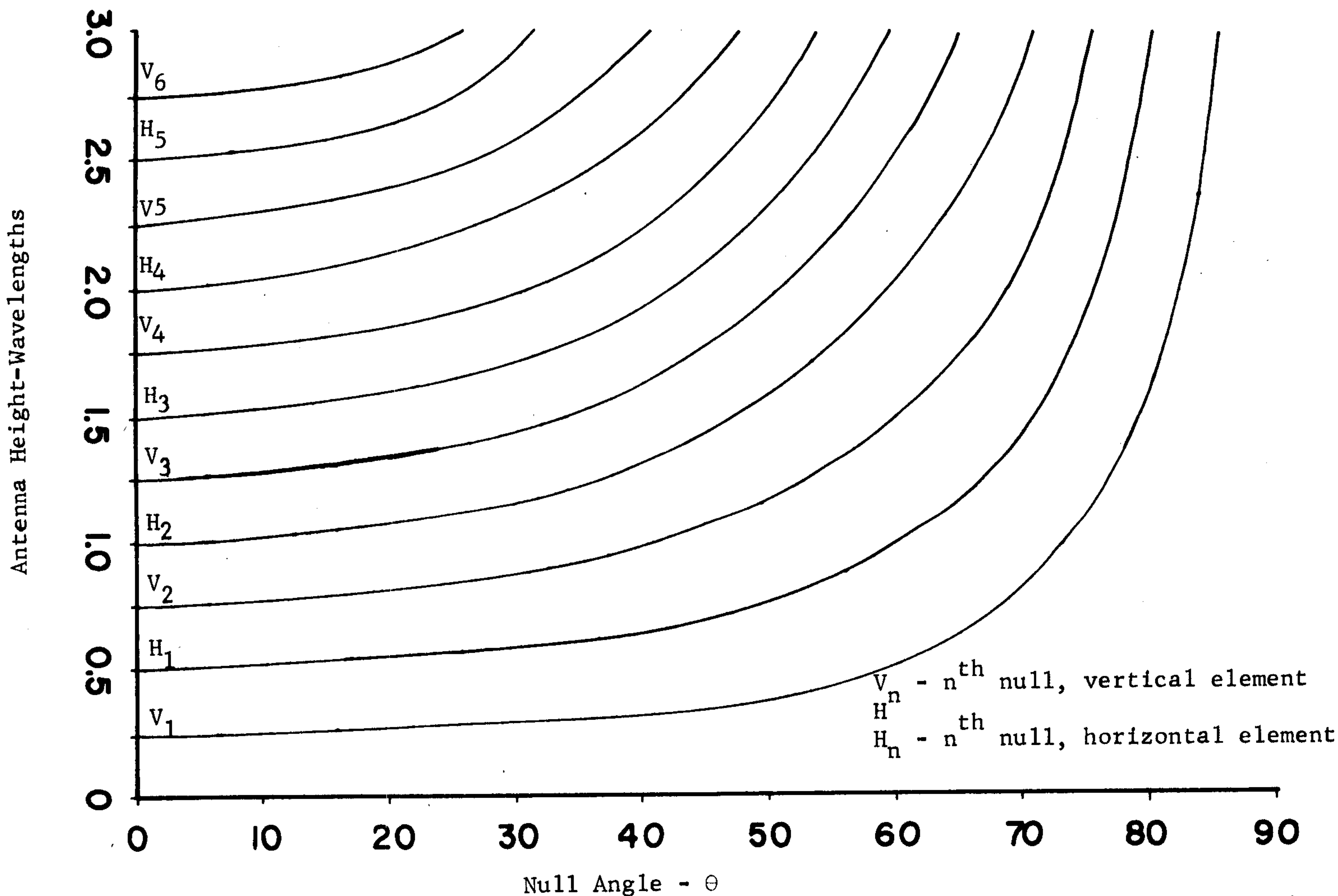

Fig. 7--Null angles as a function of antenna height above a perfectly conducting ground plane for both θ and ϕ polarization.

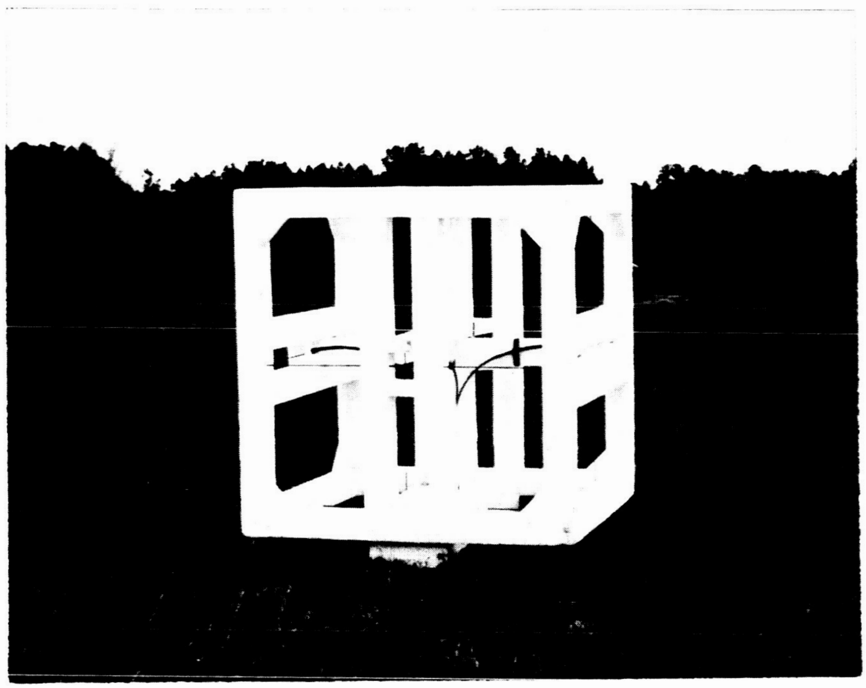

Fig. 8--Photograph of the VHF direction finder prototype.

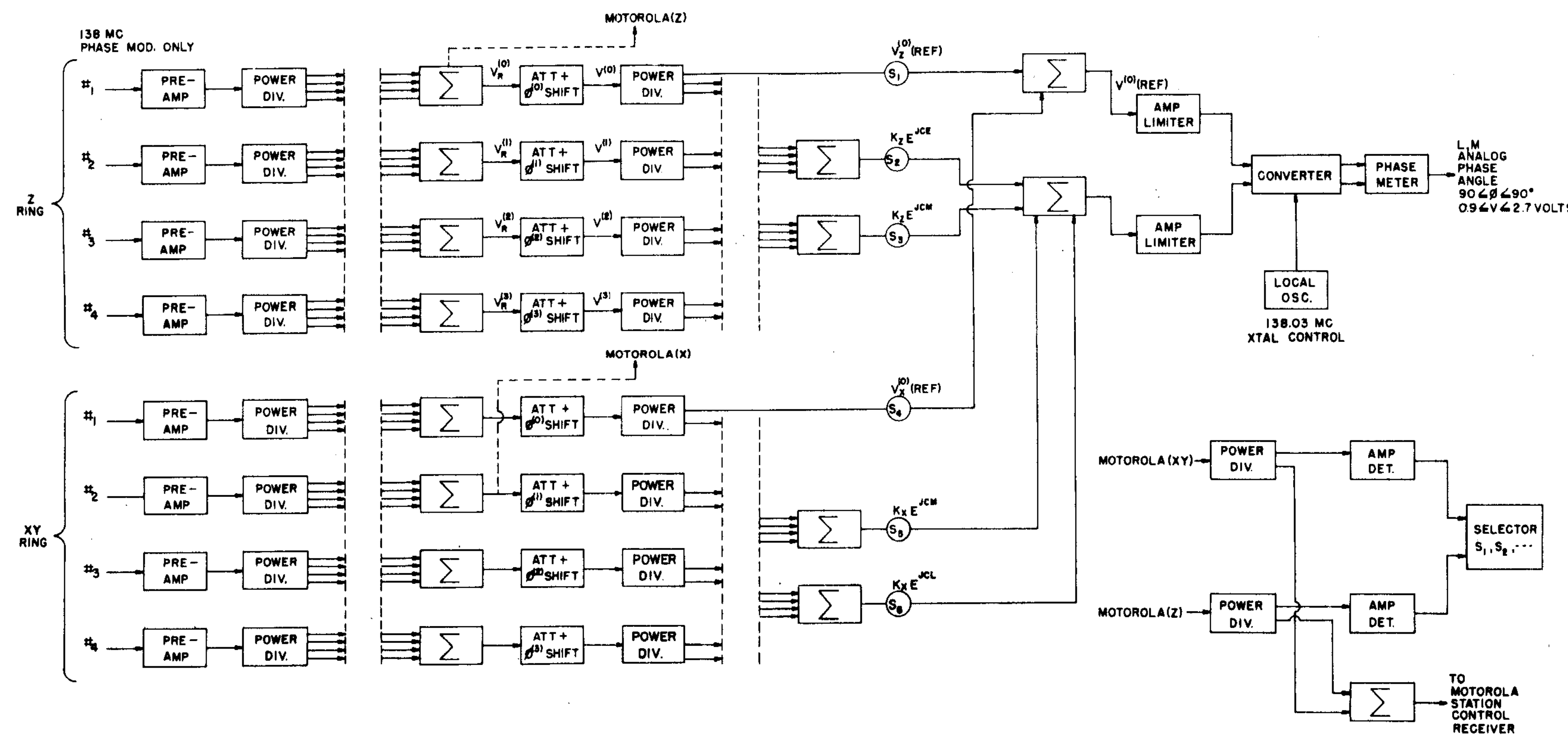

FIG. 9--THE VHF DIRECTION FINDING SYSTEM

III. CONCLUSIONS

There are several antenna forms which meet the basic requirements for direction finding systems. The one chosen and analyzed in this report meets these requirements. It also consists of simple elements, i.e., half-wave dipoles. It performs satisfactorily when used with a ground plane to overcome the troublesome multipath reception problems. The practical difficulties encountered in the processes whereby the desired information is extracted from the direction finding system are overcome by simple logic circuitry. A suitable output signal is available for the station control receiver.

Further investigations in the future may be directed toward improving the antenna system. An improvement in the system would be realized if the number of pre-amplifiers in the system could be reduced from eight to four. Another improvement would result if the need for limiting (before phase measurement) were eliminated. These suggestions merely indicate refinements of the present scheme, and not basic design changes.

APPENDIX A

The following figures demonstrate the angular dependence of the various received signals.

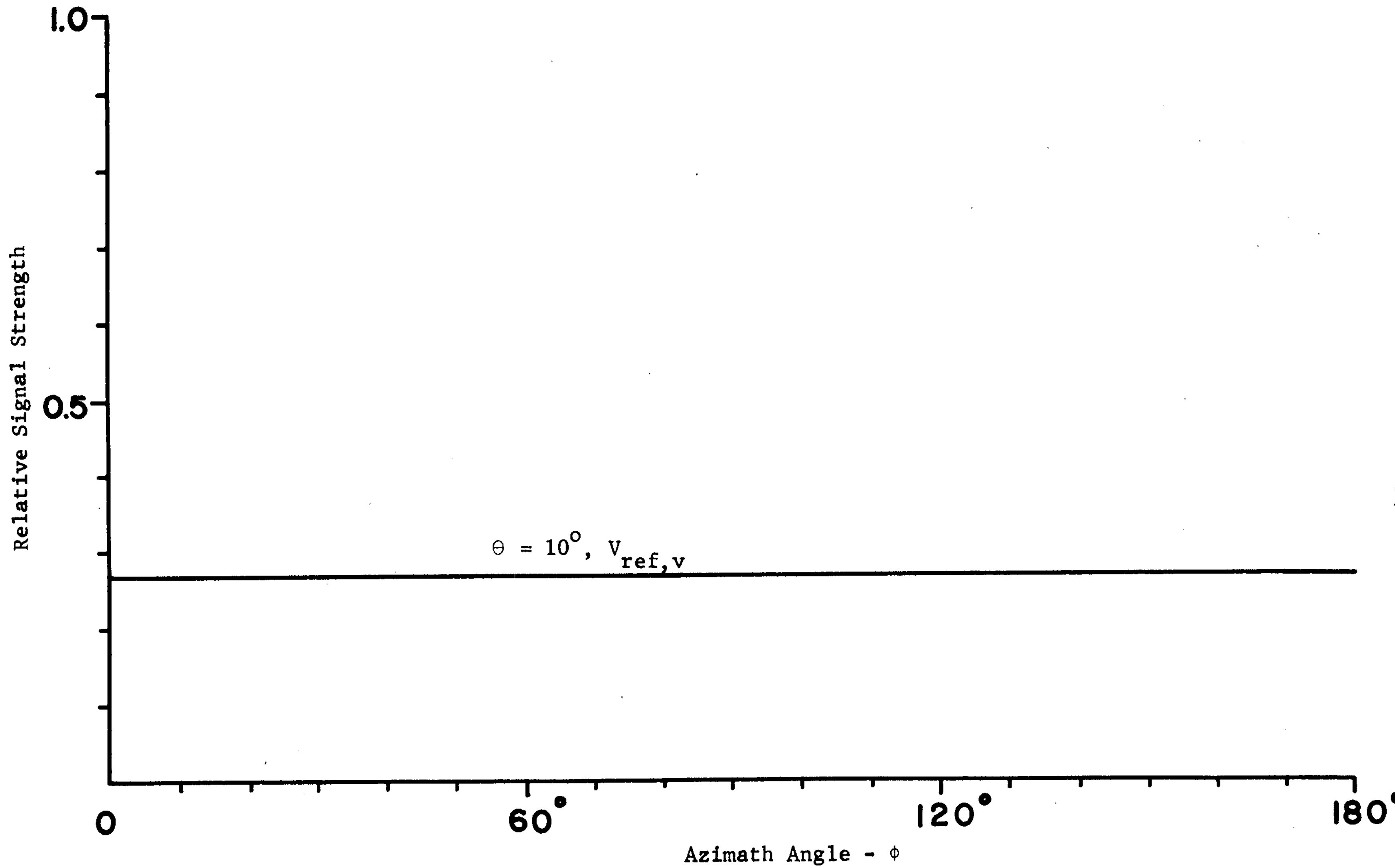

Fig. A-1--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

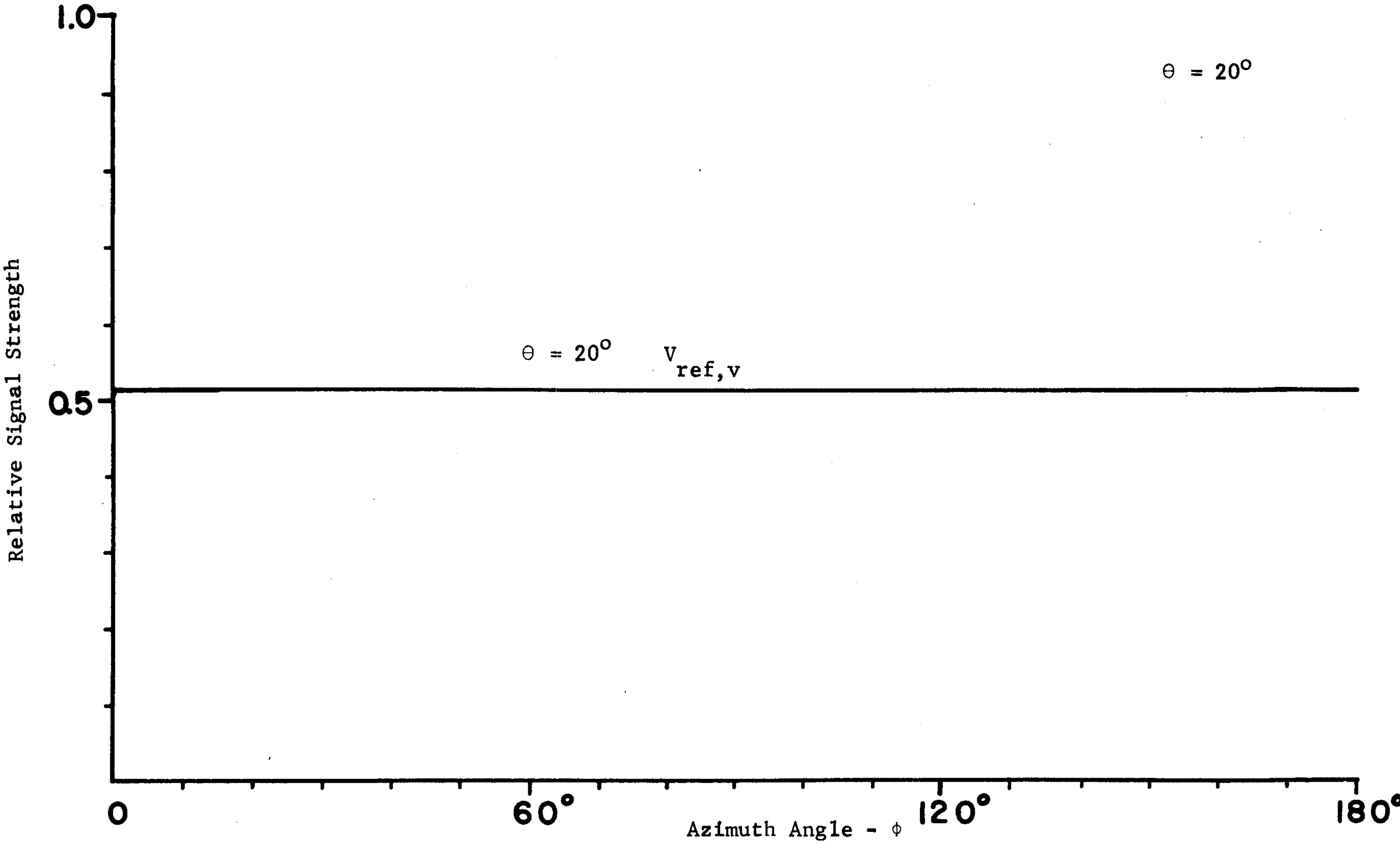

Fig. A-2--Directional characteristics of received signal-reference signal from vertical ring $V_{ref,v}$.

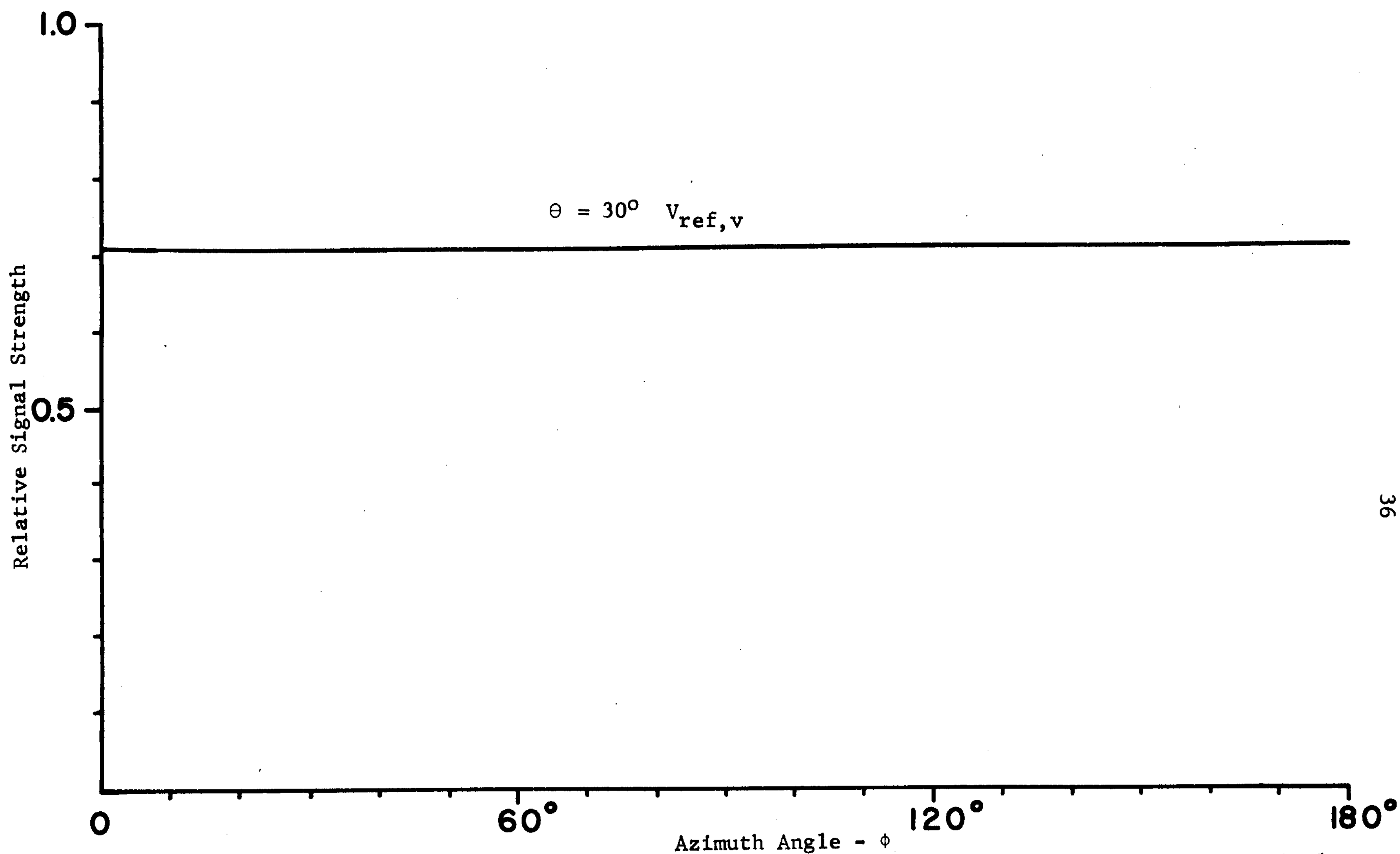

Fig. A-3--Directional characteristics of received signal-reference signal from vertical ring $V_{ref,v}$.

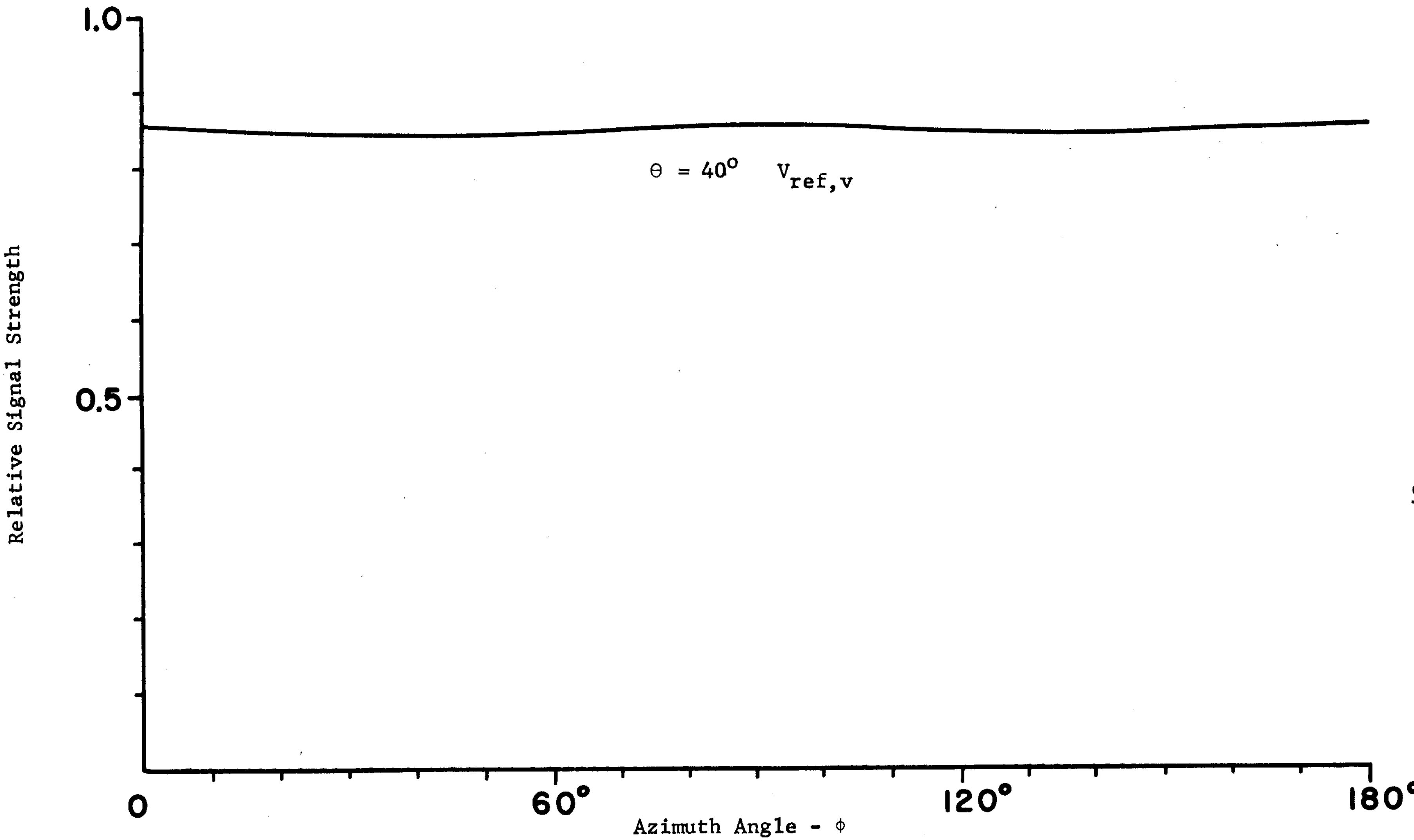

Fig. A-4--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

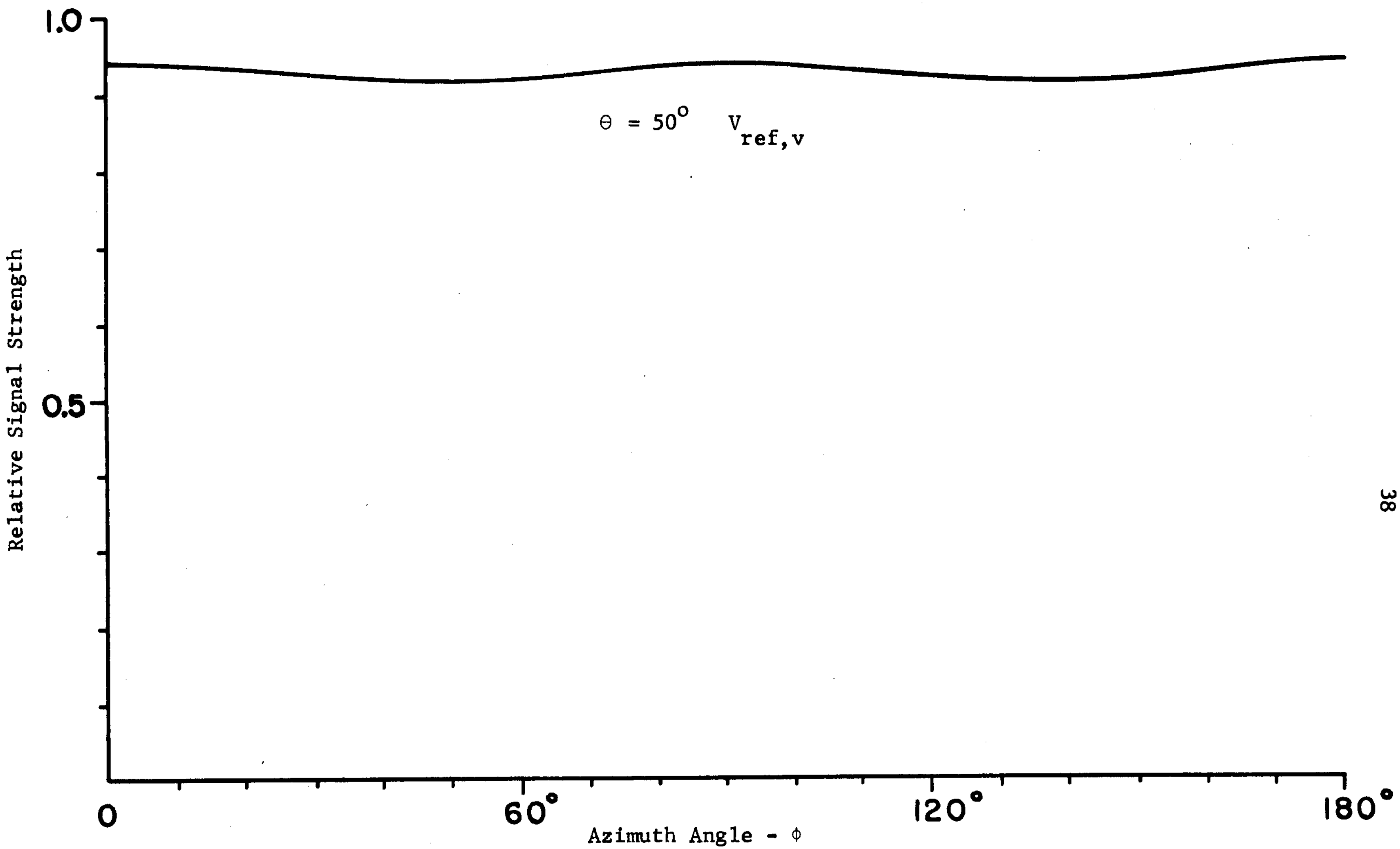

Fig. A-5--Directional characteristics of received signal-reference signal from vertical ring $V_{ref,v}$.

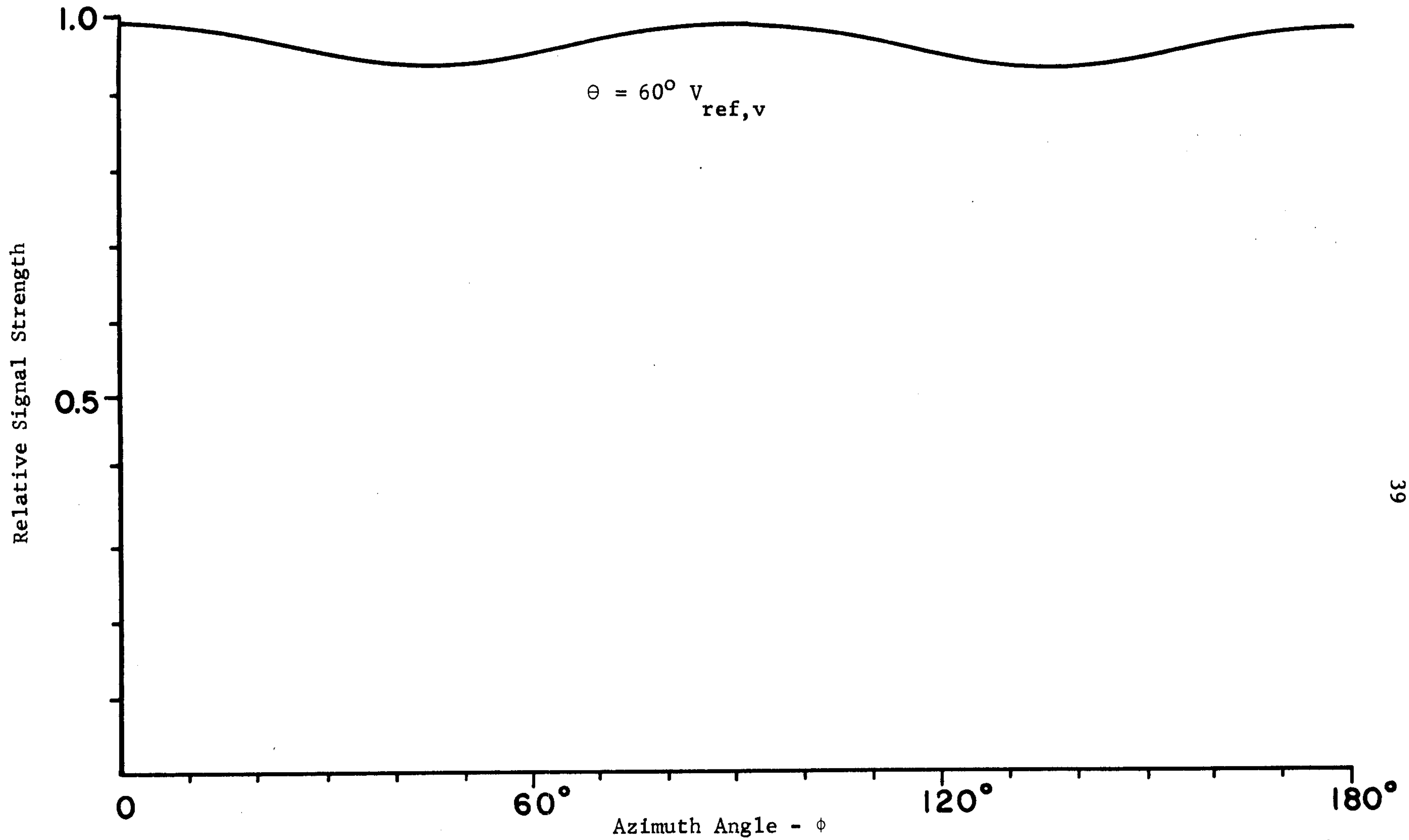

Fig. A-6--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

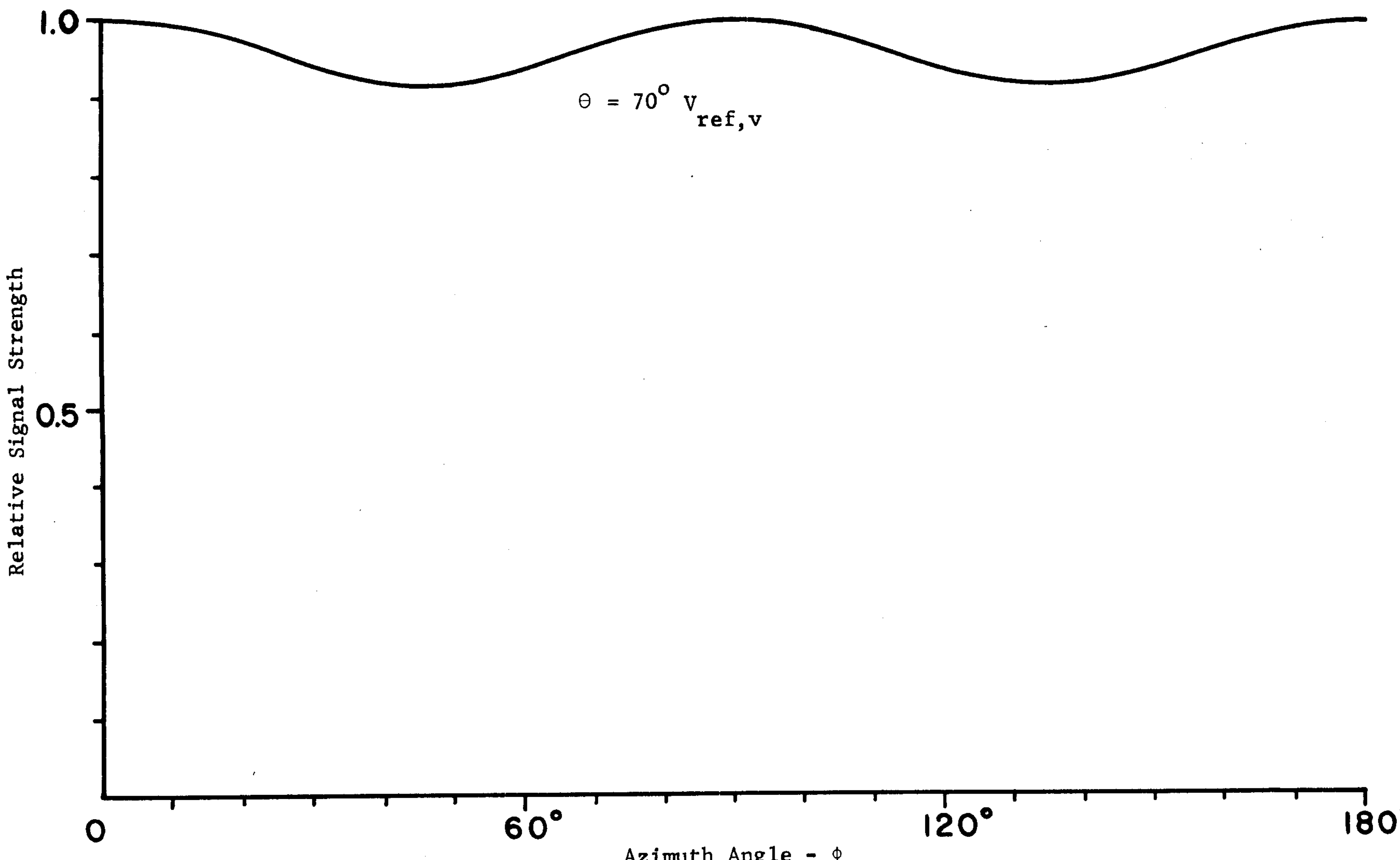

Fig. A-7--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

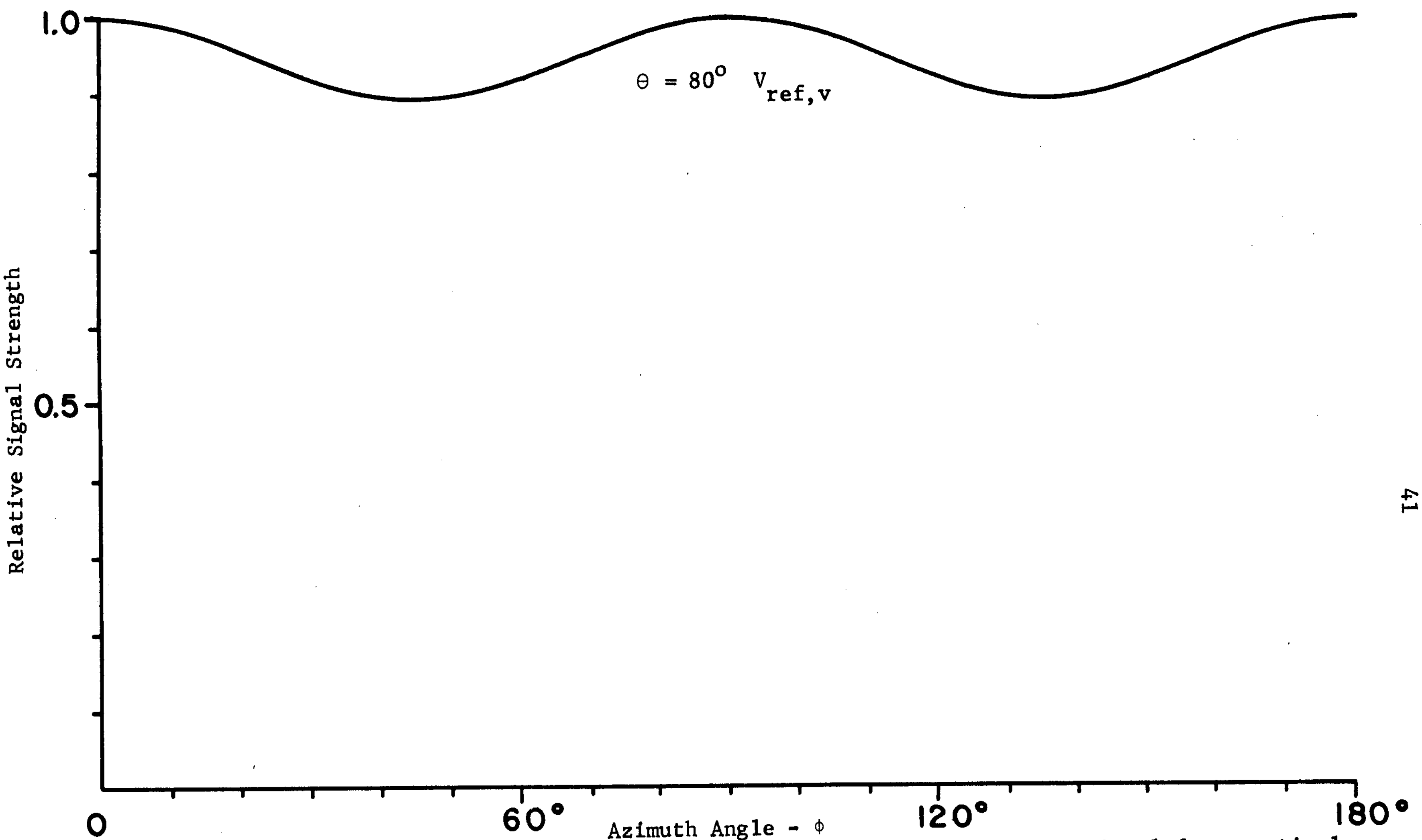

Fig. A-8--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

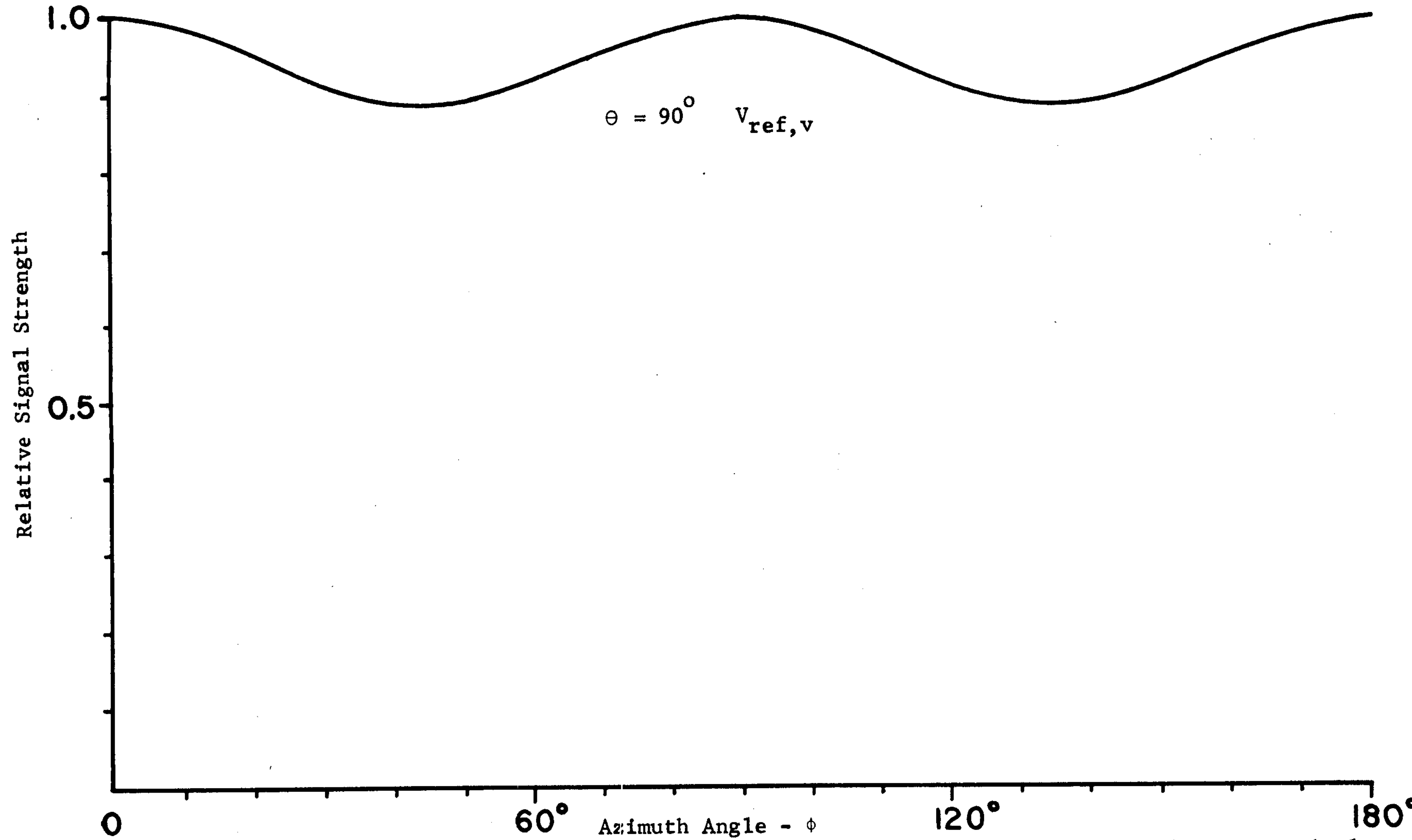

Fig. A-9--Directional characteristics of received signal-reference signal from vertical ring, $V_{ref,v}$.

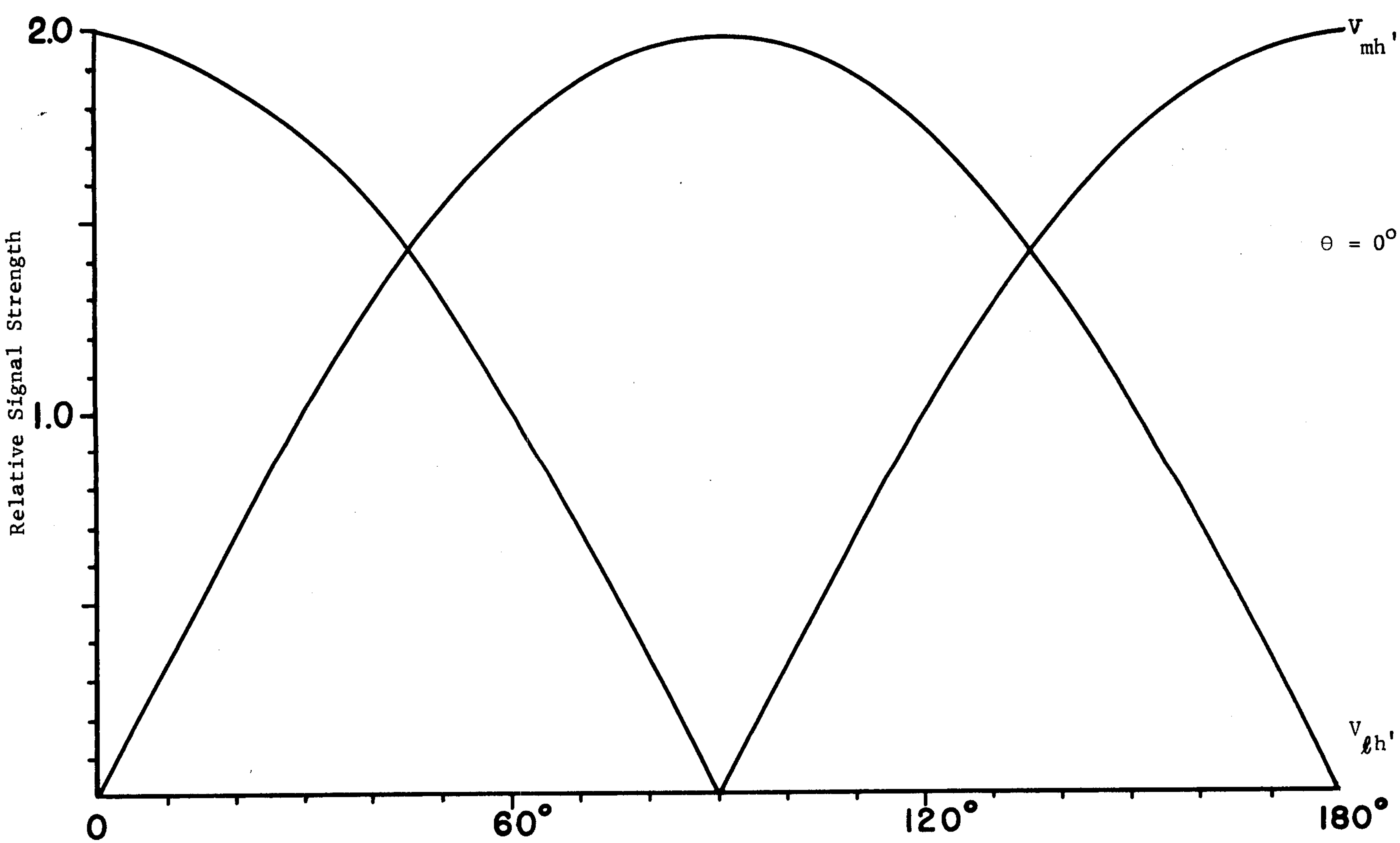

Fig. A-10--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V'_{\ell h}$, V'_{mh}.

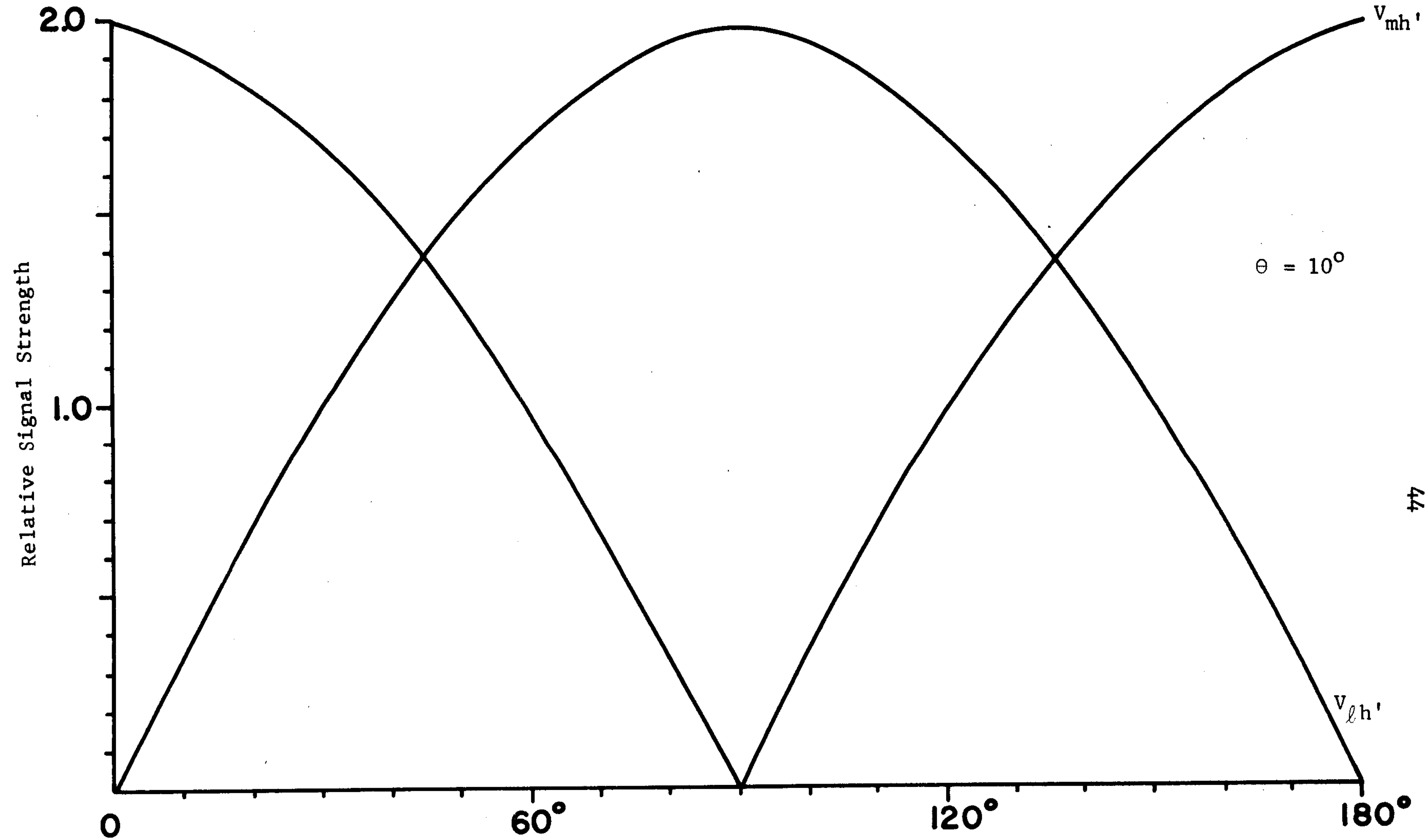

Fig. A-11--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V'_{\ell h}$, V'_{mh}.

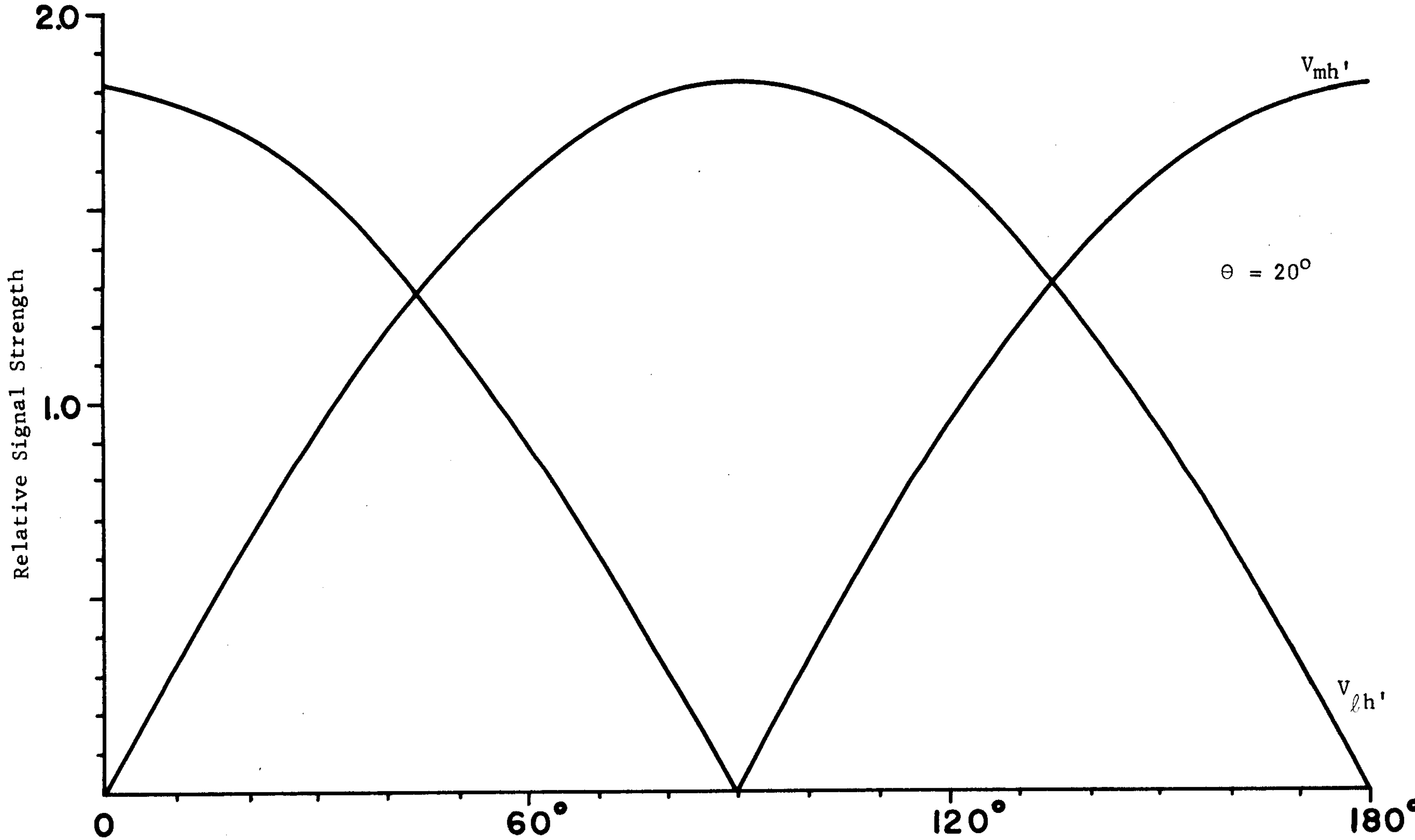

Fig. A-12--Directional Characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V_{\ell h}'$, V_{mh}'.

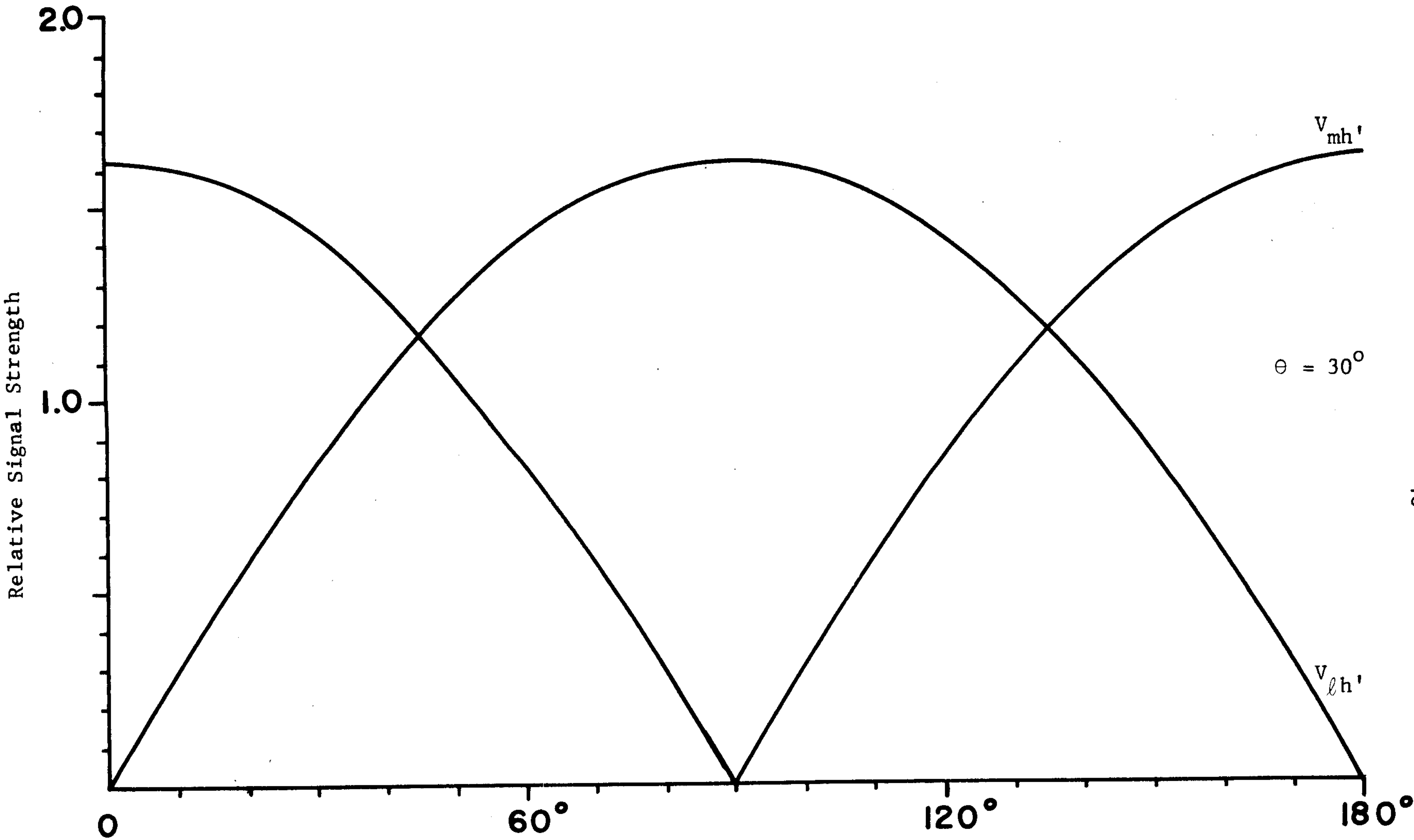

Fig. A-13--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V_{\ell h}'$, V_{mh}'.

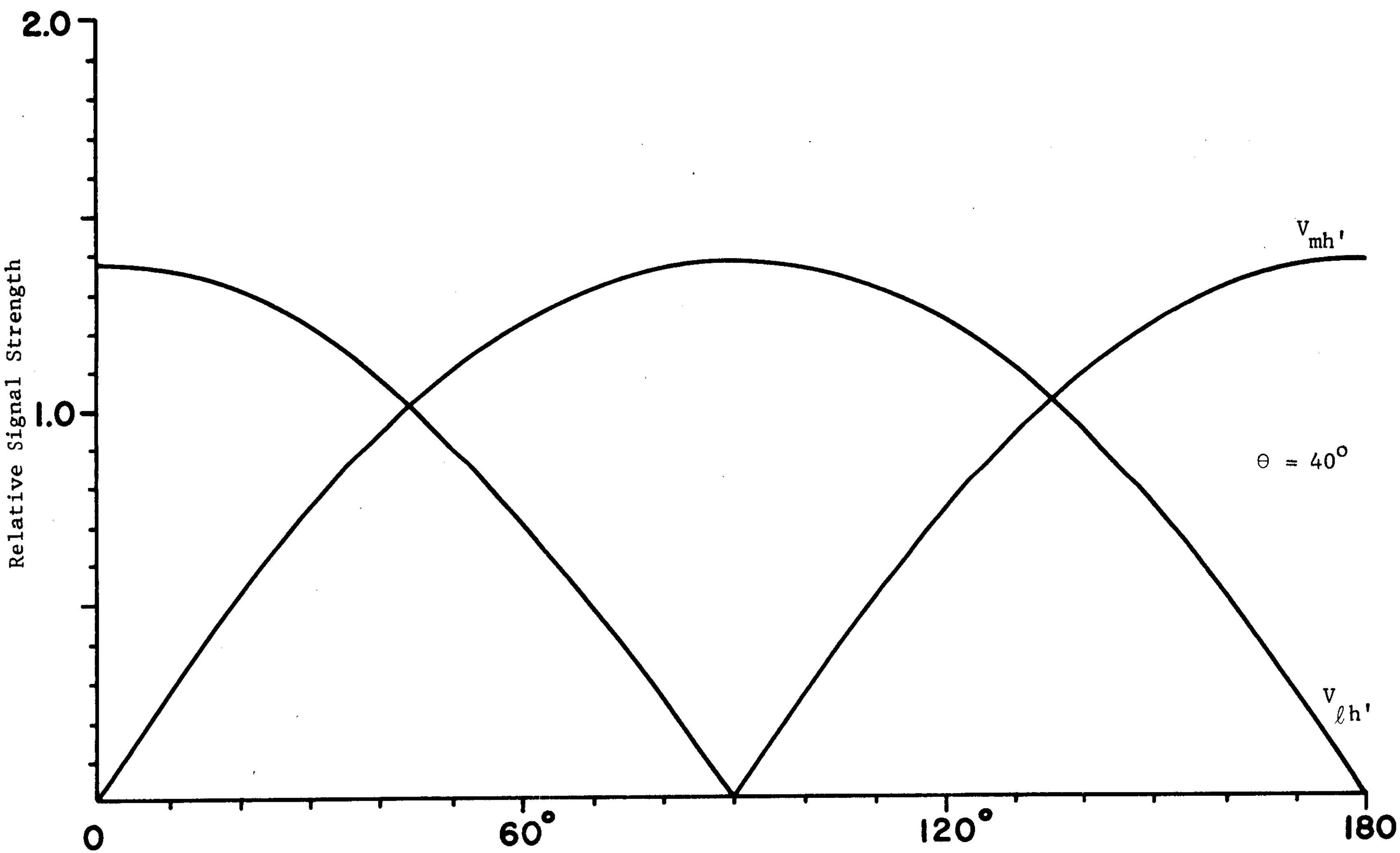

Fig. A-14--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V_{\ell h}'$, V_{mh}'.

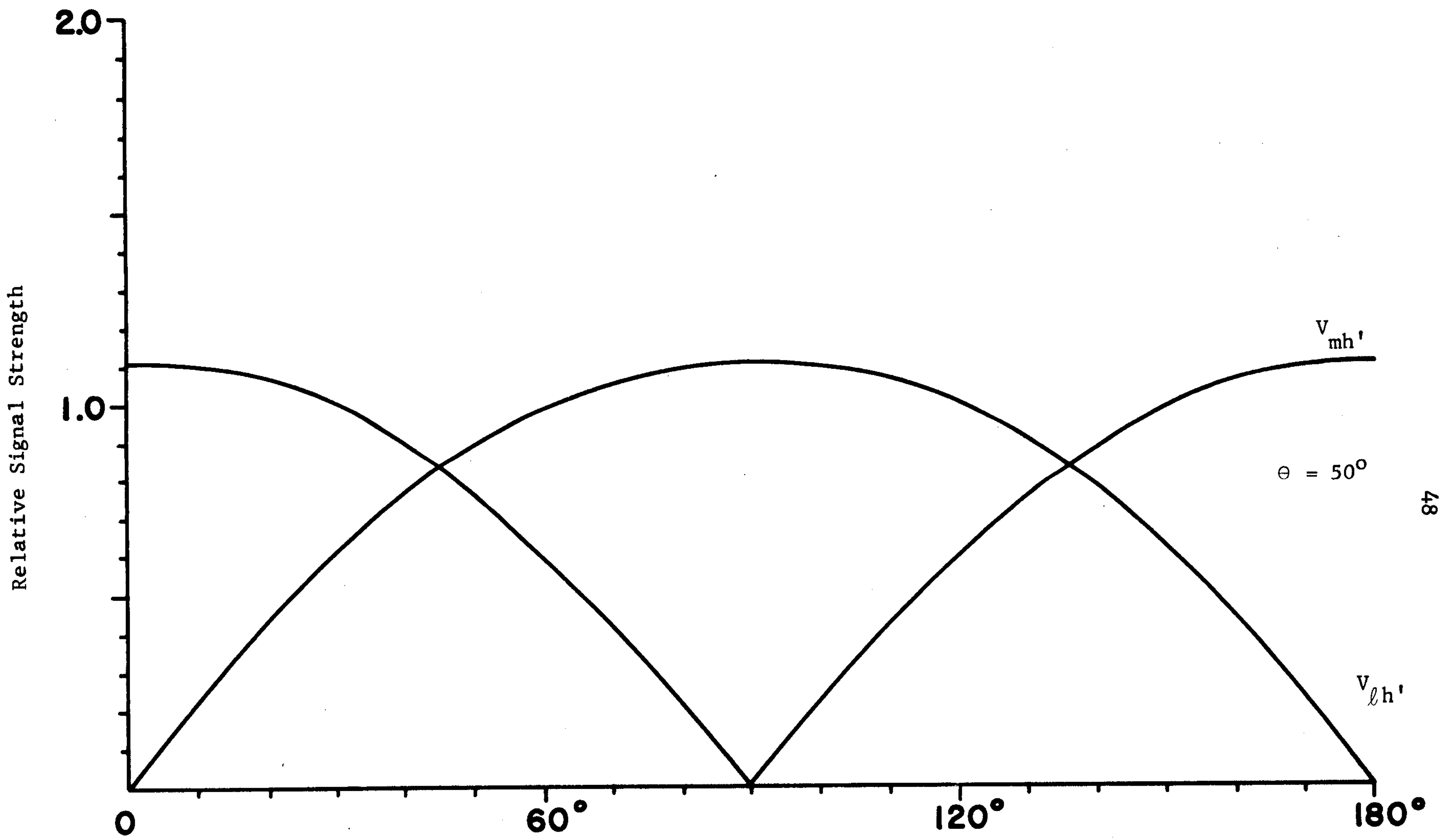

Fig. A-15--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V_{\ell h}'$, V_{mh}'.

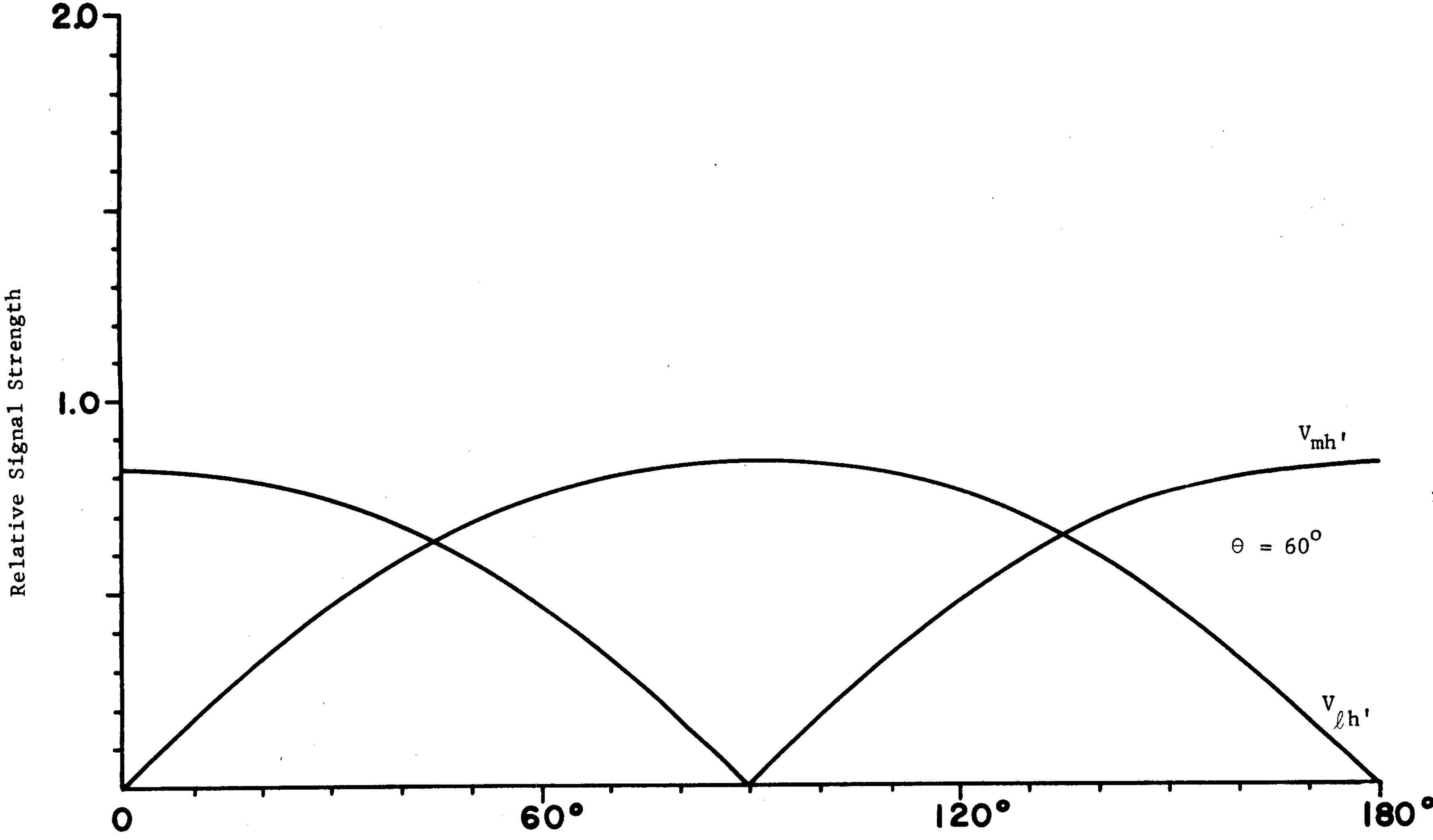

Fig. A-16--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V'_{\ell h}$, V'_{mh}.

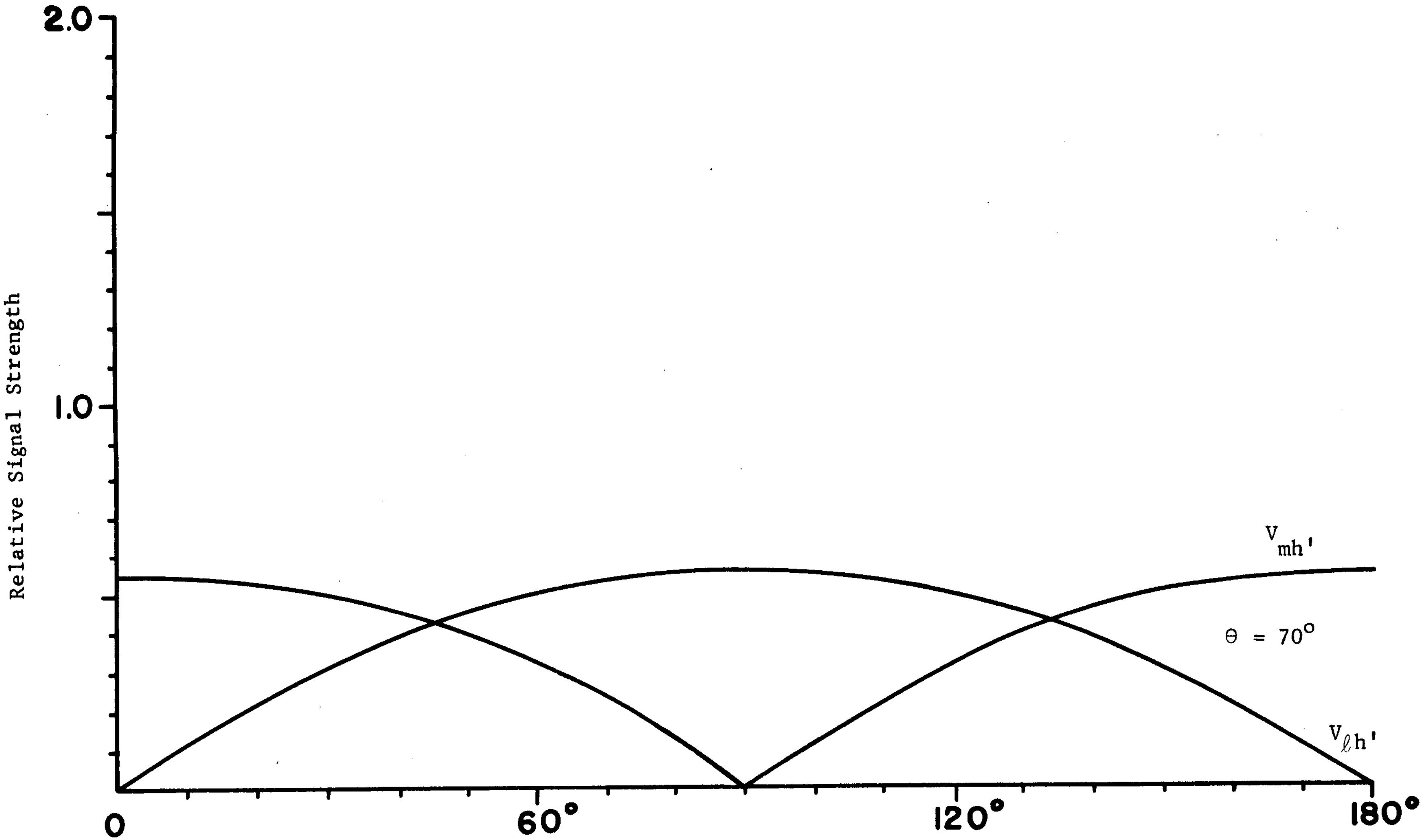

Fig. A-17--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V'_{\ell h}$, V'_{mh}.

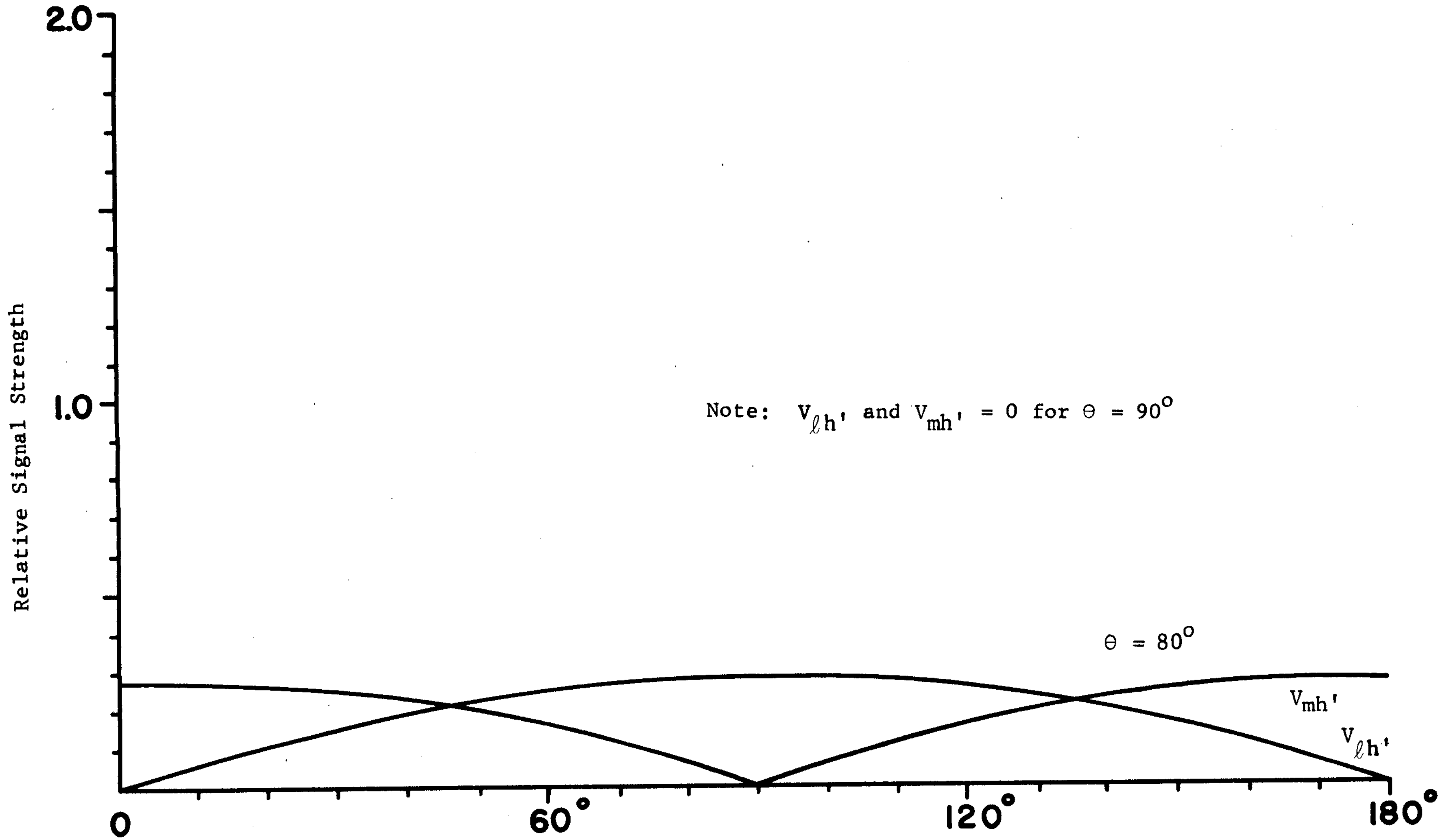

Fig. A-18--Directional characteristics of received signal-phase signals from horizontal ring for Θ-polarization $V_{\ell h}'$, V_{mh}'.

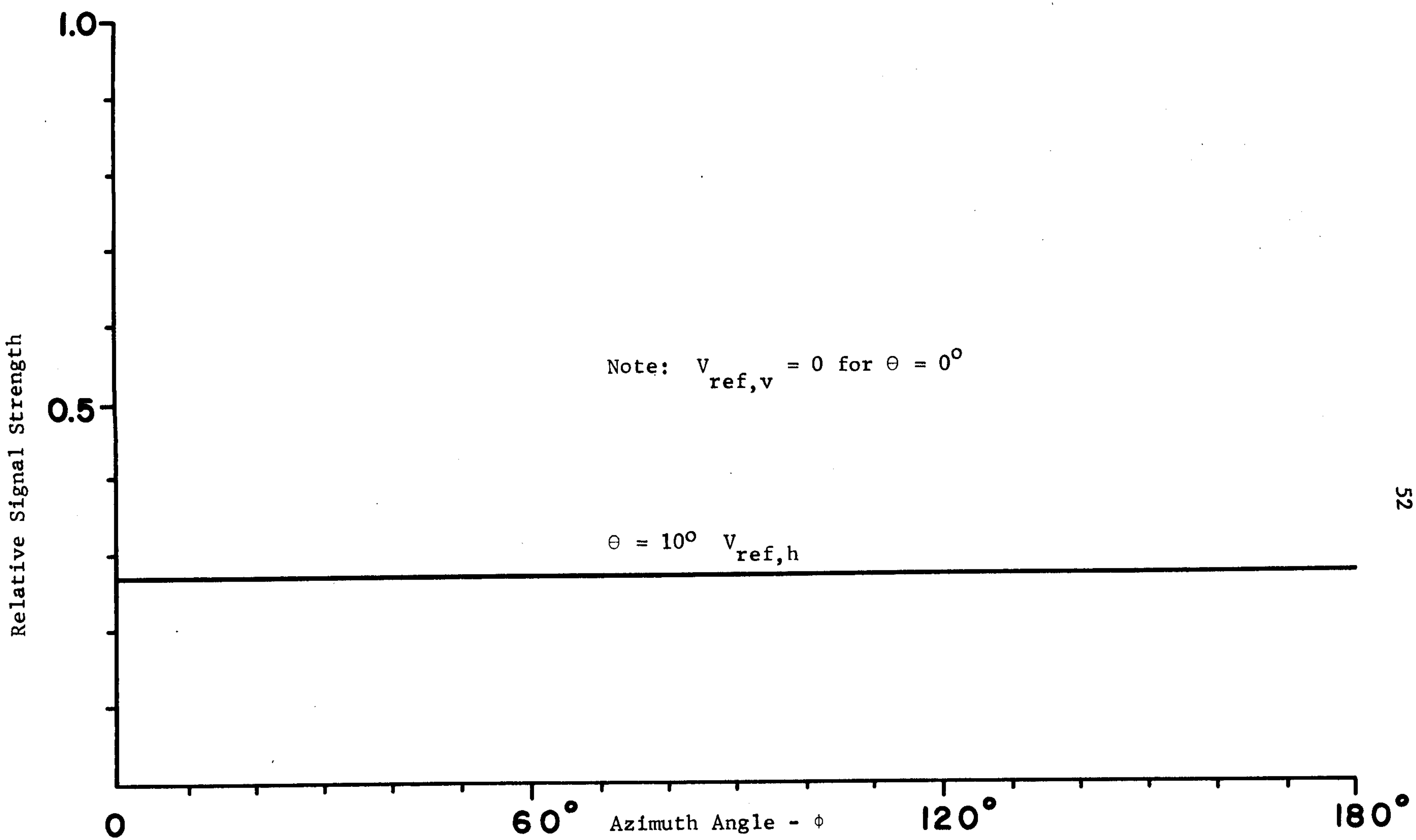

Fig. A-19--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

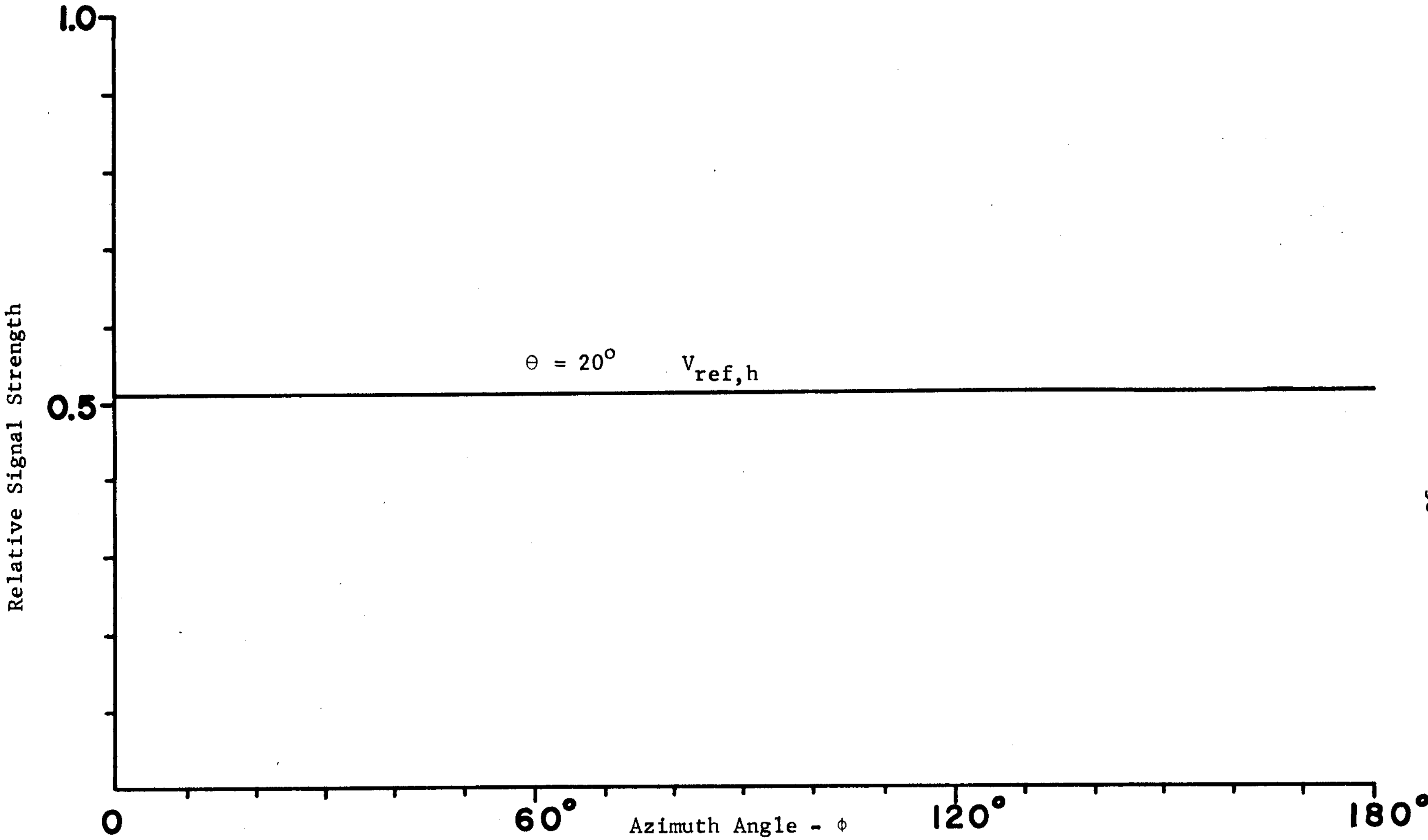

Fig. A-20--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

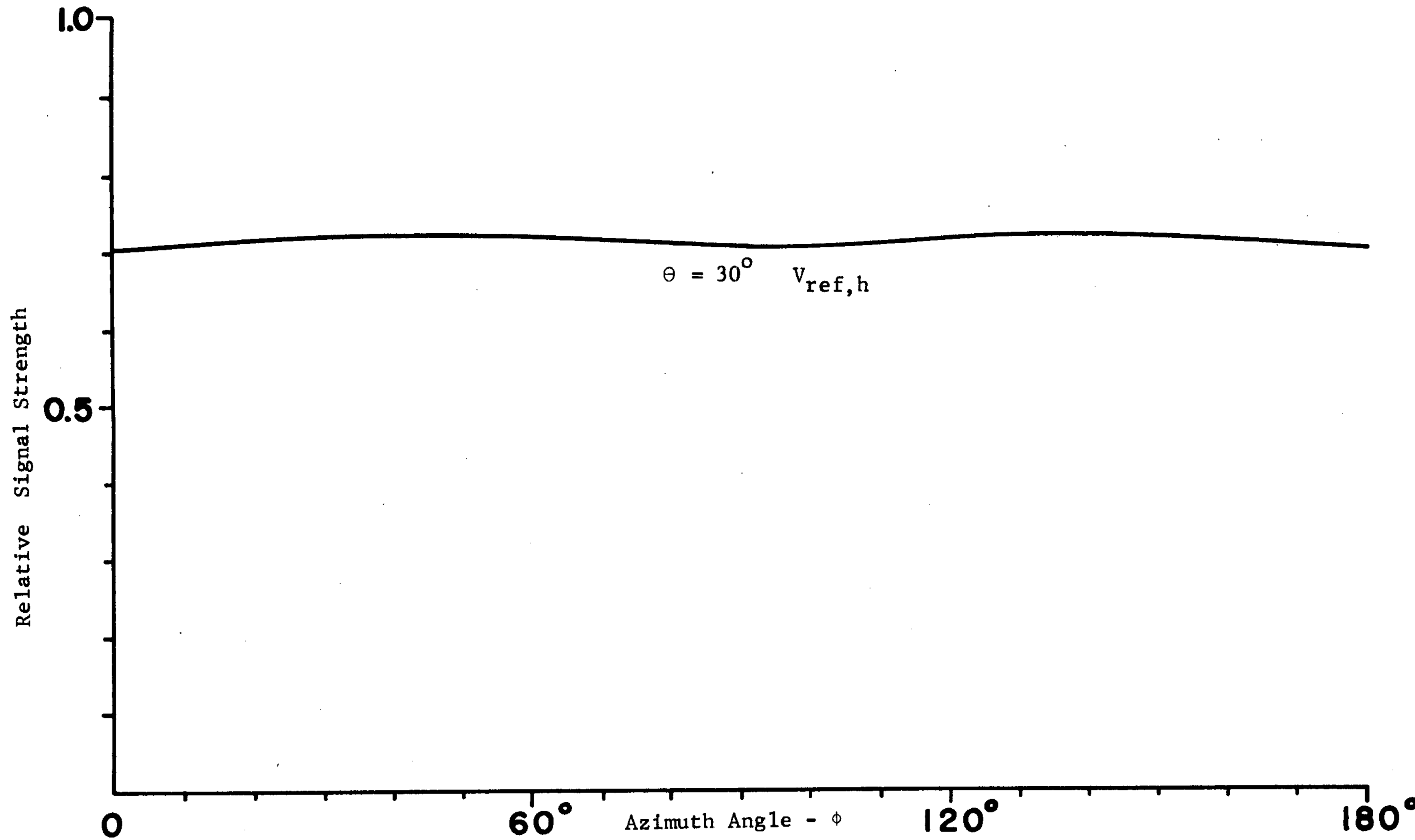

Fig. A-21--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

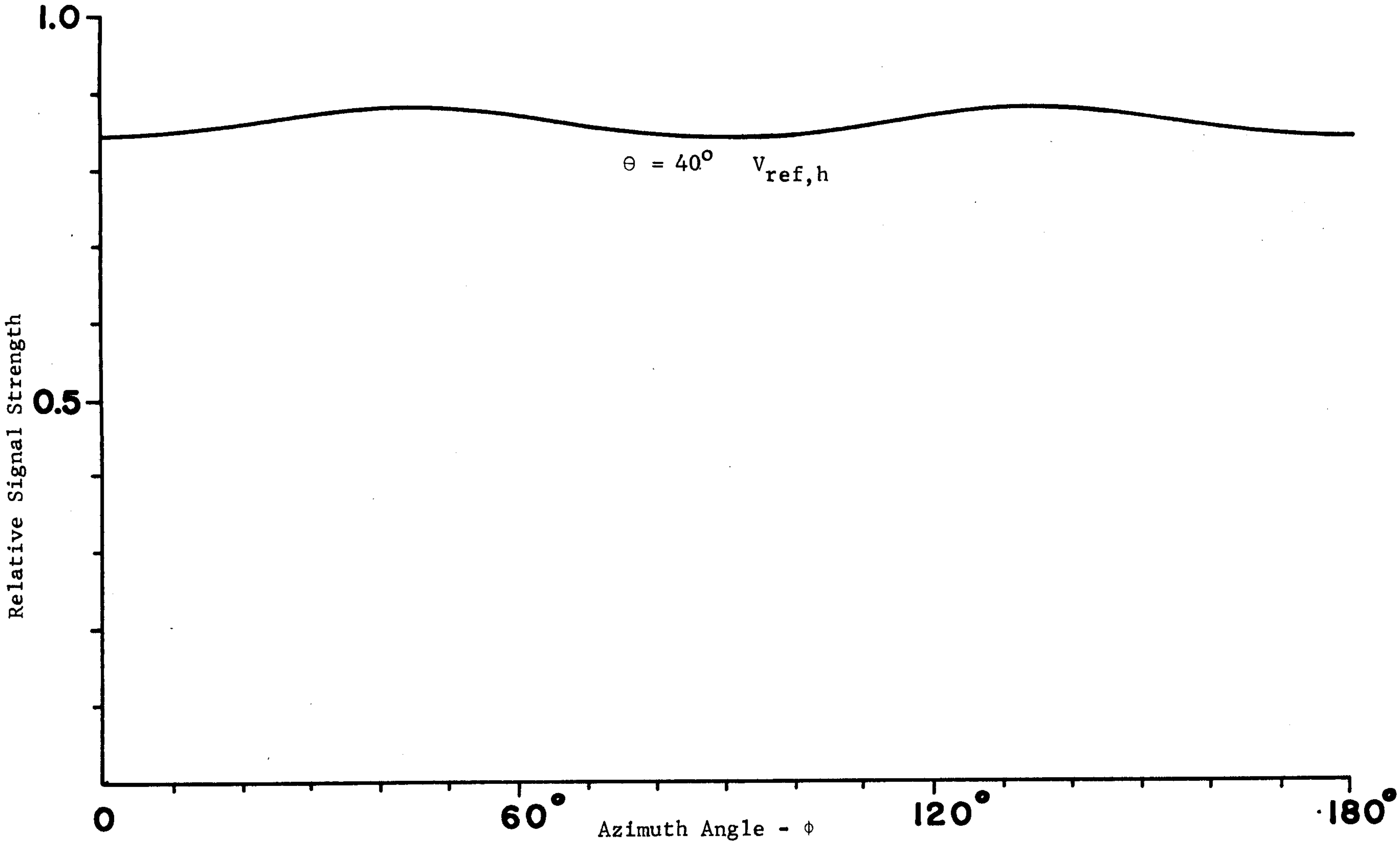

Fig. A-22--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

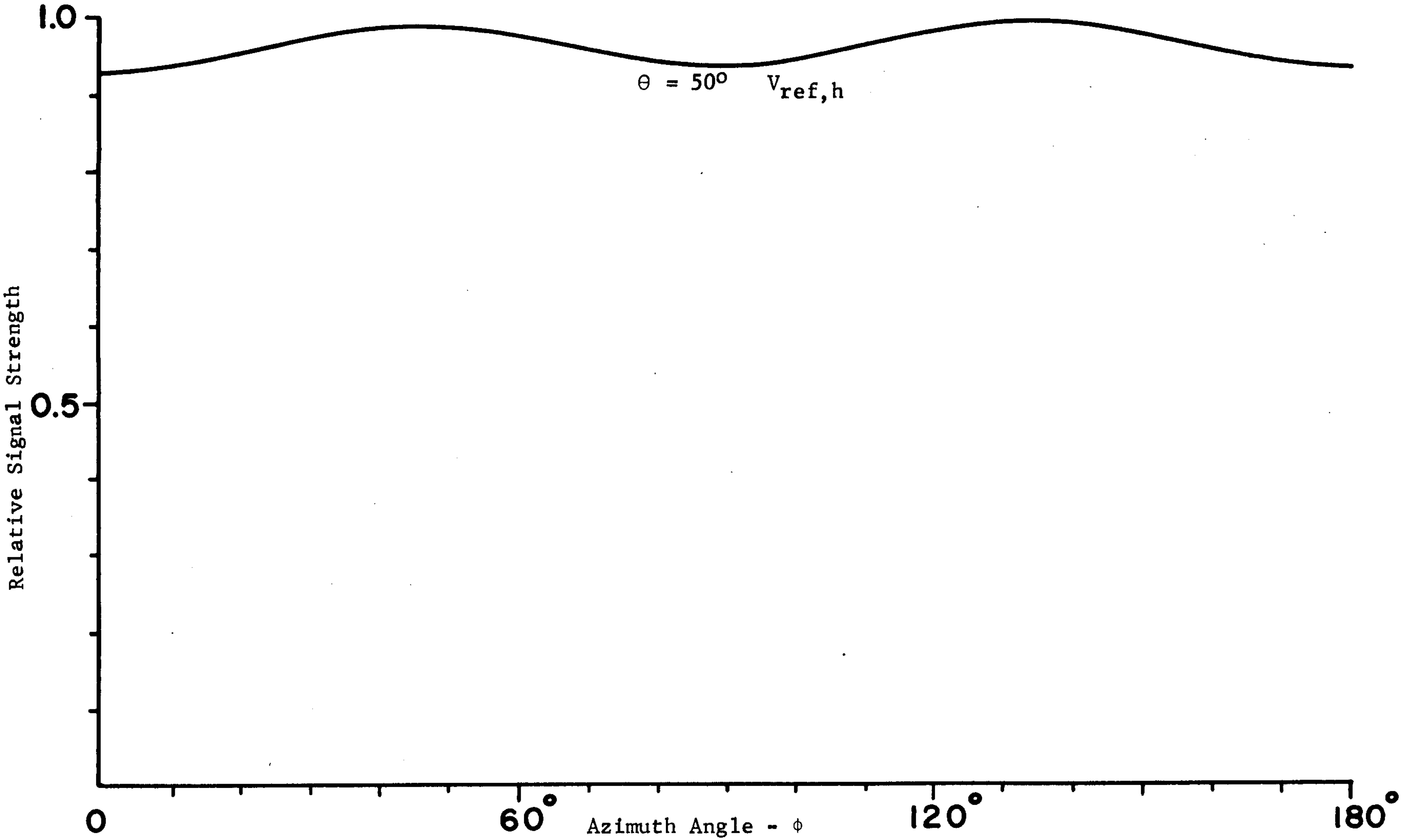

Fig. A-23--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

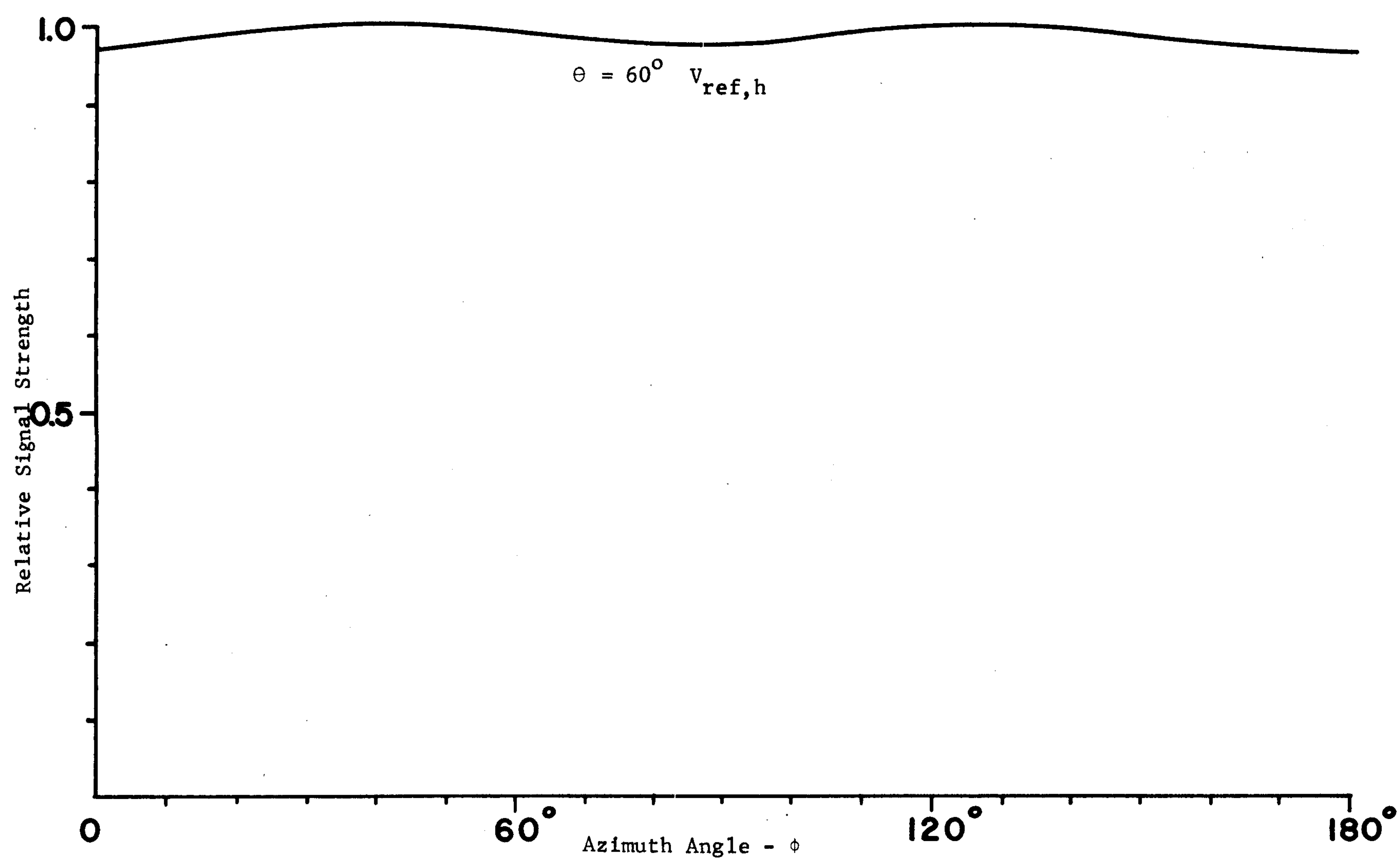

Fig. A-24--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

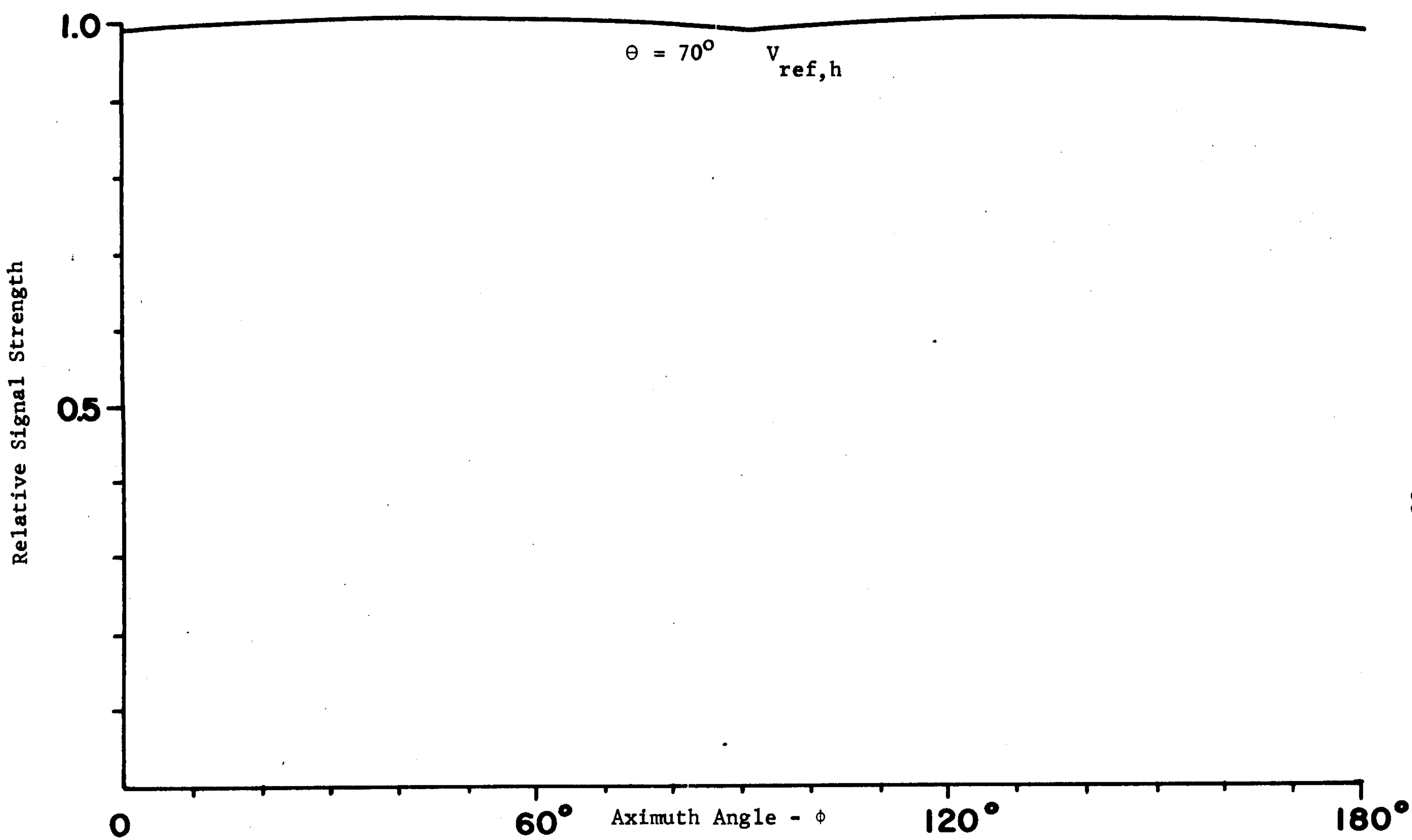

Fig. A-25--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

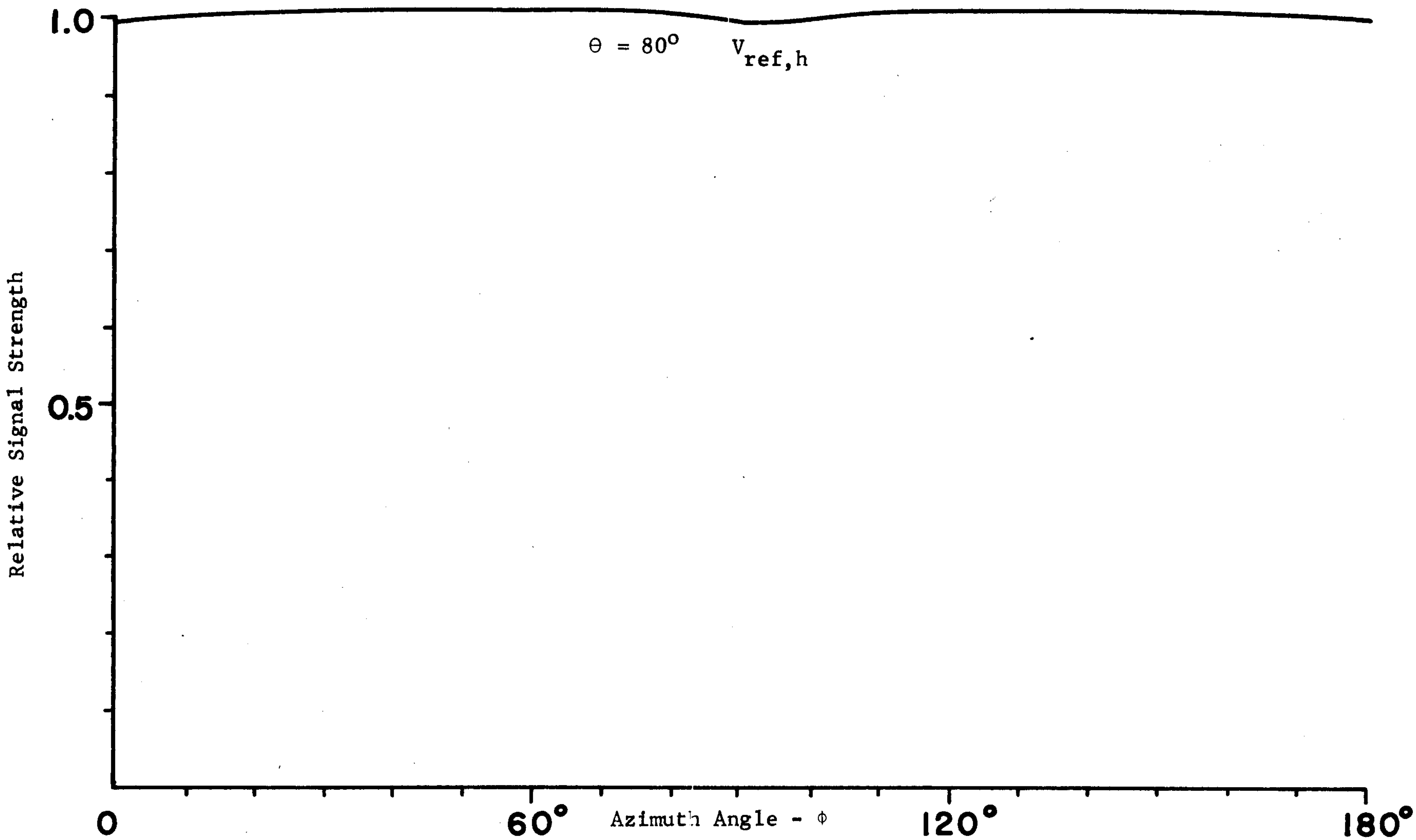

Fig. A-26--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

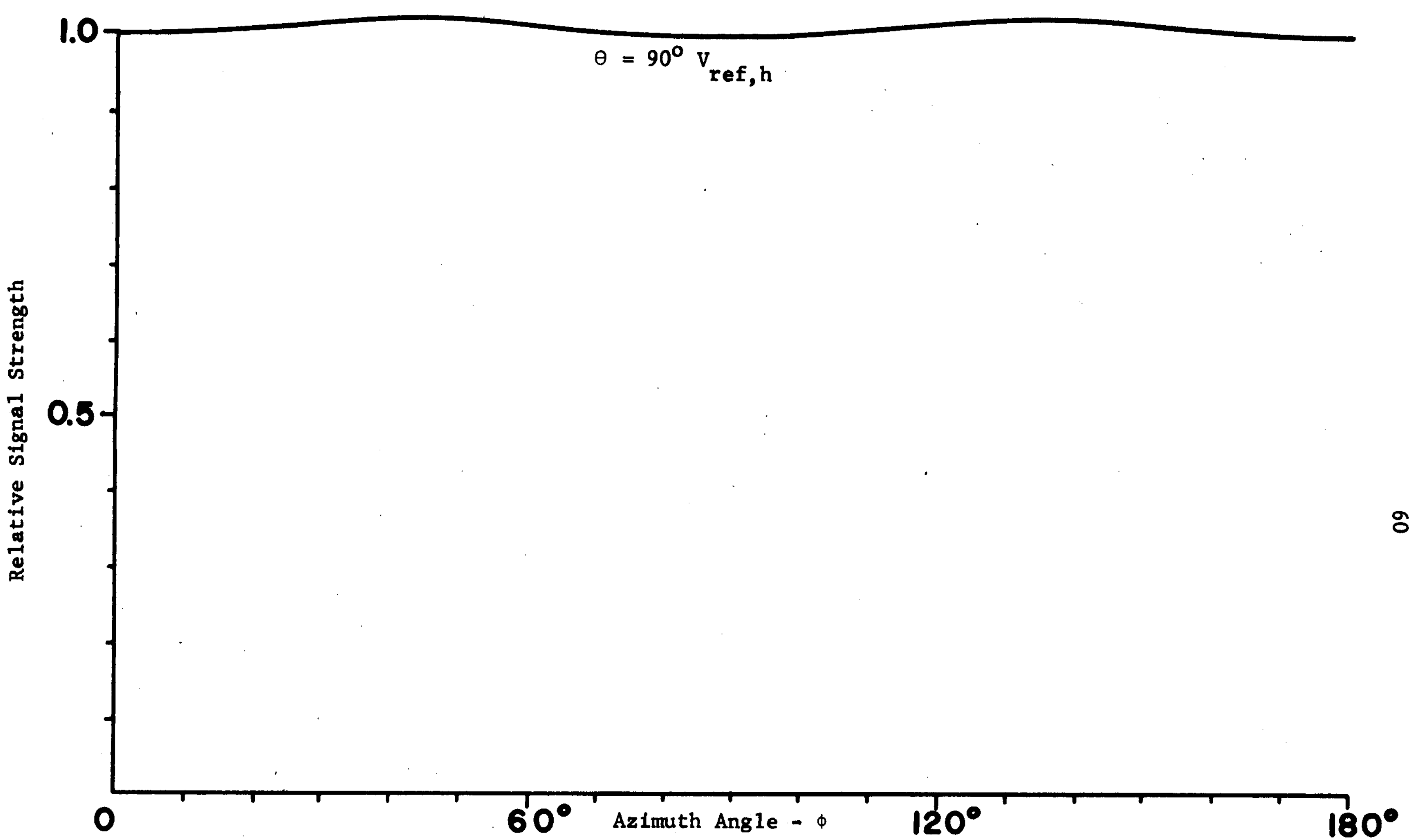

Fig. A-27--Directional characteristics of received signal-reference signal from horizontal ring for ϕ-polarization - $V_{ref,h}$.

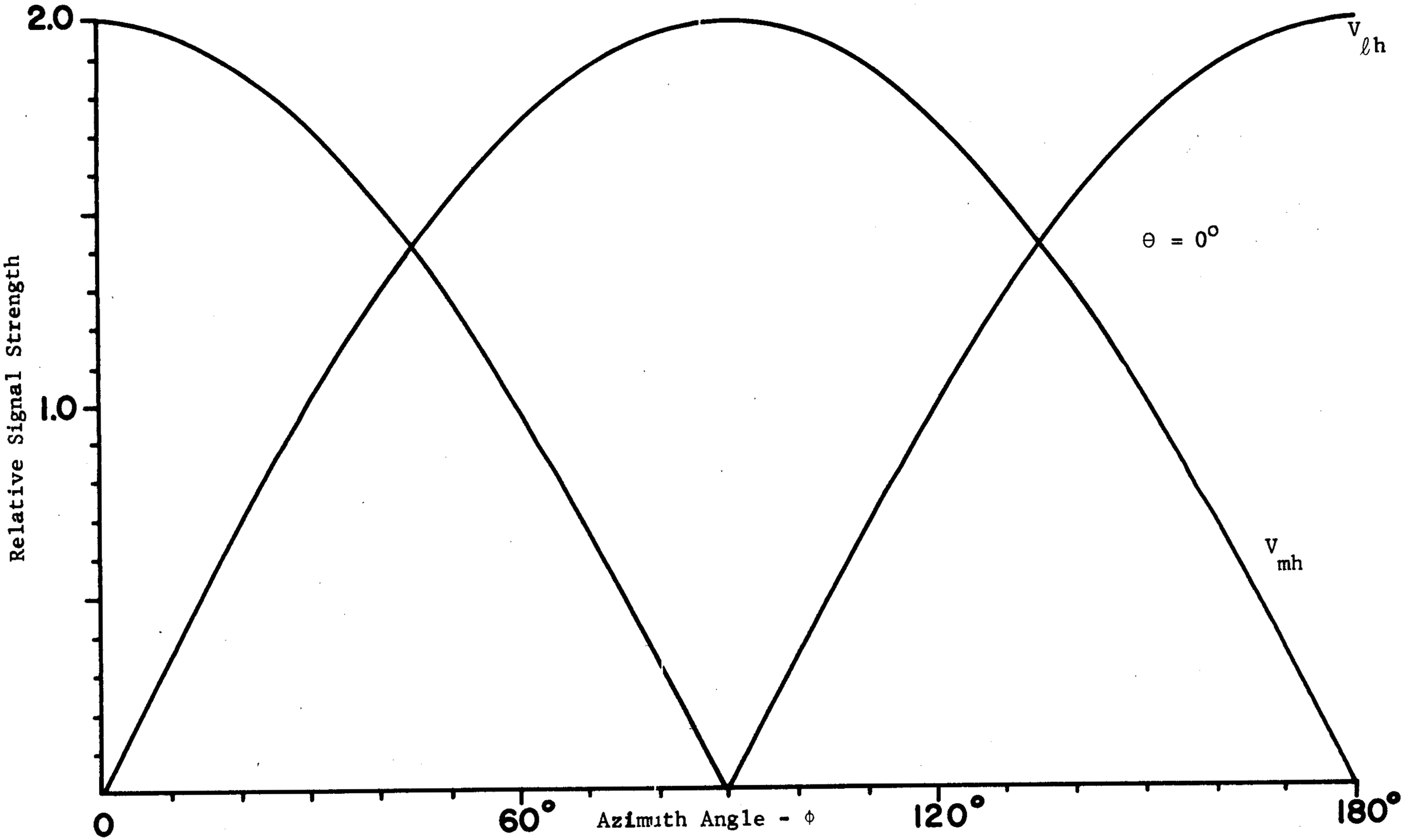

Fig. A-28--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

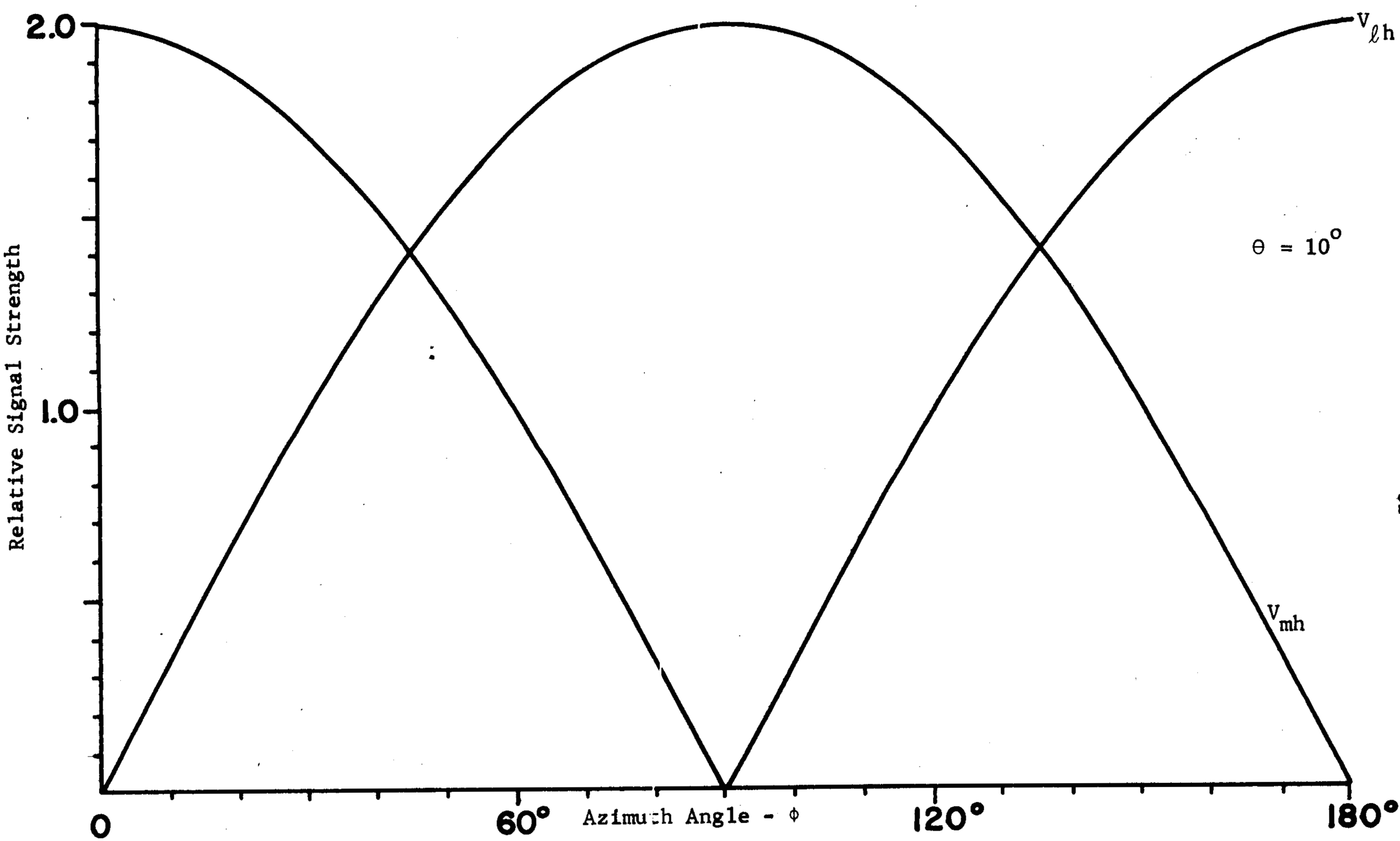

Fig. A-29--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

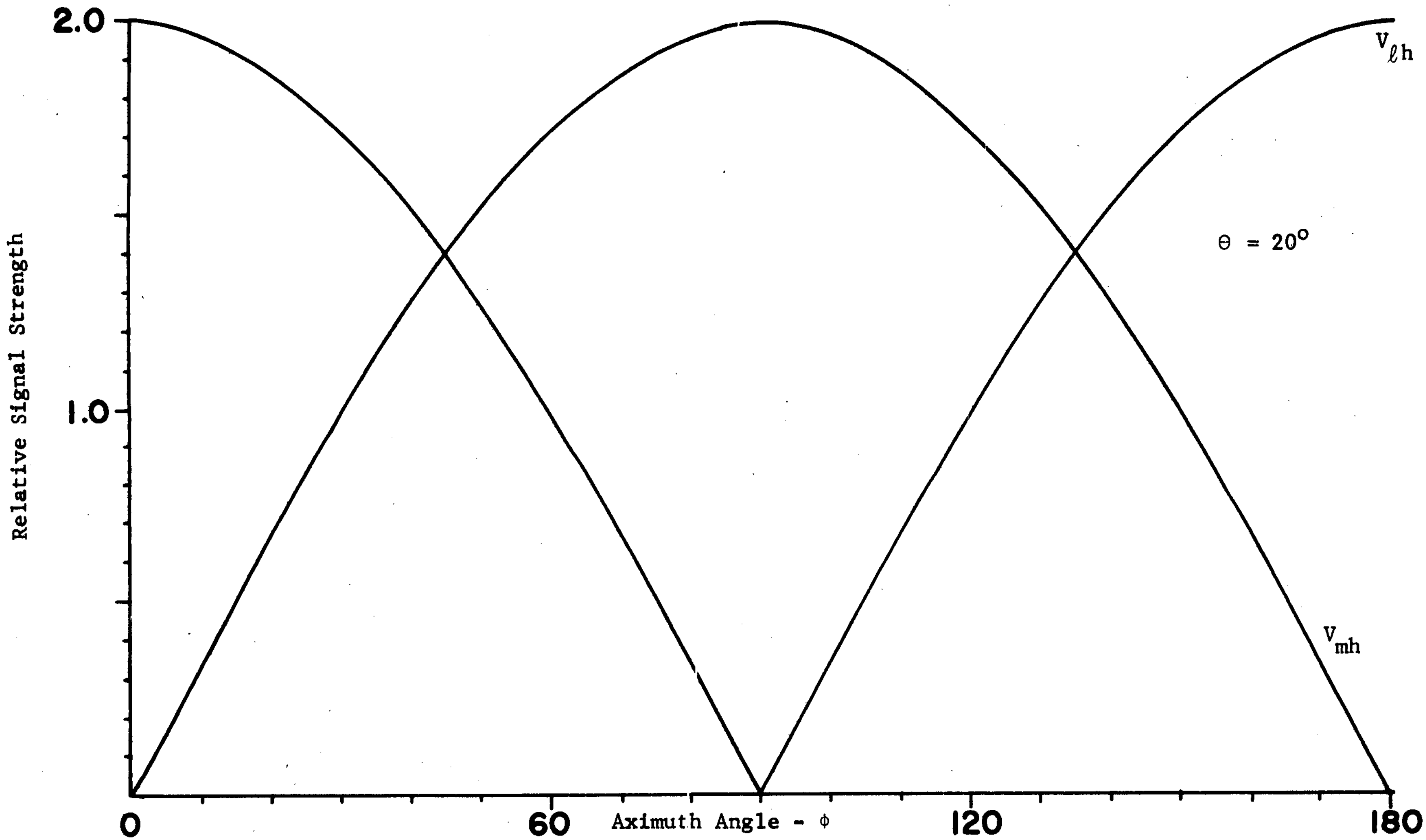

Fig. A-30--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

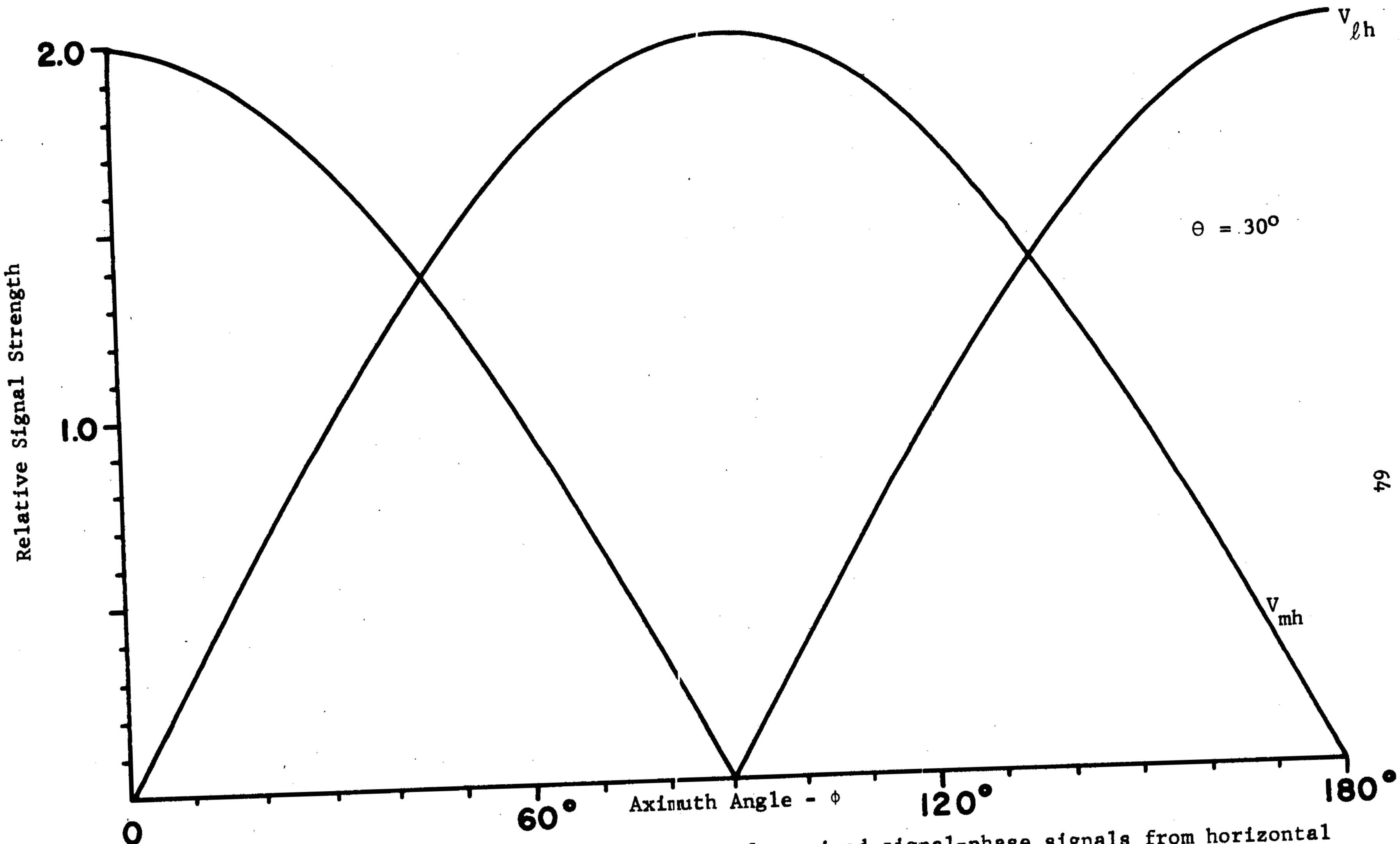

Fig. A-31--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

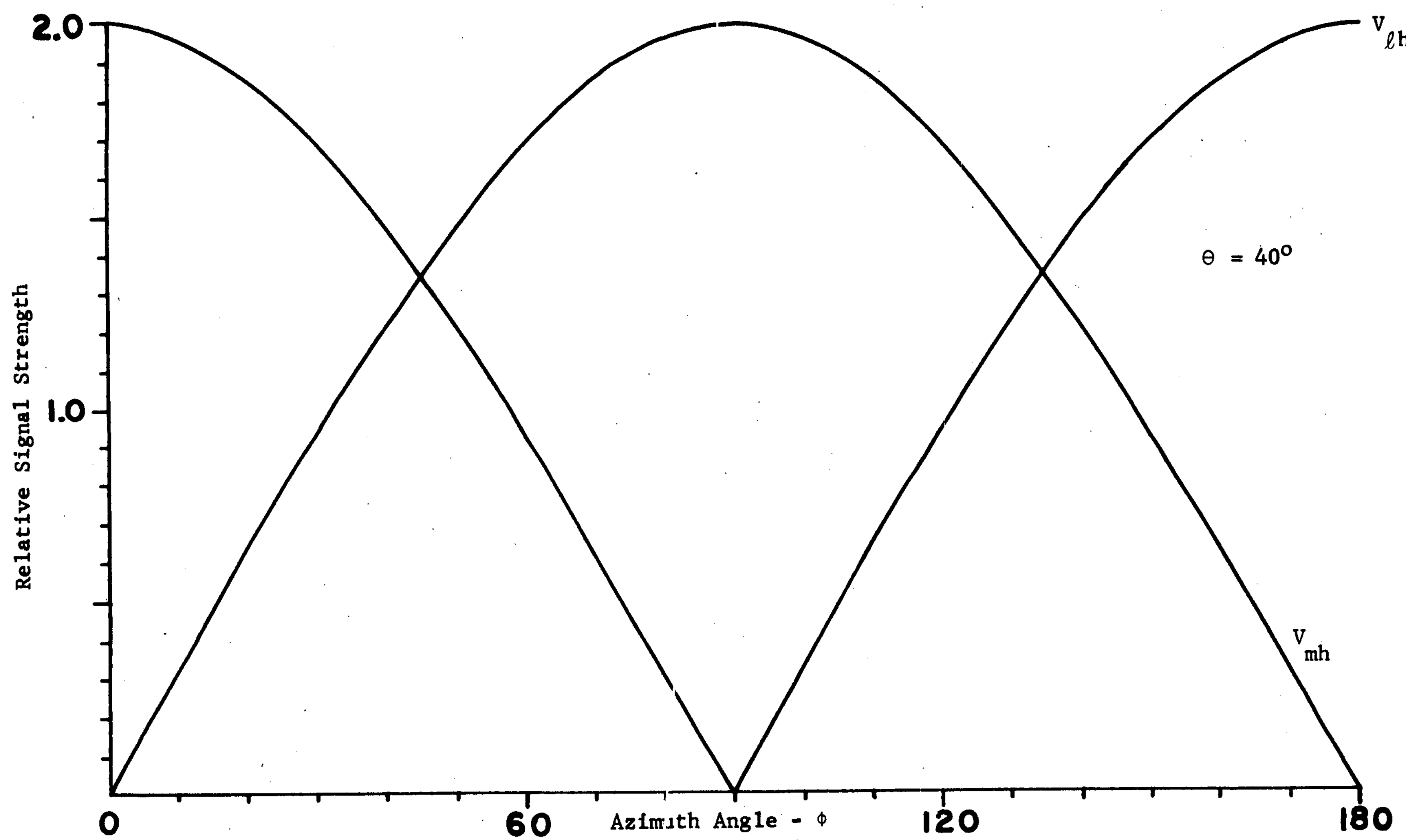

Fig. A-32--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

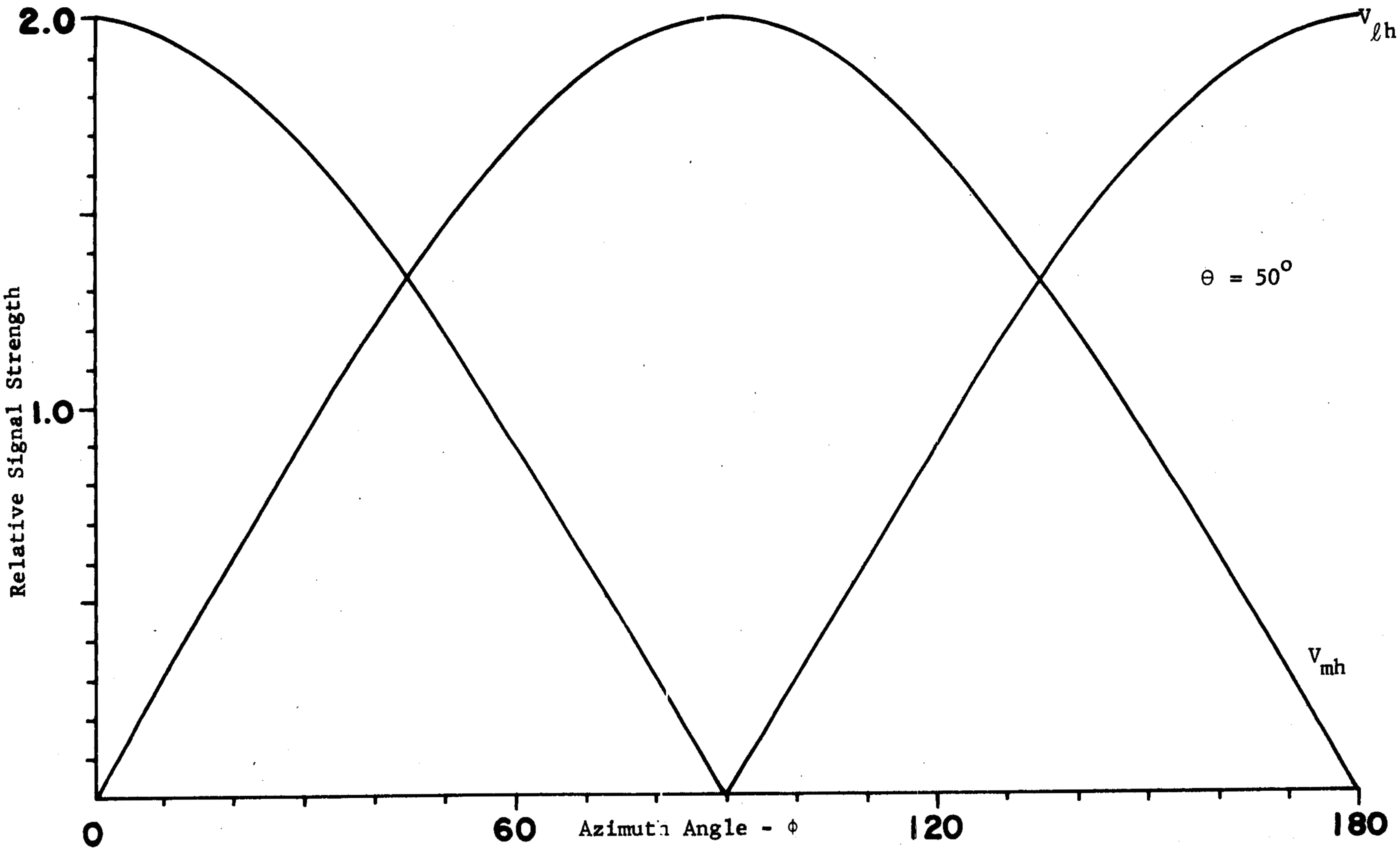

Fig. A-33--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

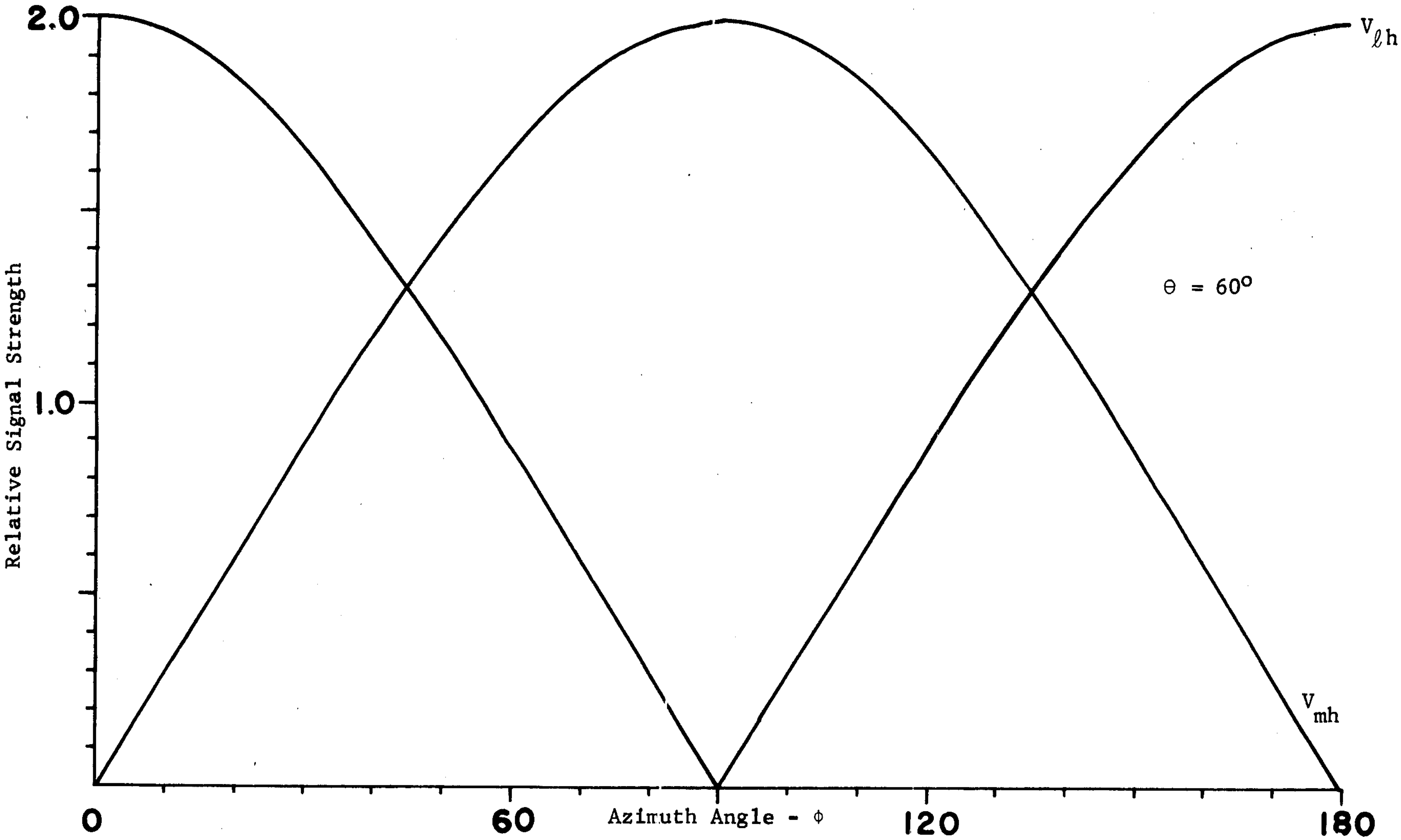

Fig. A-34--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}, V_{mh}$.

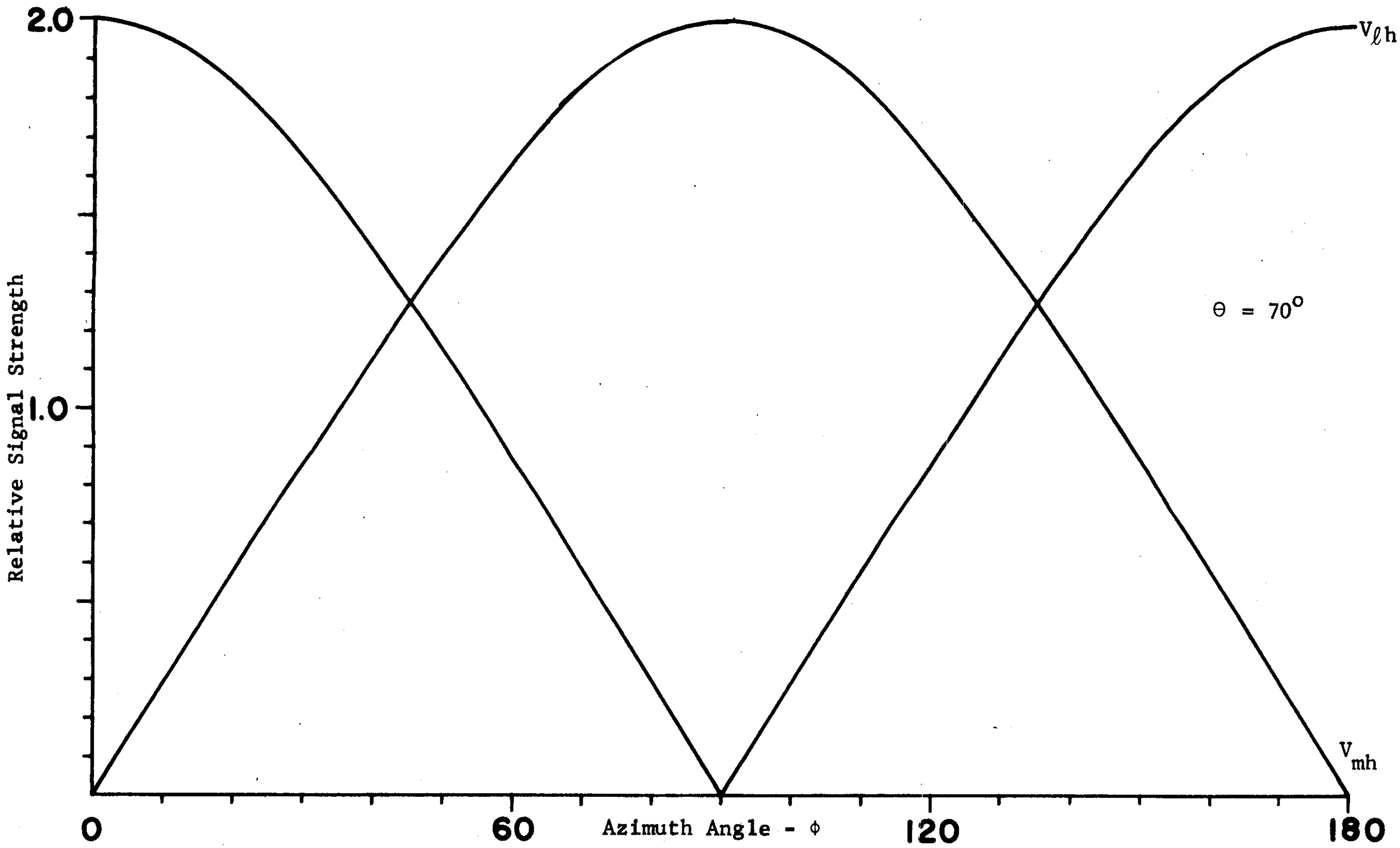

Fig. A-35--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

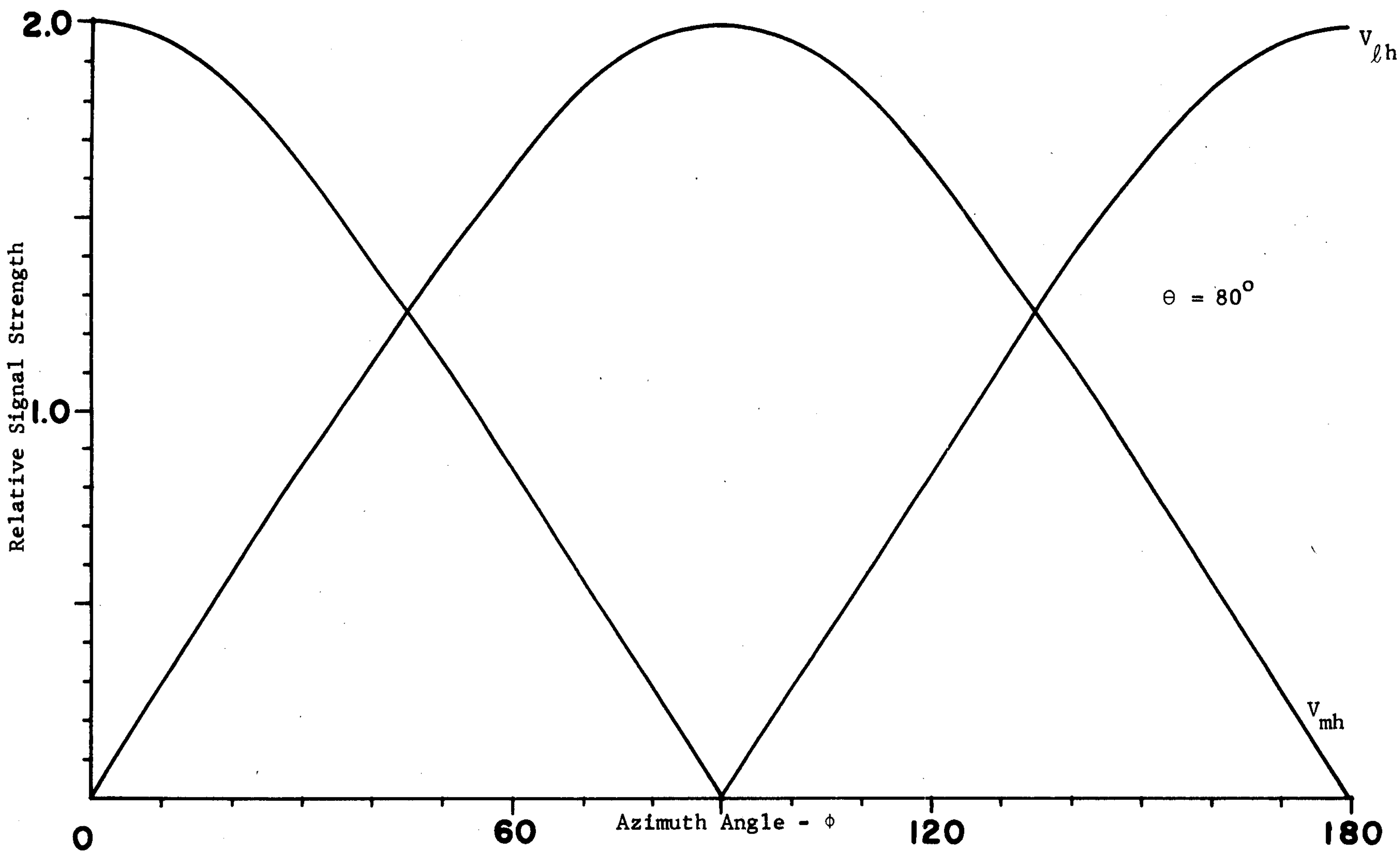

Fig. A-36--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

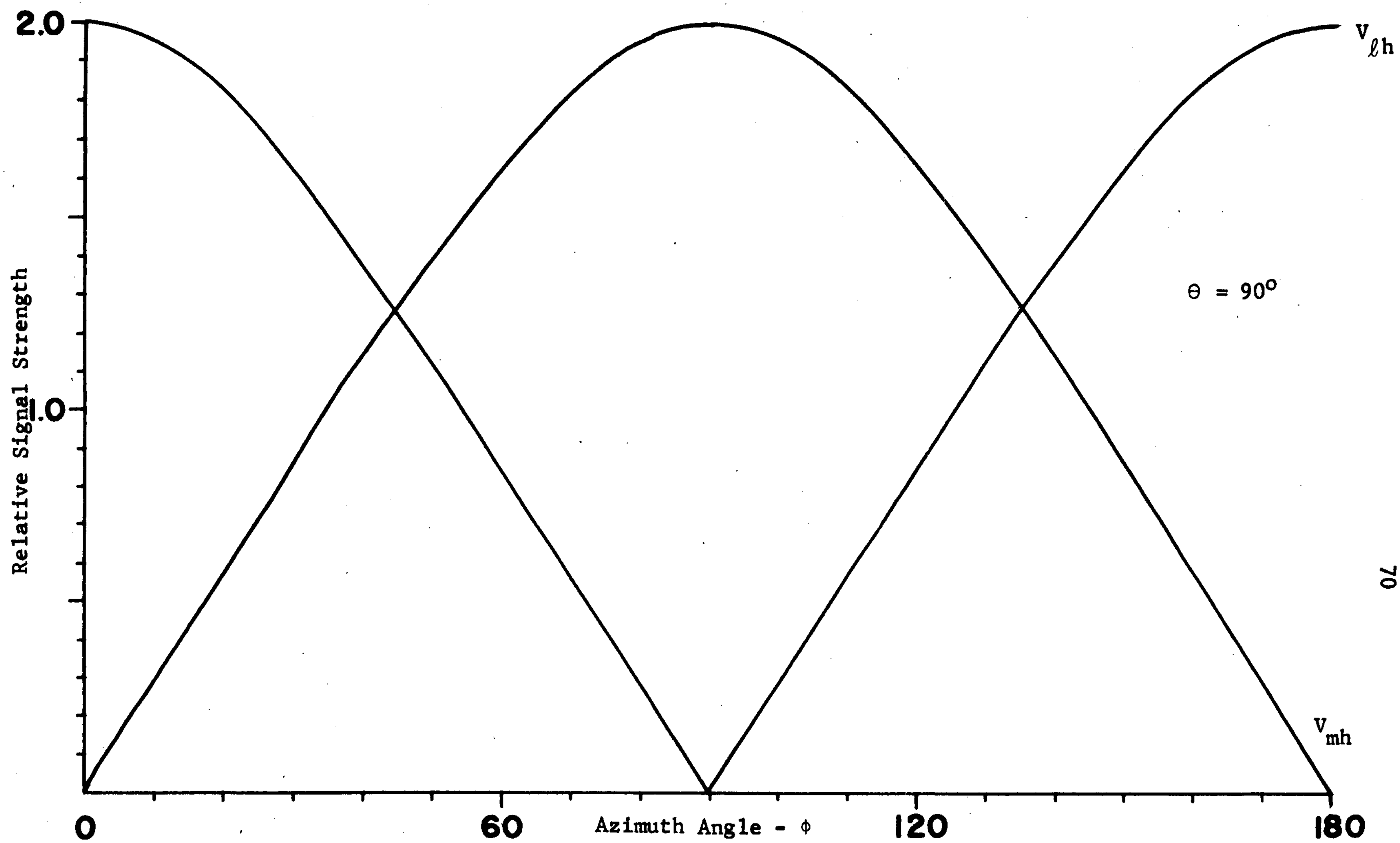

Fig. A-37--Directional characteristics of received signal-phase signals from horizontal ring for ϕ-polarization - $V_{\ell h}$, V_{mh}.

APPENDIX B

The following is the computer program used to compute the normalized directional characteristics of the received signal. The quantities listed below are referred to by the equation number in the body of the report.

PROGRAM SYMBOL	EQUATION NUMBER
V_1	(31a)
V_2	(32a)
V_3	(32b)
V_4	(32c)
V_5	(33a)
V_6	(33b)
V_7	(33c)

```
$JOB      EE304T   HAYES
$PAGE              20
$IBJOB
$IBFTC
      T=0.0
    5 P=0.0
    6 S1=COS(1.570796*SIN(T)*SIN(P))
      S2=COS(1.570796*SIN(T)*COS(P))
      S3=1.-SIN(T)**2*SIN(P)**2
      S4=1.-SIN(T)**2*COS(P)**2
      T1=T*180./3.14159
      P1=P*180./3.14159
      V1=-COS(1.570796*COS(T))/SIN(T)*(S2+S1)
      V2=COS(T)*(SIN(P)*S1*SIN(1.570796*SIN(T)*COS(P))/S3
     1  -COS(P)*S2*SIN(1.570796*SIN(T)*SIN(P))/S4)
      V3=-2.*COS(T)*SIN(P)*S1/S3
      V4=2.*COS(T)*COS(P)*S2/S4
      V5=COS(P)*S1*SIN(1.570796*SIN(T)*COS(P))/S3
     1  +SIN(P)*S2*SIN(1.570796*SIN(T)*SIN(P))/S4
      V6=-2.*COS(P)*S1/S3
      V7=-2.*SIN(P)*S2/S4
      WRITE(6,100)T1,P1,V1,V2,V3,V4,V5,V6,V7
      P=P+5.*3.14159/180.
      IF(P.LT.3.1416) GO TO 6
      T=T+5.*3.14159/180.
      IF(T.LT.1.5708) GO TO 5
  100 FORMAT(1X,2F10.1,7F15.4)
      STOP
      END
$ENTRY
$IBSYS
```