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RM-4949-NASA, The Effective Directivity of an Isotropic Antenna Looking Down Through the Atmosphere, R. L. Kirkwood, July 1966.

PURPOSE: To investigate the effect of the ionosphere on the effective directivity of an isotropic, low-frequency antenna looking down on the earth from a satellite.

SCOPE: The factor by which the ionosphere reduces the actual energy density at the satellite is derived in the form of a ratio representing effective antenna gain. A model for the ionosphere is developed, and the antenna directivity obtained at various frequencies is estimated. The antenna directivity at optimum frequency of observation (1.3 to 1.5 times the critical frequency) is then compared with the directivity that a broadside array would have if no ionosphere were present.

CONCLUSIONS: The horizontal displacement of a ray passing through the ionosphere can have a significant effect on the field of view of a nearly isotropic antenna located above the ionosphere. This effect is sufficiently great that the ionosphere does little to limit the field of view if the frequency of observation is as much as twice the critical frequency of the F layer. A moderate and reasonably predictable restriction of the field of view can be obtained, however, if the frequency used is about 1.3 to 1.5 times the critical frequency. Thus, even if the orientation of the satellite is not controlled, an appreciable directivity can be obtained by placing an isotropic antenna on the satellite and letting the ionosphere restrict the field of view.

BACKGROUND: This is an extension of an earlier RAND study for NASA, in which it was suggested that the ionosphere might be used to limit the field of view of a non-directional antenna on a satellite, possibly providing a useful means for observing the radio frequency signals from thunderstorms. (See RM-4417-NASA, Determination of Thunderstorm Density by Radio Observations from a Satellite, January 1965.)

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MEMORANDUM
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JULY 1966

THE EFFECTIVE DIRECTIVITY OF AN ISOTROPIC ANTENNA LOOKING DOWN THROUGH THE IONOSPHERE

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PREFACE

An earlier report[1] has suggested that the ionosphere might be used to limit the field of view of a nondirectional antenna on a satellite. This might be a useful means for observing the radio frequency signals from thunderstorms. This report estimates the amount of directivity that might be obtainable from such a system.

These two reports conclude the planned work on this problem. They constitute part of a series of studies dealing with satellite meteorology that are being conducted for the National Aeronautics and Space Administration by RAND.

ABSTRACT

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An analysis is made of the effect of the ionosphere on the apparent directivity of an isotropic antenna that looks down at the earth from a satellite. It is shown that at frequencies of more than twice the critical frequency of the ionosphere, the ionosphere has little influence on the directivity of the antenna, but at a frequency of 1.3 to 1.5 times the critical frequency, appreciable directivity is obtained. This directivity is compared to that which a broadside array would have if no ionosphere were present.

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I. INTRODUCTION

A previous report (1) has discussed the possibility of estimating the distribution of thunderstorm activity over the surface of the earth by satellite observations of the radio frequency signals generated by lightning flashes. The satellite system by which such observations are made can be considerably simplified by observing frequencies only slightly above the critical frequency of the F layer. At these frequencies the field of view is limited by the ionosphere itself, with the result that the antenna on the satellite can be essentially isotropic, and its orientation does not need to be controlled. Although observations could be made at a much higher frequency (possibly two or three hundred megacycles), the ionosphere would then be essentially transparent, and the field of view would need to be limited by a properly oriented, directional antenna on the satellite. This would require a more complex satellite system than would the lower frequency observations, but would give observations that are independent of the properties of the ionosphere.

In comparing these two methods of detecting lightning strokes it is of considerable interest to compare their ability to separate signals originating at widely separated points on the earth's surface. In the high-frequency system this separation is accomplished by the directivity of the antenna, and the system's ability to separate desired signals from undesired ones can be determined directly from its antenna pattern. In the low-frequency system, however, the relative directivity of the system is determined by the properties of the ionosphere. It is the object of this report to investigate the effect of the ionosphere on the effective directivity of an isotropic, low-frequency antenna.

II. THE EFFECTIVE DIRECTIVITY GIVEN BY THE IONOSPHERE

An electromagnetic ray which starts from the surface of the earth at an angle of Φ_0 with the vertical will normally penetrate the ionosphere only if sec $\Phi_0 < f/f_c$, where f is the frequency of the electromagnetic wave and f_c is the critical frequency of the F layer. If the path of the ray through the ionosphere were straight (shown by the dotted line in Fig. 1), the only signals received by the satellite would be those from sources that lie within a cone whose vertex is at the satellite, whose axis is vertical, and whose half-angle is $\sec^{-1} f/f_c$. However, the actual path of a ray that penetrates the ionosphere is curved (shown by the solid line in Fig. 1) with the result that signals coming from sources outside the given cone will also be detected. Signals received at the satellite from sources far outside this cone will have been greatly displaced as they pass through the ionosphere, and their energy will be widely dispersed. Therefore, these signals will be much weaker than if there were no ionosphere. The factor by which the incident energy density is decreased will be estimated here and compared to the relative aperture of a high-frequency receiving antenna in order to compare the effectiveness with which low- and high-frequency observations can locate the source of the signal. It will be seen that the horizontal displacement of a ray as it passes through the ionosphere considerably decreases the effective directivity of the low-frequency system, which suggests that the observed frequency should be as close to the critical frequency as possible.

To find the energy density incident on the satellite, it is

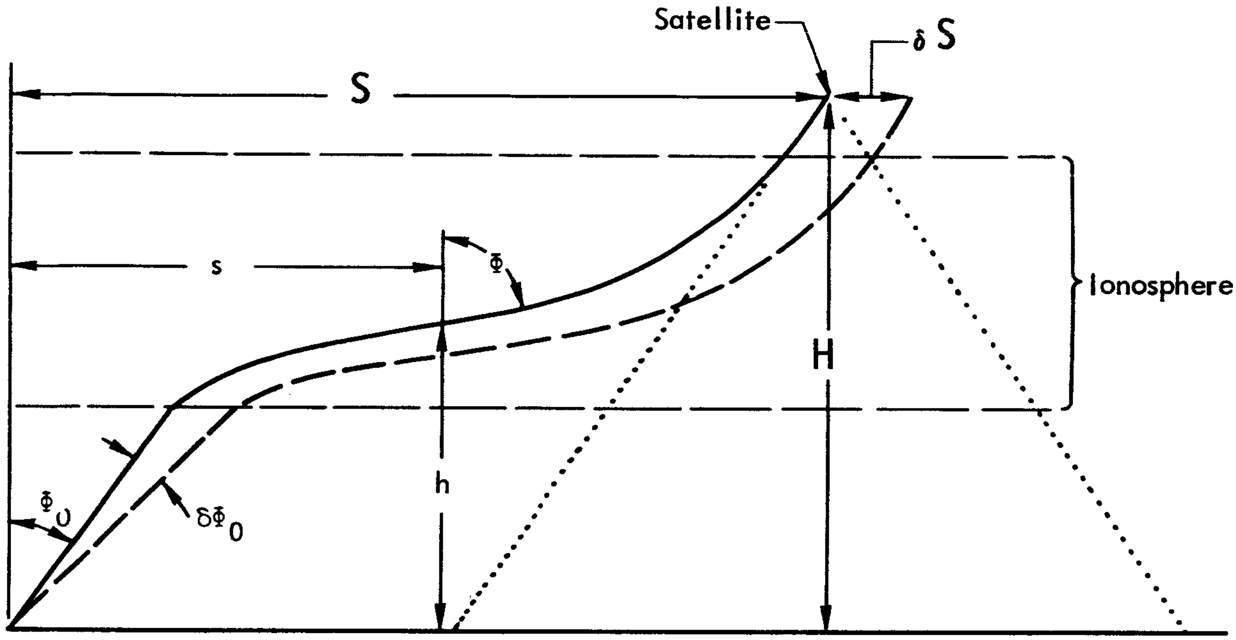

Fig. 1—Geometry of a ray passing through the ionosphere

convenient to consider a second ray from the same source. This ray is emitted at an angle $\Phi_0 + \delta\Phi_0$ with the vertical, as shown by the dashed line in Fig. 1. The first ray reaches the satellite at an altitude H and a horizontal distance S from the source, where it is detected by the satellite. The second ray reaches this altitude at a horizontal distance $S + \delta S$ from the source. It is assumed that the satellite is well above the region of greatest electron density in the ionosphere, so that the rays make nearly the same angle with the vertical at the satellite altitude as at the source. Therefore, the separation of the two rays at the satellite, measured perpendicular to the rays, is $\delta S \cos \Phi_0$. If we consider two planes perpendicular to the surface of the earth, one passing through the source and the satellite, and a second passing through the source but making an angle $\delta\theta$ with the first plane, it is clear that all of the energy in the region bounded by these two planes and by the two rays considered above will pass, at the satellite, through a small rectangle whose sides are $S\delta\theta$ and $\delta S \cos \Phi_0$ and whose area is, therefore, $S \cos \Phi_0 \, \delta\theta\delta S$.

This energy is emitted by the source into the solid angle bounded by the angles $\delta\theta$ and $\delta\Phi_0$. This solid angle has a magnitude of $\sin \Phi_0 \, \delta\theta\delta\Phi_0$. Assuming that the source emits energy isotropically in all directions above the horizon, the energy in any solid angle of this magnitude would have passed through an area $(H^2 + S^2) \sin \Phi_0 \, \delta\theta\delta\Phi_0$ at the satellite if there were no ionosphere. Therefore, the presence of the ionosphere reduces the actual energy density at the satellite by a factor equal to the ratio of two areas -- the one through which the energy would have flowed if there had been no ionosphere and the one through which it flows with the ionosphere present. If this factor is denoted by e, then

$$e = \frac{(H^2 + S^2) \sin \Phi_0 \, \delta\theta \delta\Phi_0}{S \cos \Phi_0 \, \delta\theta \, \delta S}$$

$$= \frac{H^2 + S^2}{S} \tan \Phi_0 \frac{\delta\Phi_0}{\delta S} \tag{1}$$

This ratio e represents the effective antenna gain of an isotropic antenna looking down through the ionosphere at a source whose angular separation from the vertical is $\tan^{-1}(S/H)$; it differs from a true antenna gain only in that it is not normalized to make the integral of e over all solid angles equal to 4π.

Finally, to evaluate the ratio $\delta\Phi_0/\delta S$ which appears in Eq. (1), it is necessary to determine the path of a ray through the ionosphere for an arbitrary value of Φ_0. Neglecting the effect of the magnetic field of the earth, the path of a ray is determined by the effective refractive index of the ionosphere, which is given by

$$\mu = \sqrt{1 - \frac{f_p^2}{f^2}} \tag{2}$$

where f is the frequency associated with the ray and f_p is the plasma frequency of the ionsophere at the point under consideration. The plasma frequency f_p is a function of the ionospheric electron density only, which is assumed to depend only on the altitude h. The path of the ray is then determined from Snell's Law, which states that $\mu \sin \Phi$ is constant along the path, where Φ is the angle between the ray and the vertical, as shown in Fig. 1. At the source $\mu = 1$ and $\Phi = \Phi_0$, so

$\mu \sin \Phi = \sin \Phi_0$ at all points along the path. In particular, when the ray has reached the altitude h at a horizontal distance s from the source (see Fig. 1), where its slope is $1/\tan \Phi$, it follows that

$$\frac{ds}{dh} = \tan \Phi = \frac{\sin \Phi}{\sqrt{1 - \sin^2 \Phi}} = \frac{\sin \Phi_0}{\sqrt{\mu^2 - \sin^2 \Phi_0}}$$

When μ is given as a function of h this equation can be integrated to give S. If μ is given by Eq. (2),

$$S = \tan \Phi_0 \int_0^H \frac{dh}{\sqrt{1 - f_p^2/(f \cos \Phi_0)^2}} \tag{3}$$

When f_p is given as a function of h, Eq. (3) can be integrated to determine S and the result differentiated to give $\delta S/\delta \Phi_0$, from which e is determined by Eq. (1).

III. AN APPROPRIATE MODEL FOR THE IONOSPHERE

To evaluate S exactly from Eq. (3), f_p must be given for all values of h, which means that the ionospheric electron density must be known at all altitudes. However, it is easily seen that most of the details of the electron density profile are unimportant in the present application, and a reasonable approximation for S can be obtained from a knowledge of the electron density only at altitudes where the electron density is near its maximum value. This follows from Fig. 1, where it is apparent that the region in which Φ has its maximum value is the one which has the greatest effect in changing the value of S from what it would have been if there were no ionosphere. Since $\mu \sin \Phi = \sin \Phi_0$ at all points on the ray, Eq. (2) gives

$$\sin \Phi = \frac{\sin \Phi_0}{\sqrt{1 - f_p^2/f^2}} \qquad (4)$$

From this equation it is seen that Φ has its maximum value in the region in which $\sqrt{1 - f_p^2/f^2}$ has its minimum value, or where f_p is nearly equal to its maximum value. The fact that the region where f_p has its maximum value is the region which has the greatest effect on the value of S is also clear from Eq. (3) because, as f_p comes closer to $f \cos \Phi_0$, the denominator in the integrand decreases and large contributions are made to the integral which determines S. Since f_p is greatest where the electron density is greatest, the effect of the ionosphere on the value of S comes mostly from the region where the electron density is greatest.

If N is the electron density and h_m is the altitude at which N has its maximum value N_m, then $N(h)$ can be expanded in a power series about the point $h = h_m$ in the form

$$N = N_m \left[1 - \frac{1}{2L^2}(h - h_m)^2 + \ldots\ldots\right]$$

where L is a parameter that must be determined from the actual electron distribution in the ionosphere. The plasma frequency f_p is proportional to $\sqrt{N}$ and has a maximum value equal to the critical frequency f_c of the F layer. It follows that f_p is given by

$$f_p^2 = f_c^2 \left[1 - \frac{1}{2L^2}(h - h_m)^2 + \ldots\ldots\right]$$

In the region where the electron density is near its maximum value, only the first two terms in this expansion need be considered. In other regions of the ionosphere, the value of f_p will not usually have a great effect on the value of S, so it is reasonable to use the approximation

$$f_p^2 = \begin{cases} f_c^2 \left[1 - \dfrac{1}{2L^2}(h - h_m)^2\right] & h_m - \sqrt{2}\,L < h < h_m + \sqrt{2}\,L \\ 0 & \text{otherwise.} \end{cases} \qquad (5)$$

If Eq. (5) is substituted into Eq. (3), we have

$$S = \tan \Phi_0 \left\{ \int_0^{h_m - \sqrt{2}\,L} dh + \int_{h_m - \sqrt{2}\,L}^{h_m + \sqrt{2}\,L} \frac{dh}{\sqrt{1 - [f_c/(f \cos \Phi_0)]^2\,[1 - (h - h_m)^2/(2L^2)]}} \right.$$

$$\left. + \int_{h_m + \sqrt{2}\,L}^{H} dh \right\}$$

These integrals can be evaluated explicitly. If we let

$$\alpha = \frac{f_c}{f \cos \Phi_0} \tag{6}$$

and

$$\beta = \frac{2\sqrt{2}\, L}{H} \tag{7}$$

then

$$\frac{S}{H} = \tan \Phi_0 \left[1 + \beta \left(\frac{1}{2\alpha} \ln \frac{1 + \alpha}{1 - \alpha} - 1 \right) \right] \tag{8}$$

Differentiating Eq. (8) with respect to Φ_0 gives

$$\frac{\delta S}{\delta \Phi_0} = \frac{S}{\tan \Phi_0} + H \tan^2 \Phi_0 \left(1 + \beta \frac{\alpha^2}{1 - \alpha^2} \right)$$

Thus Eq. (1) becomes

$$e = \frac{1}{S/H} (1 + \frac{S^2}{H^2}) \tan^2 \Phi_0 \frac{1}{S/H + \tan^3 \Phi_0 [1 + \beta\, \alpha^2/(1 - \alpha^2)]} \tag{9}$$

If ψ denotes the angle between the vertical and a straight line drawn from the satellite to the source, it is seen from Fig. 1 that

$$\tan \psi = \frac{S}{H} \tag{10}$$

When f/f_c and L/H are specified, these equations are sufficient to determine e as a function of ψ, which then gives the effective sensitivity of the antenna-ionosphere system as a function of the actual direction of the source. To determine this function we need only consider a set of values of Φ_0 lying in the range between zero and $\cos^{-1}$ fc/f, which includes all values of Φ_0 for which a ray will penetrate the ionosphere. For each of these values of Φ_0, α is determined from Eq. (6). From the value of L/H, β is determined from Eq. (7), and S/H can then be found from Eq. (8). Then e and ψ can be found from Eqs. (9) and (10), and e can be plotted as a function of ψ to give the desired result. In this process it is interesting to note that, if β is very small, the ray will not be received at the satellite unless the source lies in the cone of half-angle $\sec^{-1} f/f_c$. Therefore, the simple theory used previously(1) is valid for a satellite at an altitude so high that β is negligible. At lower altitudes, the displacement of the ray as it passes through the ionosphere will appreciably alter the effective directivity of the system. We must now determine reasonable values for f/f_c and L/H.

The ratio f/f_c has been considered previously.(1) If f is much greater than f_c, the ionosphere becomes transparent over a wide range of the angle Φ_0 and does little to limit the field of view of the antenna on the satellite. If f is only slightly greater than f_c, small unpredictable variations in f_c will have a great effect on the size of the field of view and lead to inaccurate estimates of the density of thunderstorms. It was suggested that the best value of f/f_c would be between 1.5 and 2, although slightly lower values could be used if necessary.

The value of L can be determined from curves showing the electron density of the F layer as a function of height. A group of such curves obtained from rocket soundings, most of which were conducted during the daytime, has been compiled by Croft.(2) The fitting of the curve given in Eq. (5) to these experimental curves is only approximate, but shows that L will usually lie between 60 and 100 km. The curves also show that h_m is usually about 300 km.

Alternatively, L can be estimated theoretically assuming that the F layer is a Chapman layer. In the analysis of such a layer it is assumed that the free electrons come from ionization that is produced primarily by solar radiation, and hence the electron density reaches its maximum when the sun is at its zenith. Thereafter, the electrons either recombine with the positive ions or attach to neutral molecules, and the electron density decreases. However, the shape of the curve of electron density versus altitude is the same as when the sun was at its zenith, while the total number of free electrons decreases throughout the rest of the day and the night. Therefore, the shape of this curve is determined by the equilibrium established at noon between the rate at which electrons are produced and the rate at which they are removed by recombination, attachment, or some more complex process. At altitudes greater than 200 km it appears that the predominant process is more complicated than recombination or attachment alone, but results in an equilibrium condition similar to that produced by attachment in that the equilibrium electron density is proportional to the rate at which free electrons are generated by ionization. (For a more detailed discussion, see Reference 3, section 9.2.) Under these conditions the electron density has the form

$$N = N_m e^{\left[1 - \frac{h - h_m}{h_s} - e^{-(h - h_m)/h_s}\right]} \qquad (11)$$

where h_s is the atmospheric scale height, defined so that the change dp in the pressure p associated with a change dh in the altitude, is given by $dp/p = -dh/h_s$. Assuming that air behaves like a perfect gas,

$$h_s = \frac{kT}{mg} \qquad (12)$$

where k is Boltzmann's constant, T is the absolute temperature, m is the average molecular mass, and g is the acceleration due to gravity. In the vicinity of $h = h_m$, Eq. (11) can be rewritten by using the series expansion

$$e^x = 1 + x + \frac{x^2}{2!} + \ldots + \frac{x^n}{n!} + \ldots$$

and it becomes

$$N = N_m[1 - (h - h_m)^2/(2h_s^2) + \ldots]$$

This implies that

$$f_p^2 = f_c^2[1 - (h - h_m)^2/(2h_s^2) + \ldots]$$

and comparison of the leading terms of this expansion with Eq. (5) shows that $L = h_s$. The scale height h_s depends on both the altitude and the latitude. At an altitude of about 300 km it has a value of about 50 to 100 km.

From both these points of view it appears that a reasonably representative value of L might be about 80 km. Taking the satellite altitude H to be about 450 miles or roughly 720 km, Eq. (7) gives the value of β to be about 0.3. Using this value of β in Eqs. (8), (9), and and (10), curves of e as a function of ψ have been computed for values of f/f_c of 1.3, 1.5, and 2.0. The results are plotted in Figs. 2, 3, and 4 respectively.

Two additional curves are also shown in these figures. One of the curves gives the relative sensitivity of the system to sources of equal intensity in various directions from the satellite. If the source of radiation is near the earth's surface, the distance from the source to the satellite will vary as $1/\cos\psi$. Since the intensity of the signal varies inversely as the square of this distance, the effective sensitivity of the system to a signal whose source is at the angle ψ will be proportional to $e \cos^2 \psi$; this quantity has been plotted in Figs. 2, 3, and 4. The other curve shown in Figs. 2, 3, and 4 is the one based on the assumption that the path of the ray through the ionosphere is a straight line. If this were true, only signals for which $\psi < \cos^{-1} (f_c/f)$ would be received, and therefore the angle $\cos^{-1}(f_c/f)$ is shown in Figs. 2, 3, and 4.

From Fig. 4 it is seen that the effective antenna pattern is very broad at a frequency of twice the critical frequency. At this frequency the effective gain has dropped to half its maximum value at an angle of about 62° from the vertical. If the height of the satellite is about 450 miles, the angle between the vertical and the horizon is about 64°, so we might expect that signals from even the most distant thunderstorms would be received with an effective antenna gain equal to about half the maximum gain. Although the analysis given above assumes that the earth is flat and, therefore, cannot be applied all the way to the horizon, there is

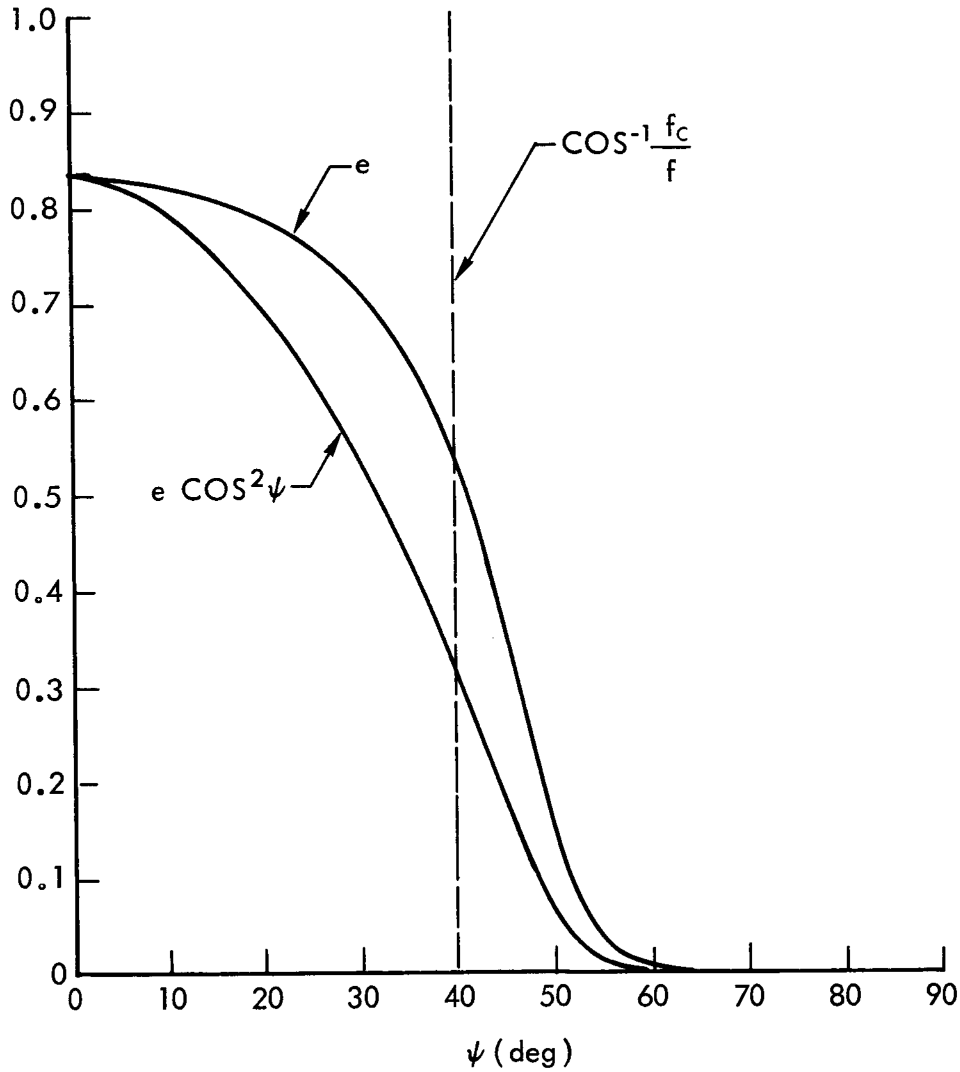

Fig. 2—Plot of the effective gain of an isotropic antenna looking down through the ionosphere at a frequency of 1.3 times the critical frequency

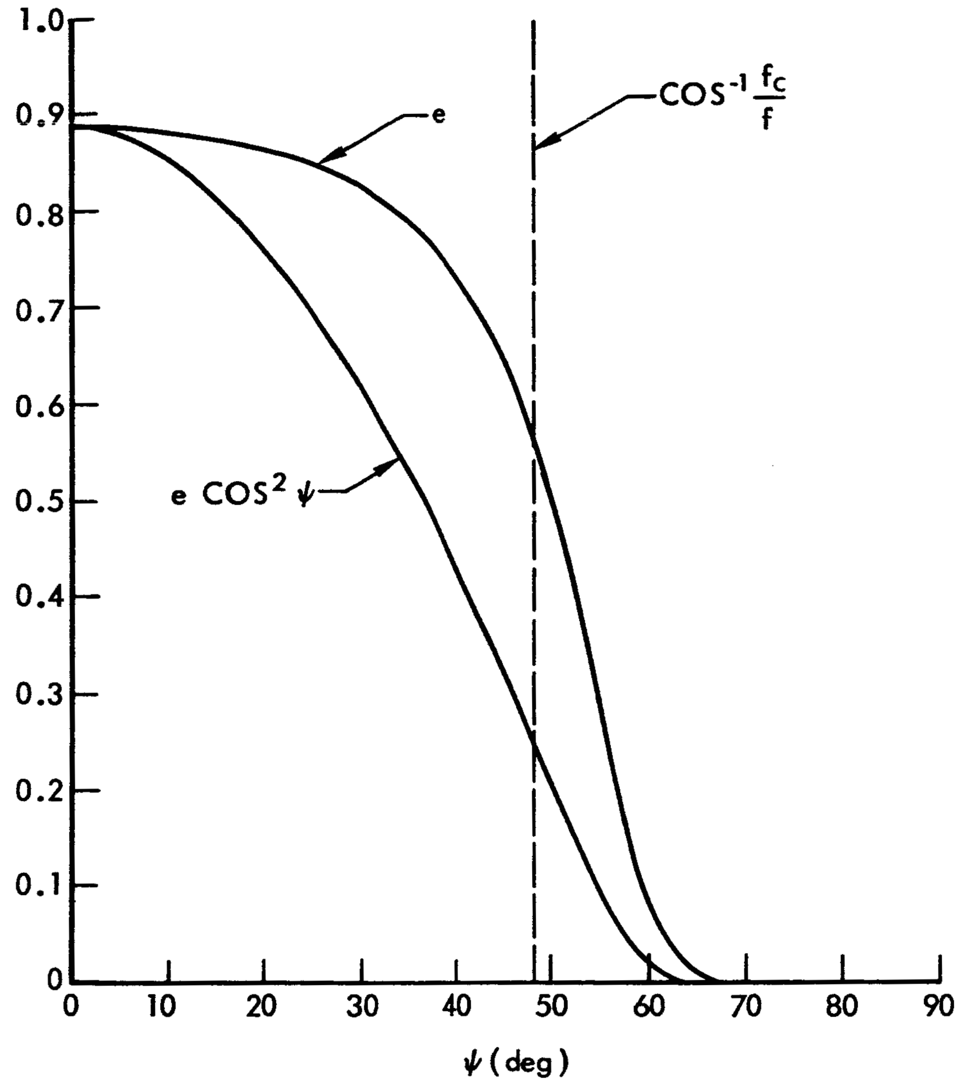

Fig. 3—Plot of the effective gain of an isotropic antenna looking down through the ionosphere at a frequency of 1.5 times the critical frequency

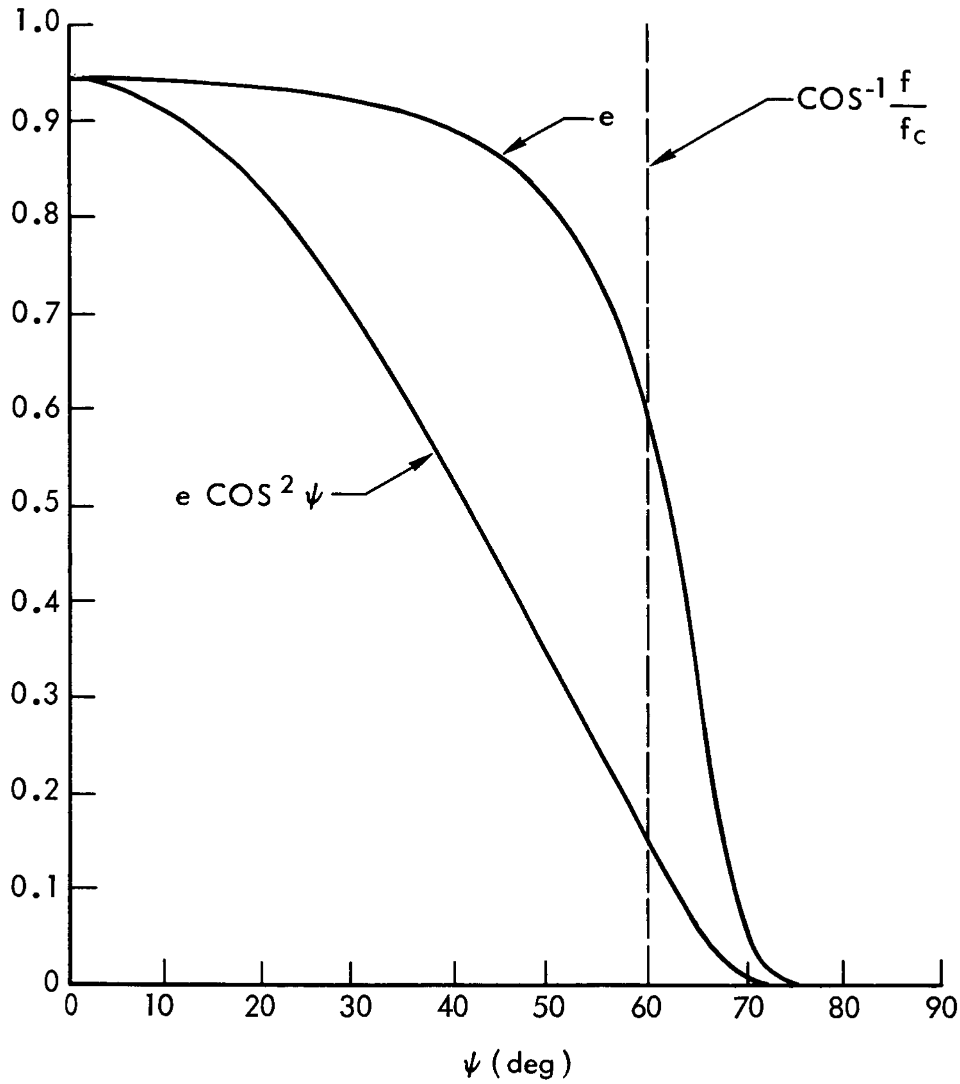

Fig. 4—Plot of the effective gain of an isotropic antenna looking down through the ionosphere at a frequency of 2.0 times the critical frequency

still good reason to believe that this conclusion is qualitatively correct. The fact that the ionosphere is much closer to the satellite than is the earth means that the curvature of the ionosphere will affect the analysis much less than does the curvature of the earth, with the result that the calculated directivity of the antenna-ionosphere system should be at least qualitatively correct even for signals coming from very near the horizon. It is reasonable to conclude that although the ionosphere may contribute slightly to the directivity of the antenna system if the frequency is twice the critical frequency, the effect is not a very marked one, and it is desirable to operate the system at a frequency closer to the critical frequency to achieve a reasonable directivity.

From Fig. 3 it is seen that when the observed frequency is 1.5 times the critical frequency, the effective gain at $\psi = 64°$ is very small. In fact, the effective gain drops to about a tenth of its maximum value when $\psi = 60°$. From Fig. 2 it is seen that at a frequency of 1.3 times the critical frequency the effective gain drops to about a tenth of its maximum value when $\psi = 52°$. Thus at frequencies below 1.5 times the critical frequency the field of view is appreciably limited by the ionosphere. However, at frequencies less than 1.3 times the critical frequency, the analysis given previously[(1)] shows that the errors produced by the unpredictability of the critical frequency can be very large. For this reason it is not desirable to operate at these frequencies unless the errors can be eliminated by a direct determination of the critical frequency in the region immediately below the satellite.

IV. COMPARISON WITH AN ACTUAL ANTENNA

If the ionosphere is not used to limit the field of view, a directional antenna should be used. It is of interest to see how large such an antenna would have to be to achieve a directivity similar to that given by the ionosphere. If the antenna is a two-dimensional broadside array with its elements spaced a half wavelength apart and the main lobe of its pattern directed downward, and if it has n elements in one direction, its gain in the vertical plane containing that direction is proportional to

$$g^* = \left[\frac{\sin\left(\frac{n\pi}{2}\sin\psi\right)}{n\sin\left(\frac{\pi}{2}\sin\psi\right)}\right]^2 \tag{13}$$

where ψ is the angle measured from the vertical in the given plane. Here g^* is arbitrarily normalized to have a value of one when $\psi = 0$ but is otherwise directly comparable to the quantity e defined in the previous section. The actual antenna pattern also includes a factor that describes the gain of the individual elements of the array, but such a factor should also be included in computing the total effective gain of the antenna-ionosphere system if the antenna is not truly isotropic, so that e and g^* are directly comparable quantities.

If $f/f_c = 1.3$, it is seen from Fig. 2 that e drops to half its maximum value when ψ is about 44°. For this value of ψ, Eq. (13) gives $g^* = .214$ even if only two elements are used in the antenna, that is, if n = 2. In other words, using only two elements in the antenna array gives a much narrower pattern at the half-power points than can be obtained with even the lowest usable value of f/f_c. A more detailed comparison of these two systems is given in Fig. 5, where the value of $e(\psi)/e(0)$ as a function of ψ for f/fc is 1.3 and can be directly compared to the value of g^* for $n = 2$. It is apparent that even a two-element broadside array discriminates more between signals from different directions in the central part of the pattern than does the narrowest pattern determined by the properties of the ionosphere. However, on the outer edges of the pattern, where the effective gain of either system is less than about 0.1, the ionosphere gives greater directivity than does the two-element broadside array, and it is in this region that discrimination against unwanted signals is most desirable. This suggests that the directivity given by the ionosphere when $f = 1.3\ f_c$ is at least as useful as that given by a two-element broadside array.

If the antenna array were composed of four parallel half-wave doublets whose centers were at the corners of a square whose side is 1/2 wavelength long, the outside dimension of the entire array would be 1 wavelength by a 1/2 wavelength. At a frequency of 300 Mc this antenna would be only 1/2 by 1 meter in size. Even if the frequency of observation were lowered to 100 Mc to improve the signal-to-noise ratio, these dimensions would be only 1.5 by 3 meters and should not be difficult to achieve on a satellite. Thus it is clear that a system designed for use on a satellite whose orientation in space is controlled should use a directional antenna at a frequency high enough so that the ionosphere is transparent. However, if the measurements are to be made from a satellite whose orientation is not controlled, the antenna system can be very simple and still considerably better than a nondirectional system, if the effective directivity of the ionosphere is used to limit the field of view of a nearly isotropic antenna. In this case the

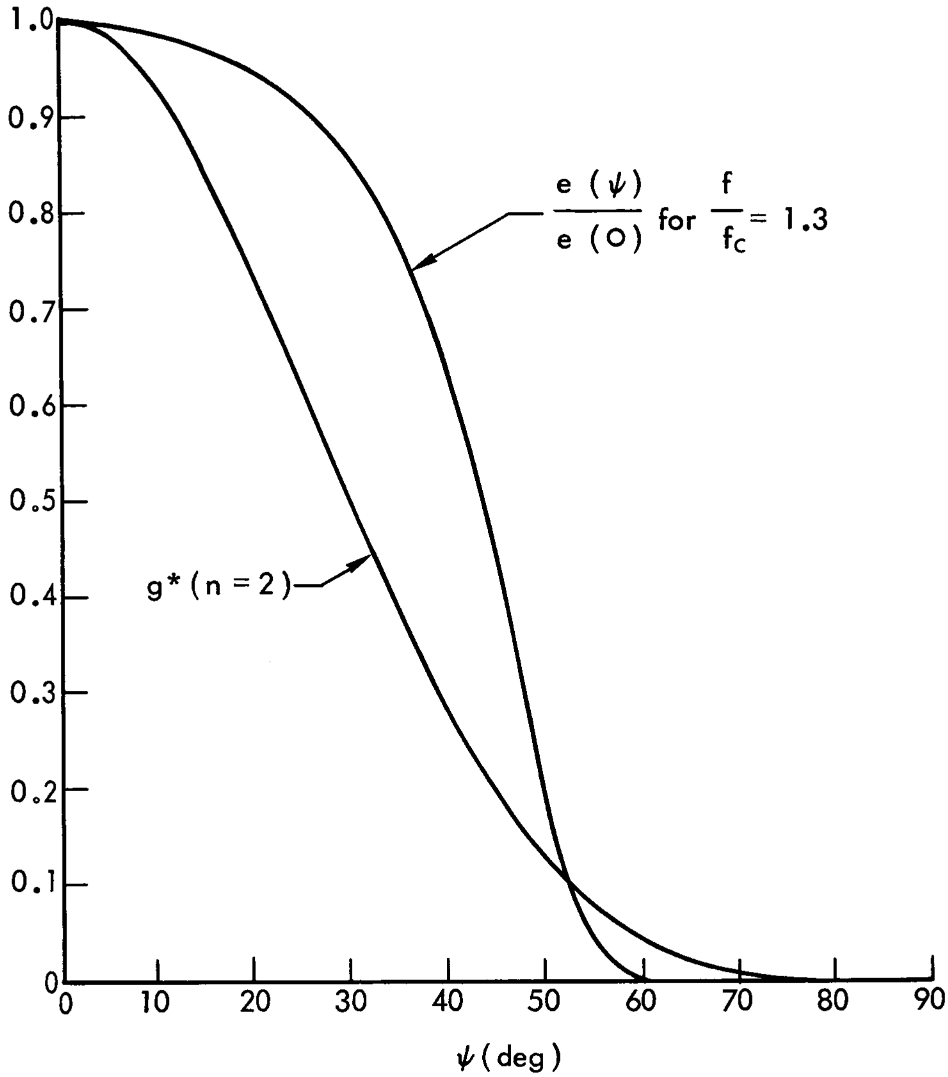

Fig.5—A comparison of the value of $e(\psi)/e(0)$ at a frequency of 1.3 times the critical frequency with the pattern of a two-element broadside array

frequency of observation should be kept as close to the critical frequency of the ionosphere as possible. In view of our uncertain knowledge of the critical frequency, a frequency of about 1.3 to 1.5 times the predicted critical frequency appears to be optimum.

V. CONCLUSIONS

The horizontal displacement of a ray passing through the ionosphere can have a significant effect on the field of view of a nearly isotropic antenna located above the ionosphere. This effect is great enough that the ionosphere does little to limit the field of view of the antenna, if the frequency of observation is as much as twice the critical frequency of the F layer. However, a moderate and reasonably predictable restriction of the field of view can be obtained, if the frequency used is about 1.3 to 1.5 times the critical frequency of the F layer. Thus, even if the orientation of the satellite is not controlled, a useful directivity can be obtained by using an isotropic antenna on the satellite and by letting the ionosphere restrict the field of view.

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