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SERVICE RANGE FOR AIR-TO-GROUND COMMUNICATIONS AT FREQUENCIES ABOVE 50 MC

By R. S. Kirby, J. W. Herbstreit and K. A. Norton

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INDEX — Page

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ABSTRACT

Propagation aspects of air-ground communications are analyzed. Contours of constant received signal strength are shown in the form of lobes for various frequencies. It is shown that, for systems with equivalent transmitted power, ground antenna height and transmitting and receiving antenna gain, the service range decreases as the frequency is increased. This is due primarily to a decrease in the absorbing area of the receiving antenna and to a larger number of nulls in the lobe structure arising from interference between direct and ground-reflected waves. Ground-station antenna-height diversity and tilted-array ground antenna systems are discussed as a means of improving coverage as the operating frequency is increased.

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I. Introduction

In 1947 the U. S. Air Forces requested the National Bureau of Standards to study propagation aspects of communications systems in the proposed aircraft communications band from 225 Mc to 400 Mc. This study was carried out in two parts as follows: air-to-ground communications, and air-to-air communications. A considerable amount of theoretical information was furnished to the Department of Defense. In addition, members of the Central Radio Propagation Laboratory participated actively in flight evaluation tests held in 1948 and 1949 and conducted by the U. S. Navy for the determination of propagation characteristics at these frequencies. The results of these tests were made the subject of a report by the U. S. Navy[1] in which the experimental data supported the theoretical treatment to a very high degree. This paper will treat only the air-to-ground problem; the air-to-air phase is the subject of another paper.[2]

II. Propagation Aspects of Communications

A. Free-Space Propagation

Consider the transmitter and receiver of a communications circuit to be in free space with no ground or obstructions in any way influencing the circuit. Under these conditions, several well known fundamental relations exist between transmitter power, antenna gain, field strength, receiver sensitivity, and maximum range of communications.[3,4] First of all, field strength varies inversely as the distance from the source. Further, the field strength at any point in space from an antenna radiating a given amount of power and with a given radiation pattern will be independent of frequency. For instance, for a half-wave dipole antenna radiating one kilowatt, the free-space field strength, E_0, in the direction of maximum radiation at a distance of one mile is 137.6 millivolts per meter for any frequency. The absorbing area of receiving antennas of equivalent directivity decreases with increasing frequency resulting in less available power at the receiver terminals for given field strengths. It has been shown for these same antennas that in order to deliver a constant voltage across the input of the receiver, the field strength must increase in proportion to the frequency. It follows from these considerations that the free-space maximum range for such communications systems is inversely proportional to frequency.

B. Propagation over the Smooth Earth in the Average Washington, D.C. Atmosphere.

Over a smooth spherical earth the space wave at the receiving antenna is composed of a direct wave corresponding to the free-space wave and a ground-reflected wave. Figure 1 shows the physical representation of these waves. The space-wave field strength is the victorial summation of the direct and ground-reflected wave fields and for 100% reflection over a plane surface it would vary between zero and twice the free-space field strength. If contours of equal field strength are drawn they take the form of lobes in vertical cross section. The position of the lobes depends on ground antenna height, frequency, and, to a lesser extent, polarization and ground constants. In general, there is a lobe for every half wavelength in height of the ground antenna. These factors are further discussed in the appendix.

The ground affects the reflected wave in several ways. For any finite conductivity and dielectric constant of the reflecting surface, some of the energy is absorbed depending on the angle of incidence. At grazing incidence for all infinite plane conducting surfaces having finite conductivity, the reflection coefficient is unity and the phase change upon reflection is 180°. In this case, the path lengths of the direct and ground-reflected waves would be equal and the two waves would be out of phase resulting in a zero space-wave field strength. In addition to the above changes due to penetration and absorption, the ground-reflected wave energy is diverged upon reflection from a curved surface, such as the spherical earth. For practical purposes, this divergence is negligible except at low elevation angles, where it must be considered. Figure 2 shows typical values of the magnitude of the reflection coefficient, $|R'|$, and phase angle, c, (as defined in the appendix) of the ground-reflection coefficients for horizontal and vertical polarization.

The ordinary large-scale atmospheric gradients of refractive index cause radio rays generally to be bent slightly downward. The amount and manner of bending that the ray undergoes at points within the line of sight vary somewhat with time, geographic location, and with altitude. Consequently for our study of the systematic effects of propagation on the service range we are concerned primarily with the average effect of refraction and neglect these instantaneous effects. To a very good first approximation the average effect of refraction can be allowed for by assuming that we are dealing with an earth whose radius in four-thirds of the actual radius, and that this larger earth has no atmospheric refraction. This will hereafter be called the "four-thirds earth". Second order corrections can and have been made in this paper. These corrections are quite small and can be neglected completely without risk of appreciable error in the final result. For the reader who is interested in such second-order corrections their theory and application is indicated in the appendix.

III. Representation of Coverage

The region within which the direct and ground-reflected waves make up the primary mode of propagation is sometimes referred to as the interference region and is considered to be that portion of space lying above the radio horizon. The calculations in this paper deal primarily with this region, although some consideration is given to the diffraction region below the horizon.

In order to show the systematic effects of propagation on the expected coverage, the communications systems are assumed, for the examples in this paper, to have characteristics which are considered typical of an operational air-to-ground system. The transmitter power is assumed to be six watts. Service range is shown in terms of the input voltage across the terminals of a receiver with a 50-ohm input impedance. Contours are shown for 3 µv, 6 µv, 12 µv and 24 µv receiver input voltage. The contour representing maximum coverage which would be applicable to a given communications system would depend to a large extent upon the effective sensitivity of the receivers. From various experiments it has been determined that a value of approximately 3 µv for the minimum usable receiver input signal voltage is representative of operational receivers in good working order. This value is approximately twenty decibels above kTB noise, assuming 100-kc noise bandwidth. The factor of twenty decibels arises from the additional noise contributions of the receiver itself and of external noise, plus the necessity for sufficient signal-to-noise ratio to insure intelligibility. Variations in the gain and noise figure of the early stages in the receiver may possibly increase this minimum required signal up to considerably higher values in some cases. It appears from the lack of detailed quantitative data on minimum required signals that further study of this factor is desirable. If we assume 3 µv to be the minimum usable input voltage, the 3 µv lobes describe the boundary of the air space within which it is possible to carry on usable communication when the entire system is in good operating condition. In addition, transmission-line, mismatch and other circuit losses between transmitter, receiver, and associated antennas, are lumped together as a communications system loss. A factor of six decibels is considered typical of such losses and the voltage contours for the examples in this paper have been prepared assuming this 6 db overall system loss. Considerable variation from these values can be expected in practice, with a consequent modification of the ranges of communications obtained. These modifications may be considered in terms of the communications system loss; for example, if the communications system loss were 12 db instead of 6 db as assumed for our computations, the effect is the same as if the receiver sensitivity were 6 µv with 6 db system loss instead of 3 µv with 6 db system loss. Consequently with 12 db system loss our 6 µv contour would show the region of communications rather than our 3 µv contour.

Figures 3 through 12 show lobe diagrams calculated using the methods outlined in the appendix for various conditions of frequency, polarization, ground antenna height, and types of ground antennas. Figures 3 through 6 show the effect on the coverage of increasing the radio frequency. The constants used in calculating these diagrams are as follows: transmitting and receiving antennas are idealized half-wave dipoles with power gain of 1.64 relative to an isotropic antenna; transmitter power, six watts; ground antenna height, thirty-five feet; transmission over smooth earth of good conductivity; and a communications system loss of six decibels. With increasing frequency the number of lobes increases and has a finer structure, while the free-space maximum range decreases. From the above considerations the free-space maximum range for 3-μv receiver input voltage would be expected to vary under these average conditions inversely with frequency as follows: 139 Mc, 509 miles; 243 Mc, 289 miles; 328 Mc, 214 miles; 1000 Mc, 70 miles. These ranges are characteristic only of the specific conditions assumed and it should be remembered that receiver and antenna variations can increase them by a factor of 2 or decrease them by a factor of 10 approximately. In the maxima of the lobes the distances to the three microvolt contours are nearly twice these values. Cancellation in the minima is not complete since some of the energy in the ground-reflected wave is absorbed upon reflection. For horizontal polarization, reflection is much more complete so that very deep nulls occur and the phase angle, c, is little different from zero at all angles of incidence. Figure 7 shows a typical coverage diagram using horizontal polarization. A comparison of Figures 5 and 8 shows the effect on the lobe structure of increasing the height of the ground antenna. There are more lobes with finer structure for the higher antenna, which indicates, if this is to be avoided, a requirement for an upper limit to the height of the ground antenna.

Antennas encountered in operational installations, in particular, those mounted on the aircraft, can be expected to deviate considerably from the pattern of the idealized half-wave dipole. This is largely a matter of directivity, aircraft antenna radiation patterns in general having many lobes. An analysis of the horizontal radiation patterns of three different antennas operating at frequencies scaled to be the equivalent of from 130 Mc to 175 Mc when mounted on a model of a P2V type aircraft shows the radiation or reception with reference to an idealized half-wave dipole to be distributed in azimuth as follows: ten percent of the directions more than +1.5 decibels; fifty percent of the directions more than -3.4 decibels; 90 percent of the directions more than -11.0 decibels. These data are too meager to be considered representative of aircraft antenna directivity variations but provide some idea of the allowance which must be made for antenna directivity effects in order to ensure reliable operation. Thus, based on the above data, the communications system loss would be increased to the order of 18 db, and thus the service area would be expected to lie within our 12-μv lobes if operation is to be reliable for 90% of the possible aircraft orientations in level flight.

IV. Operational Aspects

In trying to communicate with the ground an aircraft flying toward a ground installation at a constant altitude would find, upon entering the lowest lobe, that it would be possible to communicate for some distance until a null is reached, whereupon communications may be impossible until the next lobe is reached. This might occur several times, depending upon the particular manner in which the circuit was set up, i.e., height of aircraft, frequency, etc. Figure 13 shows theoretical and experimental curves of receiver input voltage versus distance for an aircraft approaching a ground station at an altitude of 10,000 feet. For this figure a ground antenna height of 75 feet is used with a frequency of 328 Mc and transmission is over water. The three graphs show the effect of polarization on the received signal strength. The experimental curves were obtained simultaneously on three receivers recording the output of three types of antennas used for picking up the signals emanating from a circularly polarized radiator on the aircraft. For unbiased comparison the voltages for the vertically and horizontally polarized antennas were adjusted upward by three decibels since only half of the power is radiated in either plane component of polarization. The different effects on the lobes are clearly shown. The nulls are very deep with horizontal polarization and communication "drop outs" occur through the higher nulls even at very short ranges. With vertical polarization, the nulls are very evident, but because of more absorption of the ground-reflected energy, they are not nearly so deep. With circular polarization, and at the low angles of elevation where the lobes for each polarization component are nearly superimposed, the field strength in the nulls lies somewhere between that for horizontal polarization and that for vertical polarization. At the higher angles of elevation the two lobe structures are more nearly interposed and some filling in of the nulls occurs under some conditions. It should be noted that the results shown on this figure were obtained with the antennas specially mounted on the aircraft in such a way as to minimize the variations in directivity and the aircraft flew with a constant orientation relative to the ground station. Even under these circumstances there were some departures from the theory and these are attributed to residual variations in aircraft directivity and instantaneous effects of the atmosphere and irregularities in the reflecting surface of the water. Similar measurements were made over land with smooth terrain in the vicinity of the ground station and the results were similar to those shown in Fig. 13. No measurements were made over rough terrain but some analysis of its expected effects on the lobe structure is given later in this paper.

Because of the serious effect of deep minima upon the reliability of a system for air-to-ground communications, it is felt that the proper way to make coverage comparisons of various systems would involve consideration of combinations of maximum altitudes and distances within which no communication "drop outs" will be expected to occur. These altitudes and distances can be maximized, in general, by decreasing the height of the ground antenna thus reducing the number of lobes. This, however, decreases the distances at given altitudes to the lower three-microvolt contour of the lowest lobe, which is a measure of the low-angle coverage. It is obvious in selecting the height of ground antennas that consideration must necessarily involve a compromise in these factors. It is interesting to note that for a given ground-antenna height, low-angle coverage is relatively independent of frequency. As the frequency increases, the lowest lobe becomes lower which tends to increase the low-angle coverage, but at the same time the free-space maximum range is decreased. In general these factors are of comparable magnitude, and little modification of the low-angle coverage is involved.

V. Methods of Improving Coverage

Several methods for improving coverage which do not involve an increase in transmitter power have been recently proposed and investigated. The most promising methods are those using the following ground-antenna systems:

A. High-gain ground antennas.

B. Tilted-array ground antennas.

C. Height-diversity ground antennas.

The necessity for preserving and improving coverage becomes more pressing as frequencies of operation are increased and as altitude, speed, and range of aircraft are increased. It is interesting to note that lower frequency coverage patterns can be almost exactly duplicated for higher frequencies by increasing the power in proportion to the square of the ratio of frequencies and using ground antenna heights of equal numbers of wavelengths. However, the size and weight of higher powered transmitters limit their use in aircraft.

A. High-Gain Ground Antennas

The use of high-gain directive ground antennas accomplishes essentially the same result as increasing the transmitter power for both the aircraft and the ground station. For transmission from the ground using this type of an antenna, the effective radiated power is increased with a corresponding increase in the free-space maximum range. For reception at the ground station, an increase in the absorbing area of the antenna is accomplished and the minimum usable receiver terminal voltage can be obtained from weaker field strengths. This results in an increase in the free-space maximum range corresponding to the transmission case. Figure 9 shows the coverage expected when using an eight-element vertical colinear array with a gain of 7.42 decibels over a half-wave dipole and operating at 328 Mc. A comparison of this figure with Figure 5 gives an indication of the improvement to be expected when using this type of an antenna rather than a half-wave dipole. There are, of course, limits to the feasibility of this method arising from the corresponding reduction in high-angle coverage. However, high-angle coverage usually represents short ranges of communications and the radiated power in these directions need not be as high as for the longer distances.

B. Tilted-Array Ground Antennas

Further improvement with the use of high-gain arrays can be realized by tilting the antenna beam slightly upward. This reduces the intensity of the ground-reflected ray and increases the direct ray, thus substantially filling up the minima with only a small reduction in the maxima. This technique was proposed by Norton and Omberg[5] to improve radar coverage. Figure 14 shows the geometry involved in improving coverage with a directive antenna. A comparison of Figures 9 and 10 shows the improvement in coverage expected from tilting the eight-element colinear array. The angle of tilt here was determined to give maximum improvement in the direction of the null above the first lobe. Figure 15 shows a measure of the improvement in receiver input voltage expected in the null as a function of the angle of tilt in the array. The angle of tilt can be maintained in all directions by proper phasing of the individual elements in the array.

In an experimental test of this method of determining the optimum angle of tilt, angles of tilt were used slightly above and slightly below the calculated optimum value. In either case the field strength in the null was measured to be less than that for the optimum angle. In broad-band applications, the electrical angle of tilt may be held constant for a given phasing and spacing relationship of the elements, regardless of the frequency. The primary limitation to the use of high-gain ground antenna systems is that of shipboard applications, where it may be necessary to resort to stabilized mounts to overcome roll and pitch. A discussion and an example of the determination of the optimum angle of tilt is included in the appendix of this report.

C. Height-Diversity Ground Antennas

The use of height diversity in the ground antenna system makes possible the superpositioning of lobes in such a manner that the minima do not coincide, and filling-in is accomplished. For diversity reception two receivers are used. Reception is first on one receiver and then on the other, depending upon which antenna is in the stronger field; in practice the two receivers can be combined into one unit having separate rf and i.f. stages with a common audio section. Terman[6] states that the AVC voltage developed by the two receivers may be added directly and applied simultaneously to the gain of both receivers so that the receiver with the strongest signal dominates the situation and the other contributes little or nothing in the way of either signal or noise. Figure 11 shows the expected coverage for a diversity receiving system operating at 328 Mc. A comparison of this figure with Figure 7 shows how the minima for the 35-foot antenna are filled in by the lobes from the 50-foot antenna. The height of 50 feet was determined in this case to be the optimum height for the higher antenna in terms of maximum improvement in coverage over the lower antenna alone. In order to transmit from these same antennas to the aircraft, a method of transmission is necessary which maintains independence between the waves travelling over the separate paths. Gates[7] outlines one method of doing this which requires the use of two transmitters, one for each of the diversity antennas, transmitting on slightly different frequencies. The frequency difference must be small enough so that both frequencies will fall within the bandpass of the receiver, and large enough so that the beat frequency will not cause serious trouble. A difference frequency of the order of 10 kilocycles has been used successfully, the unwanted beat note being filtered out in the audio stages of the receiver. In this application the signals are mixed prior to detection in the receiver, and since they are not at the same frequency, the power available at the receiver terminals is the sum of the powers available from each transmitter. An example of the expected coverage with this system, using two six-watt transmitters, is shown in Figure 12.

In order to determine the heights of the ground antennas for optimum coverage, consideration is given to the diversity reception problem, which, because of the manner in which the signals are combined, yields somewhat less coverage than the diversity transmission case. This air-to-ground transmission link is usually the one determining the effective range of two-way communication, in any case, since the power of the ground transmitter is not likely to be as severely limited by space and weight considerations. With height diversity, the primary limitation to coverage occurs at the points of lobe crossover. In order to maximize coverage within the three-microvolt contours, it is necessary to choose antenna heights such that the three-microvolt lobes cross over at the maximum altitude. This is accomplished, in general, when the upper half of the first lobe for the low antenna crosses over the lower half of the second lobe for the higher antenna at the same altitude at which the lower half of the third lobe for the low antenna crosses over with the upper half of the third lobe for the high antenna. Over the range of frequencies from 225 Mc to 400 Mc, a ratio of heights for the ground antennas of approximately seven to ten gives this result.

The use of high-gain antennas with height diversity increases the coverage obtained corresponding to the increase in the free-space maximum ranges obtained but with the consequent reduction of high-angle coverage.

VI. Polarization Diversity

Circularly polarized transmission may be employed as a form of diversity. Independence between the transmission paths is effected by the polarization. Referring to Figure 2, it is interesting to note that the phase angle, c, of the reflection coefficient differs for vertically and horizontally polarized waves, hence the two ground-reflected components cannot arrive simultaneously out of phase with the direct-wave components. For perfect conducting reflecting surfaces, the phase difference of the two ground-reflected components is 180°, and under this condition the maxima and minima for the two polarizations considered separately would be perfectly interposed. However, with ground constants of any practical interest, this effect is very slight at angles of elevation below the Brewster angle. The most pronounced case is that of sea water, as shown in Figure 13. Here the Brewster angle is fairly low. For poorer conducting surfaces, such as land, the effect is even less noticeable. At angles above the Brewster angle, the maxima and minima are more nearly interposed, but these angles correspond to short ranges of communications, and the effect is of little value here.

VII. Irregular Terrain

Ground-reflected rays are shown for simplicity in Figure 1 to occur at a point. Actually, the entire surface of the earth is illuminated and reradiates elementary waves in all directions. Over smooth earth at any particular receiving location, the resulting intensity of all of these waves very nearly equals that of the waves reflected from within a small elliptical area in the neighborhood of the ray reflection point as determined by the laws of geometrical optics. This elliptical area is called a Fresnel zone. The intensity and phase relationships of the remaining waves very nearly cancel each other out. A more complete discussion of reflection properties over irregular terrain is included in the paper concerning air-to-air propagation.[2]

The length of the ray path to the edge of the entire first Fresnel zone is one-half wavelength longer than the geometrical ray path. It is within this zone that irregularities in terrain would be expected to have the greatest effect upon the reflected signal. The Rayleigh limit suggests a convenient way of describing the degree of flatness required for specular reflection. This limit shows that irregularities causing path-length differences from smooth earth of the order of less than, say $\lambda/8$, are of negligible importance, and essentially specular reflection would be expected to take place. A transition between specular reflection and a random-phased reflection takes place as the irregularities are increased so that the path length differences are greater than $\lambda/8$. In general, the effect of irregularities is to cause filling-in of the lobe minima and less development of the lobe maxima. The dimensions of the major and minor axes of the first Fresnel zone ellipses for the maximum of the first lobe are tabulated for comparison using a ground antenna height of 35 feet:

Frequency	Major Axis	Minor Axis	d_1	d to center of ellipse
139	0.71 mile	100 feet	0.125 mile	0.38 mile
243	1.30 miles	100 feet	0.229 mile	0.69 mile
328	1.76 miles	100 feet	0.309 mile	0.93 mile
1000	5.33 miles	100 feet	0.944 mile	2.83 miles

The center of the ellipses are displaced from the point of geometric ray path reflection at d_1 in the direction along the major axis toward the higher antenna. As the grazing angle increases, the ellipses become smaller, thus restricting the area within which irregularities are of greatest importance. Norton and Omberg[5] have shown that the permissible height deviation within the first Fresnel zone for a well developed k^{th} lobe is $\Delta h = h_1/4(2k-1)$ where h_1 is the ground antenna height.

When the irregularities in height are large with respect to the above limits they will be important outside as well as inside the first Fresnel zone but in this case the average energy of the ground-reflected components is small and the net effect on the received field is correspondingly small.

VIII. Summary

The propagation problems involved in the service ranges for air-to-ground communications are primarily the result of lobes caused by interference between the direct and ground-reflected rays as well as a systematic decrease in free-space maximum range with increasing frequency. Coverage diagrams are shown for varying conditions of frequency, polarization, ground antenna heights, etc. To form a systematic basis for comparison, the minimum usable receiver input voltage is assumed to be a constant value of 3 μv and antenna radiation patterns are idealized. Wide variations from these conditions can be expected in practice. For simplicity, the effects of the variations can be allowed for by modifying the value assumed for communications system loss. In general, it is shown that as the frequency of operation is increased, aside from equipment becoming more complex, the propagation characteristics become less suitable for communications. The lobe structure becomes finer with more nulls to contend with, and the absorbing area of antennas decreases, thus decreasing the ranges of communications. These restrictions can be overcome within limits by resorting to the use of elaborate ground installations such as high-gain tilted arrays and height diversity transmission and reception. Because of the severe restrictions in size and weight of equipment to be carried in the aircraft, little can be done to improve communications at that end. Antennas for aircraft must be relatively non-directive thus necessarily being of low gain. If the limitations in spectrum space require the use of higher frequencies, the methods outlined in this paper should prove beneficial in improving coverage.

APPENDIX

A. Calculation of Coverage Diagrams

A discussion of the procedures used in calculating the coverage diagrams of this paper is presented here to enable the reader to make similar calculations as well as to show the application and limitations to the use of the methods and of the approximations. In the region well above the radio horizon the curves were determined in accordance with the interference theory at large heights, while those well below the radio horizon were determined in accordance with the diffraction theory. That portion of the curves in the immediate vicinity of the radio horizon was obtained by interpolating between these results.

Ground constants representative of the terrain involved are chosen for the determination of reflection coefficients. In this paper, values of the dielectric constant, $\epsilon = 15$, and conductivity, $\sigma = 10^{-2}$ mhos/meter, were chosen as being representative of overland propagation. For seawater calculations these values become $\epsilon = 81$ and $\sigma = 4.64$ mhos/meter. The plane-wave reflection coefficient, $|R'|$, and its phase angle, c, are determined as a function of the ground constants, frequency, and elevation angles by the following equations:

$$R_v' = \frac{n^2 \sin \psi_2' - \sqrt{n^2 - \cos^2 \psi_2'}}{n^2 \sin \psi_2' + \sqrt{n^2 - \cos^2 \psi_2'}} \cong |R_v'|\ e^{i(\pi - c_v)} \cong -|R_v'|\,e^{-ic_v}$$

(Vertical Polarization) (1)

$$R_h' = \frac{\sin \psi_2' - \sqrt{n^2 - \cos^2 \psi_2'}}{\sin \psi_2' + \sqrt{n^2 - \cos^2 \psi_2'}} \cong |R_h'|\ e^{i(\pi\ c_h)} \cong -|R_h'|\ e^{-ic_h}$$

(Horizontal Polarization) (2)

where $n^2 = \epsilon + ix$; $x = 1.79731\ \ 10^4\ \frac{\sigma}{f_{mc}}$; and ψ_2' is the angle the incident ray makes with the reflecting surface. The angle c_v is an angle between 0 and π and equals $\pi/2$ at the psuedo Brewster angle of incidence corresponding to the minimum reflection; c_h is a small negative angle at all angles of incidence. As a typical example the values of $|R'|$ and c are plotted graphically against $\tan \psi_2'$ for both polarizations with $f_{mc} = 328$ Mc in Figure 2. Equations (1) and (2) for the plane-wave reflection coefficients are derived by satisfying the boundary conditions of electromagnetic theory for plane waves incident on a plane surface. In our present application the waves are not plane since the transmitting and receiving antennas are at finite heights above the reflecting surface and, in addition, the earth is spherical rather than plane. However, it has been shown by Norton[8] that (1) and (2) are still applicable when the transmitting and receiving antennas are at finite heights above the plane surface provided a surface wave component is added to the resulting solution. This surface wave component has been shown by Norton[9] to be unimportant when the transmitting and receiving antennas are more than a few wavelengths above the surface and so may be neglected in our present application. Furthermore, van der Pol and Bremmer[10] have shown that the reflection coefficient appropriate to the spherical surface is not appreciably different from the above plane-surface values when the additional spreading due to the divergence of the energy reflected from a spherical surface is separately taken into account. For the above reasons we have adopted (1) and (2) as being representative, with reasonable accuracy, of the values of the reflection coefficient to be expected from theoretical considerations in our present application.

When, as in our case, the reflection takes place over a spherical surface rather than a plane surface the rays are diverged resulting in a further decrease in field strength of the reflected wave. This attenuation is accounted for in a divergence factor, D. To a good approximation, this factor may be expressed as follows:

$$D = \left[1 + \frac{2d_1 d_2}{kad \tan \psi_2'}\right]^{-1/2} \qquad (3)$$

In (3) ka is the effective earth's radius, d, d_1, d_2 and ψ_2' are as shown in figure 1. An exact expression for divergence has recently been derived by Riblet and Barker.[11] For ground antenna heights up to 1000 feet, aircraft altitudes up to 55,000 feet, and distances to the radio horizon, the maximum differences in the divergence factor as obtained by comparison of the above approximate and the exact Riblet and Barker solutions appear in the fourth significant figure. Thus equation (3) is considered to be a sufficiently good approximation to the divergence factor for this application, and is used in the calculations throughout this paper.

From the interference theory, the smooth-earth space-wave field strength is expressed in terms of a direct wave corresponding to the free-space wave, and a ground-reflected wave.[3] The resulting wave is the vectorial sum of these two components. Consideration must be given to both the magnitude and the relative phase of these components in order to calculate the space-wave field strength at points in the interference region. If we consider the direct wave to be equivalent to free-space propagation we have a convenient reference vector of magnitude $\frac{E_0}{d}$. To this we add the ground-reflected wave of magnitude

$\frac{E_0}{d} D |R'|$ neglecting the small-order effect of additional distance attenuation due to the longer path length for the ground-reflected ray and neglecting the difference in antenna gains for the different directions of the direct and ground-reflected rays. It can readily be seen that the space-wave field strength varies between $\frac{E_0}{d}(1 + D|R'|)$ when the two waves are in phase and $\frac{E_0}{d}(1 - D|R'|)$ when the two waves are out of phase.

The relative phase of the two waves at points within the interference region is determined from a consideration of both the phase angle of the reflection coefficient and the geometric path length difference. The phase angle of the reflection coefficient, $(\pi - c)$, is given by (1) and (2) while the phase lag of the ground-reflected ray due to path length differences is determined from geometrical considerations. Referring to Figure 1, if we let a denote the actual radius of the earth and ka its effective radius we may write with negligible error:

$$h_1' = h_1 - \frac{d_1^2}{2ka} \qquad (4a)$$

$$h_2' = h_2 - \frac{d_2^2}{2ka} \qquad (4b)$$

$$\tan \psi_2' = \frac{h_1' + h_2'}{d} = \frac{h_1'}{d_1} = \frac{h_2'}{d_2} \qquad (4c)$$

When $k = 4/3$, $ka = 5280$ miles and equations (4a, b) become:

$$h_1' = h_1 - \frac{d_1^2}{2} \qquad (5a)$$

$$h_2' = h_2 - \frac{d_2^2}{2} \qquad (5b)$$

In (5a) and (5b) h, h' are expressed in feet; d_1, d_2 in miles. The change in phase due to the path length difference, θ, can be approximately expressed as follows:

$$\theta = \frac{4\pi \; h_1' h_2'}{\lambda \; d} \qquad (6a)$$

or more conveniently

$$\theta = \frac{1.3865 \times 10^{-4} \, h_1' \, h_2' \, f_{mc}}{d} \qquad (6b)$$

In (6a) and (6b) h_1' and h_2' are expressed in feet; d in miles. The relative phase between the direct and ground-reflected wave is $[\theta + (\pi - c)]$. From the rule of cosines the ratio of space wave field strength to free-space field strength, $g(\psi_2')$, can be expressed as follows:

$$g(\psi_2') = \left[1 + (D\,|R'|)^2 - 2D\,|R'| \quad \cos(\theta - c)\right]^{1/2} \qquad (7)$$

In calculating coverage diagrams it is convenient to determine the variation of $g(\psi_2')$ with height at a fixed distance, say 100 miles. An example of the calculation of this function is presented here for a communication system in which the ground antenna is elevated 35 feet above the surface with a frequency of 328 Mc and vertical polarization.

In plotting the function $g(\psi_2')$ as indicated in the tables below it will be found helpful to proceed as follows. Select some convenient values of d_1 not too closely spaced and carry through the computations as indicated. A curve of $(\theta - c)$ as a function of d_1 is next plotted as shown in Figure 16. From this curve the values of d_1 which correspond to $(\theta - c) = n\pi$ will be obtained. These are the critical points in the analysis since it will be noted that values of $(\theta - c) = (2n-1)\pi$ correspond to lobe maxima and values of $(\theta - c) = 2n\pi$ correspond to lobe minima. Sufficient other points can then be filled in to get the desired shape of the lobes. It should also be stressed that d_1 is a convenient independent variable upon which to base these calculations because the remaining variables can be computed from it without solving any higher order equations as would be necessary if h_2 or $(\theta - c)$ had been employed. After calculating a sufficient number of points the entire curve of $g(\psi_2')$ is plotted as a function of altitude, h_2, at 100 miles in the manner shown in Figure 17.

d_1	$\frac{d_1^2}{2}$	h_1' Eq. (5a)	$\tan \psi_2'$ Eq. (4c)	d_2 $d - d_1$	h_2' $d_2 \tan \psi_2'$	$\frac{d_2^2}{2}$
8.35	35	0	0	91.65	0	4200
5	12.5	22.5	0.000852	95	427.5	4512
1	0.5	34.5	0.00653	99	3416	4900
0.305	0.046	34.954	0.0217	99.695	11425	4970
0.153	0.012	34.988	0.0433	99.847	22833	4985
0.1	0.005	34.995	0.0663	99.9	34961	4990

h_2 $h_2' + \frac{d_2^2}{2}$	θ Eq.(6b)	c Fig. 2	$\theta - c$	$\lvert R' \rvert$ Fig.2	D Eq.(3)	$g(\psi_2')$ Eq.(7)
4200	0	0	0	1.0	0	1.0
4939.5	4.37	0	4.37	0.995	0.567	0.440
8316	53.59	0.05	53.54	0.945	0.972	0.412
16395	181.61	0.18	181.43	0.842	0.997	1.839
27818	363.31	0.35	362.96	0.708	0.999	0.293
39951	556.39	0.56	555.83	0.582	1.0	1.568

Near the horizon the application of the interference theory would indicate higher field strengths than would actually be the case, as shown by the dashed portion of the curve on figure 17, and in this region other modes of propagation must be considered. The exact computation of the $g(\psi_2')$ function in this region is involved and laborious as shown by van der Pol and Bremmer[10]. However, an excellent graphical interpolation can be made between the results using the interference theory and those using the first term in the diffraction theory.

In considering the diffracted wave, the graphical methods developed by Norton[3] for the solution of the diffracted wave in terms of the surface wave and an appropriate height-gain function have been employed and are exhibited in the example below. It is suggested in studying this example that the reader have the reference paper at hand. The notation employed here will be the same.

The surface wave is the wave that is received when the transmitting and receiving antennas are very close to the ground. The nature of the surface wave at large distances is determined as a function of frequency and ground constants primarily through the parameters K and b, defined in the reference paper, which can be determined by means of the following equations with sample solutions when $\epsilon = 15$, $\sigma = 10^{-2}$ mhos/meter, and $f_{mc} = 328$:

$$x = 1.79731 \cdot 10^4 \cdot \frac{\sigma}{f_{mc}} = 0.546 \qquad (8)$$

$$\tan b' = \frac{\epsilon - \cos^2 \sigma_2'}{x} = 25.63 \qquad (9)$$

$$b' = 87.766^\circ$$

$$\tan b'' = \frac{\epsilon}{x} = 27.48 \qquad (10)$$

$$b'' = 87.916^\circ$$

$$b = 2b'' - b' = 88.086^\circ \text{ (Vertical Polarization)} \qquad (11)$$

$$K = \left[\frac{\lambda}{2\pi ka}\right]^{1/3} \left[\frac{x \cos b'}{\cos^2 b''}\right]^{1/2} = 1.038 \cdot 10^{-2}$$

(Vertical Polarization) (12)

Relative values of surface wave field strength, $f(\eta')$ at large distances are shown graphically by Norton [3] as a function of η', where

$$\eta_o = (k^2a^2 \lambda)^{-1/3} = 3.98 \cdot 10^{-2} \text{ miles}^{-1} \qquad (13)$$

$$\eta' = \beta_o \eta_o d = 6.36 \cdot 10^{-2} d \qquad (14)$$

$$E_{su} = 2E_o \eta_o \gamma f(\eta') \qquad (15)$$

The parameters β_o and γ are presented graphically by Norton [3] as functions of K and b. For this example $\beta_o = 1.597$ and $\gamma = 8.21 \cdot 10^{-6}$.

When both antennas are elevated above the earth's surface but remain well below the radio horizon the field at the receiver is the diffracted wave field. The height-gain function, $f(q,K)$, for each antenna relates the diffracted wave to the surface wave as follows:

$$E \text{ diffracted} = E_{su} \cdot f(q_1,K) \cdot f(q_2,K) \qquad (16)$$

The height-gain function is determined graphically as follows: first compute the quantities $h_{(q=1)}$, δ, and $h_{(\bar{h}=1)}$ from the following equations shown with sample solutions.

$$h_{(q=1)} = \frac{\lambda}{2\pi} \left[\frac{x \cos b'}{\cos^2 b''}\right]^{1/2} = 1.925 \text{ feet} \qquad (17)$$

$$\delta = f(K,b) = 31.65 \text{ (determined graphically [3])}$$

$$h_{(\bar{h}=1)} = \frac{(ka\,\lambda^2)^{1/3}}{\beta_o^2} = 244.9 \text{ feet} \qquad (18)$$

Obtain a sheet of log-log graph paper similar to that used in Figure 18, and label the coordinates.* Plot the point $h = h_{(q=1)}$, $f(q,K) = 1$. Superimpose this point over the point $q = 1$, $f(q) = 1$ on Norton's graph[3] showing the variation of field strength with numerical antenna height and trace the curve corresponding to $b = 83.086^\circ$. This is the

*It is convenient to use a graph paper such as Keuffel and Esser Co. No. 359-128L which has the same scale as the height-gain graphs presented by Norton.[3]

plane earth height-gain function and can be used for spherical earth heights corresponding to $q < \frac{1}{10K}$. To complete the curve plot the point $h = h_{(\bar{h}=1)}$, $f(q,K) = \delta$. Now superimpose this point over the point $\bar{h} = 1$, $f(\bar{h}) = 1$ on Norton's graph[3/] showing the variation of field strength with the parameter $\bar{h}$ at points beyond the line of sight and trace the remainder of the curve corresponding to $K = 0.01038$ as shown in Figure 18. The function $f(q,K)$ can be used to determine diffracted wave field strengths from the surface wave value for aircraft altitudes, h_2, such that

$$h_2 < \frac{1}{2}\left[d - \sqrt{2h_1} - \frac{1.5}{\beta_0 \eta_0}\right]^2 \qquad (19)$$

In (19), d is in miles, $h_{1,2}$ in feet.
At points below this limit the function $g(\psi_2')$ can be expressed as follows:

$$g(\psi_2') = 2d\,\eta_0\,\gamma' \cdot f(\eta') \cdot f(q_1,K) \cdot f(q_2,K) \qquad (20)$$

where $d = 100$ miles and $h_1 = 35'$, $\eta' = 6.36$, $f(\eta') = 1.75 \times 10^{-4}$, $f(q_1,K) = 19.5$ and $g(\psi_2') = 2.23 \cdot 10^{-7} \cdot f(q_2,K)$, at heights $h_2 < 2315$ feet. Figure 19 shows the variation of $g(\psi_2')$ with h_2 at 100 miles on a log-log scale.

This scale is used to facilitate interpolation of the values between heights 2315 feet and approximately 6700 feet, inasmuch as the field strength in this region varies approximately exponentially with altitude. This completes the calculations showing the variation of the function $g(\psi_2')$ with height, and we are now ready to proceed with the coverage diagrams.

The expected coverage for an air-to-ground communications system is expressed in terms of the receiver input voltages. It is convenient first to determine the free-space maximum ranges, d_{fsm}, corresponding to these voltages. Consider first the field strength in free space for a transmitting antenna with power gain, G, relative to an isotropic antenna, in the direction in which we are interested and radiating P_T watts of power. The free-space field intensity at r meters from the transmitting antenna, E_0, is

$$E_0 = \frac{1}{r}\sqrt{30P_TG_T} \quad \text{v/m} \qquad (21)$$

In the equatorial plane of a half-wave dipole antenna radiating 6 watts, $G_T = 1.64$ and $E_0 = 10.68\,\mu$v/m at one mile. The field strength, E_1, required to deliver the minimum required power, P_R watts, to the receiving antenna is expressed in terms of the gain, G_R, of the receiving antenna and the impedance of free space, $Z_0 = 120\pi$ ohms, by the following formula:

$$E_1 = \frac{1}{\lambda} \sqrt{\frac{4\pi Z_o P_R}{G_R}} = \frac{2\pi}{\lambda} \sqrt{\frac{120 P_R}{G_R}} \text{ v/m} \quad (22)$$

Equating (21) and (22) we obtain the following expression for the free space maximum range, d_{fsm}.

$$d_{fsm} = \frac{\lambda}{4\pi} \sqrt{\frac{P_T G_T G_R}{P_R}} \quad (23)$$

Applying (23) to the case in which the frequency of operation is 328 Mc, the transmitter power is 6 watts, half-wave dipole antennas employed for both transmission and reception, antenna power gain 1.64, and 3 uv across the terminals of a receiver with 50 ohms input impedance assumed to be the minimum detectable signal we find the free space maximum range to be

$$d_{fsm} = \frac{5.68 \times 10^{-4}}{4\pi} \sqrt{\frac{6 \times 1.64 \times 1.64}{1.8 \times 10^{-13}}} \text{ miles} = 428 \text{ miles}$$

Allowing 6 db for communications system loss, this becomes 214 miles. For other input voltages it can easily be seen that the free-space maximum range is inversely proportional to input voltage. These values are modified by the antenna directivity pattern in directions other than that of maximum radiation. Equation (23) shows that all other propagation factors being equal, the free-space maximum range is inversely proportional to frequency.

In plotting the lobe contours on 4/3 earth profile paper several approximations can be made with a high degree of accuracy. When the height of the ground antenna, h_1, is very small compared to the distance to the aircraft, d, points on the coverage diagram having a constant value of $g(\psi_2^0)$ can be assumed with negligible error to lie on a four-thirds earth slant line from the base of the ground antenna then through the height, h_2, calculated for 100 miles to all other distances in question. The error involved here is due to very slight modifications of the reflection coefficient, divergence factor and path length difference resulting from a slight shift in the point of geometric ray path reflection. The validity of using this approximation has been determined by calculating values of the $g(\psi_2^0)$ function, using the methods previously outlined, for distances of 200, 300, and 400 miles and comparing them with those obtained by extrapolating along the slant line through the value calculated for 100 miles. For the particular case in which the ground antenna height is 35 feet and the frequency of operation is 328 Mc with vertically polarized radiation, the errors resulting from this approximation were well within the plotting accuracy of approximately ±100 feet and were not apparent in the comparison. Furthermore, it has been found that the extrapolation works very well in the region at and just above the radio line of sight where other modes of propagation must be taken into account. Values of field strength at distances up to 400 miles in this region show an essentially linear attenuation with distance along the slant lines of extrapolation.

Points on the lobe contours are plotted directly on a sheet of four-thirds earth profile paper such as that used in Figures 3 through 12. These charts are designed in such a manner that any straight line in space corrected for the four-thirds earth radius shows up as a straight line on the chart. Choosing values of $g(\psi_2')$ and h_2 at 100 miles from Figure 17, points on the lobes are plotted using radial lines from the base of the ground antenna through the altitude at 100 miles to the distance, $d = g(\psi_2') \cdot d_{fsm}$ for each input terminal voltage desired as shown in Figure 20. The radio horizon is shown as an extended line from the top of the ground antenna tangent to the ground at distance $d_1 = \sqrt{2h_1}$ miles. This line can be plotted very easily using two points on the profile. From equation (5b) points along the radio horizon occur at heights and distances corresponding to

$$h_2 = \frac{d_2^2}{2} \text{ and } d = d_2 + \sqrt{2h_1}.$$ For example, when $d_2 = 200$ miles, $d = 200 + \sqrt{2h_1}$ miles and $h_2 = 20{,}000$ feet. Drawing a line through this point tangent to the earth at $d_1 = 2h_1$ completes the four-thirds earth radio horizon.

In order to correct more accurately for the average effect of gradients of refractive index a second-order correction is made to the lobes. This second-order correction, in the examples in this paper, is based on the average refractive conditions in the region of Washington, D.C., as derived by Schulkin and LaBolle[12] from an analysis of weather records. The correction to be made to the four-thirds earth ray is shown on figure 21 as a function of distance and altitude for the average refractive conditions in the region of Washington, D.C. Additional refraction corrections are derived by Schulkin and LaBolle for the geographical regions of San Juan, Puerto Rico, and Fairbanks, Alaska. A similar type of correction was first used by Bales and Norton[13] in 1943 in an analysis of radar detection ranges. Their correction was based on an empirical analysis of atmospheric refraction by Stickland [14/15] which was later shown by Schulkin[16] to be in error. Kitchen and Cooper[17] also used Stickland's analysis in their treatment of air-to-ground communications in 1948 leading them to over-correct the heights of their lobes particularly at heights above 10,000 feet, with a consequent over-reduction in the expected service range. It should be noted that this second-order refraction correction is, in any case, quite small and could be neglected completely without risk of serious error in the final results. Figure 21 shows the correction to be made to the four-thirds earth ray to correct for average refractive conditions in the region of Washington, D.C. The several curves on Figure 21 were derived from the results given by Schulkin and LaBolle[12] and indicate the height correction to be made to the lobes at distances, d_2, and the four-thirds earth altitude indicated. As an example of the method of applying this correction, it will be noted that on Figure 20 that the four-thirds earth, six-microvolt lobe intersects the curve, $d_2 = 100$ miles, at two altitudes, $h_2 = 8{,}800$ feet and 23,500 feet. From Figure 21 the altitude correction for average refractive conditions is seen to be -170 feet and [illegible]200 feet respectively. Similar height corrections are made at all other intersections and the new lobe is drawn in as shown on Figure 20.

B. <u>High-Gain Tilted Array and Height-Diversity Considerations</u>

The improvement in coverage realized by the use of high-gain tilted arrays and height-diversity ground antenna systems depends on several factors. Among these are the heights of the antenna above ground, the angle of tilt for tilted arrays, and the spacing for diversity systems. The most serious limitation to communications coverage in most cases lies in the null above the first lobe. For this reason, it is desirable to maximize the improvement in this direction. Figure 14 shows the geometry involved in tilting an antenna with a narrow beam in vertical cross section for suppression of the ground-reflected energy. For this antenna the gain in the direction of the ground-reflected ray is less than that in the direction of the direct ray. Figure 15 shows the improvement as a function of the angle of tilt which can be realized in the direction of the null above the first lobe for an eight-element colinear array of half-wave dipoles with an effective height of thirty-five feet above the ground and operating at 328 Mc. The curve shows the ratio of field intensity in the null to the free-space field intensity in the direction of maximum radiation from the antenna. In this case the null involved is elevated approximately 2.6° above the horizontal. A comparison between Figures 9 and 10 shows the effect of tilting the array on the expected coverage. In Figure 9 the maximum radiation is directed in the horizontal while in Figure 10 it is elevated 7.2°. This elevation can be effected in all azimuthal directions by proper electrical phasing of the individual elements.

In order to determine the resulting coverage from such an array, equation (7) is modified to include the effects of directivity in the ground antenna so that for equivalent distances, $g(\psi'_2)$ refers the field strength at any given elevation to the free-space field intensity in the direction of maximum radiation,

$$g(\psi'_2) = \left[g_1^2 + (g_2 D\,|R'|\,)^2 - 2g_1 g_2 D\,|R'|\,\cos(\theta - c)\right]^{1/2} \quad (24)$$

In this equation, g_1 and g_2 are antenna directivity voltage gain factors for the direct and ground-reflected rays respectively, referred to the maximum gain as unity. The $g(\psi'_2)$ function at 100 miles can be constructed from the above considerations and the resulting lobe diagram plotted following the methods described before.

To determine the coverage to be expected from height diversity systems, consideration must be given to the manner in which the signals are to be detected. To receive the signals simultaneously on two antennas, two receivers are used, the signals being combined after detection. Since the receiver which receives weaker signals contributes little or nothing in the way of either signal or noise, the resulting coverage diagrams are prepared by merely superimposing two lobe diagrams, one for the upper antenna and one for the lower and using as contours those representing the stronger signal. The points of lobe crossover now become psuedo-minima and represent the directions of least signal. The relative positions of the crossovers depend on the relative heights of the ground antennas. Maximum coverage is realized assuming three microvolts to be the minimum detectable signal, when the three-microvolt lobes cross over at a maximum height. This occurs when the two lower crossovers occur at the same altitude. For the range of frequencies of from 225 Mc to 400 Mc and for 6-watt airborne transmitters, it was found, in general, that a ratio of ground antenna heights of approximately seven to ten gave this result. In this case the crossover between the first and second lobes occurs at the same altitude as that for the two third lobes, while the crossover between the two second lobes occurs somewhat higher. Low-angle coverage has been defined in terms of the distance at given altitudes to the bottom of the lowest three-microvolt lobe. These distances increase somewhat with increasing heights of the ground antenna. However, increasing the heights of the ground antennas results in a larger number of and a finer structure of lobes, which lowers the altitude of the crossovers and can result in serious communications gaps at lower altitudes.

Height-diversity ground transmission coverage diagrams are calculated in a somewhat different manner than those for reception because of the method in which the signals are transmitted and are combined at the receiver. For this type of transmission, two transmitters are employed at the ground installation, one for each antenna. A slight difference in frequency is necessary to maintain independence in transmission. This frequency difference must be small enough so that both signals will pass through the receiver band-pass simultaneously yet sufficiently large so that the beat frequency produced can be eliminated in the receiver audio circuits. The procedure used in determining the coverage to be expected involves adding the power obtained from each transmitter as received at the aircraft. To accomplish this addition, the function $g(\psi'_2)$ versus h_2 at 100 miles is calculated separately for each of the transmitters. These two $g(\psi'_2)$ functions are then combined as the root sum of the squares of the values of the two functions occurring at equal heights. The resulting curve indicates the expected variation of the combined field strengths with respect to the free-space field of a single 6-watt transmitter with height above ground at 100 miles. From this curve contours of constant field intensity are developed in the manner similar to that outlined before, resulting in a coverage diagram such as Figure 12.

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REFERENCES

1. U.S. Naval Air Test Center, Patuxent River, Maryland, "Ultra high frequency propagation tests over land and water," Appendices A, B, and G, Project No. TED No. PTR EL 929, December 1949.

2. K. A. Norton, J.W. Herbstreit, and R. S. Kirby, "A theory of propagation over irregular terrain with an application to communication between aircraft in flight," in preparation.

3. K. A. Norton, "The calculation of ground wave field intensity over a finitely conducting spherical earth," Proc. I.R.E., vol. 29, No. 12, pp. 623-639, December 1941.

4. NDRC Committee on Propagation, Summary Technical Report, "Propagation of radio waves through the standard atmosphere," vol. 3, Chap. 1, Washington, D.C., 1946.

5. K. A. Norton and A. C. Omberg, "The maximum range of a radar set," Operation Research Staff, Office of the Chief Signal Officer, Report ORG-9-1, Feb. 1943, later published in Proc. I.R.E., pp. 4-24, vol. 35, No. 1, January 1947.

6. F. E. Terman, "Radio Engineer's Handbook," p 660, McGraw-Hill Book Co., Inc., 1943.

7. H. P. Gates, "Evaluation of diversity systems," USNEL Report No. 80, October 8, 1948.

8. K. A. Norton, "Physical reality of space and surface waves in the radiation field of radio antennas," Proc. I.R.E. vol. 25, pp 1192-1202, September 1937.

9. K. A. Norton, "The propagation of radio waves over the surface of the earth and in the upper atmosphere," Part II, Proc. I.R.E., vol. 25, pp 1203-1236, September 1937.

10. Balth van der Pol and H. Bremmer, "Further note on the propagation of radio waves over a finitely conducting spherical earth," Philosophical Magazine, vol. 27, pp 261-275, March 1939.

11. H. J. Riblet and C. B. Barker, "A general divergence formula," Journal of Applied Physics, vol. 19, pp. 63-70, January 1948.

12. M. Schulkin and V. LaBolle, "Atmospheric refraction corrections for radio field intensity coverage diagrams," in preparation.

13. W. E. Bales and K. A. Norton, "Technical report on the maximum range of detection of the German early warning radar equipment, especially when viewing large, tight formations of bomber aircraft," Headquarters VIII Bomber Command, Operational Research Section, September 13, 1943.

14. A. C. Stickland, "The effect of atmospheric refraction on the propagation of radio waves," National Physical Laboratory Report No. R.R.B./S. 10, March 1943.

15. A. C. Stickland, "Refraction in the lower atmosphere and its application to the propagation of radio waves," Meteorological Factors in Radio Wave Propagation, pp. 253-267, report of a conference held on 8 April 1946 by the Physical Society and the Royal Meteorological Society, printed by Taylor and Francis, Ltd., London.

16. M. Schulkin, "Average radio ray refraction in the lower atmosphere," Central Radio Propagation Laboratory Report No. CRPL-2-2, August 11, 1947.

17. F. A. Kitchen and D. G. Cooper, "Interim report on a theoretical analysis of the performance expected in ground-air communications using frequencies in the 100-400 Mc/s band," Admiralty Signal and Radar Establishment, Monograph No. 831, April 1948.

GEOMETRY FOR AIR-TO-GROUND COMMUNICATIONS

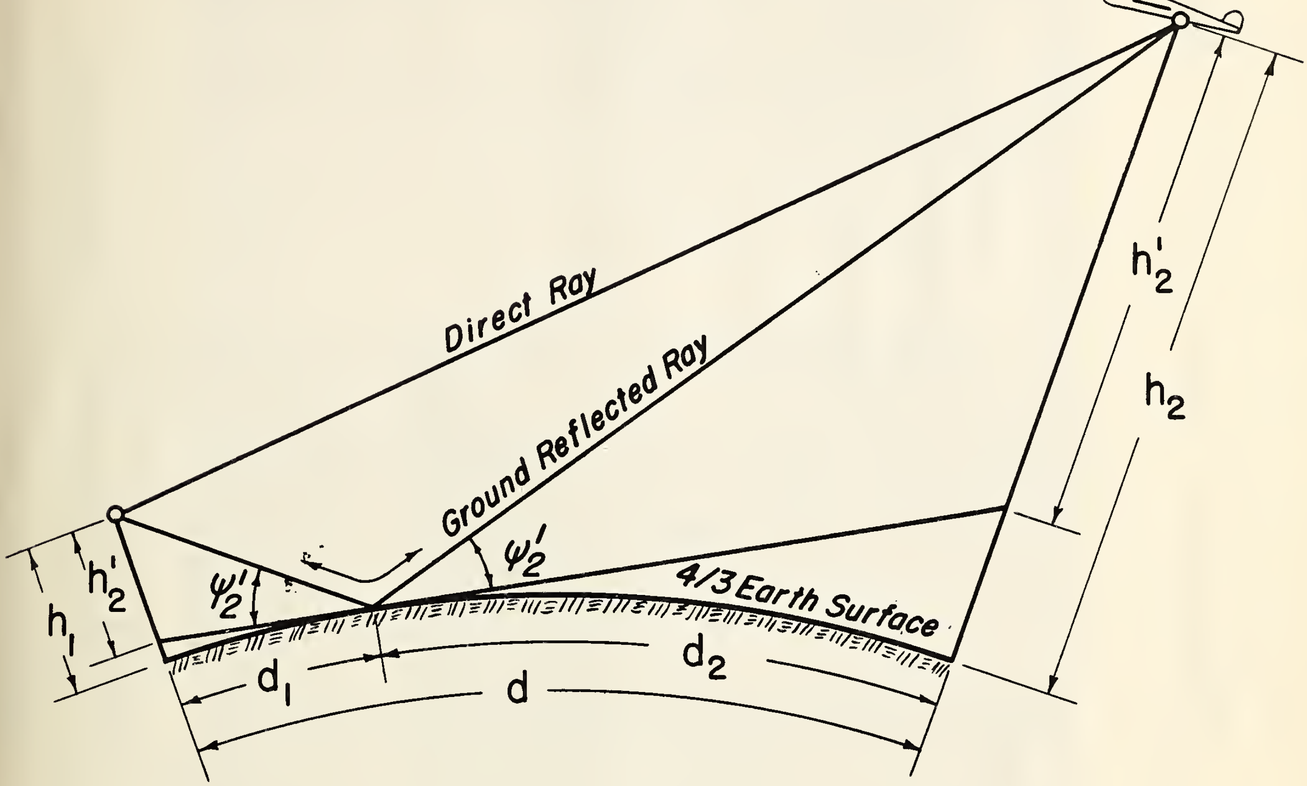

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Figure 1

MAGNITUDE AND PHASE ANGLE OF THE REFLECTION COEFFICIENT FOR 328 Mc

Dielectric constant: $\epsilon = 15$; Conductivity: $\sigma = 10^{-2}$ mhos/meter; Horizontal and vertical polarization

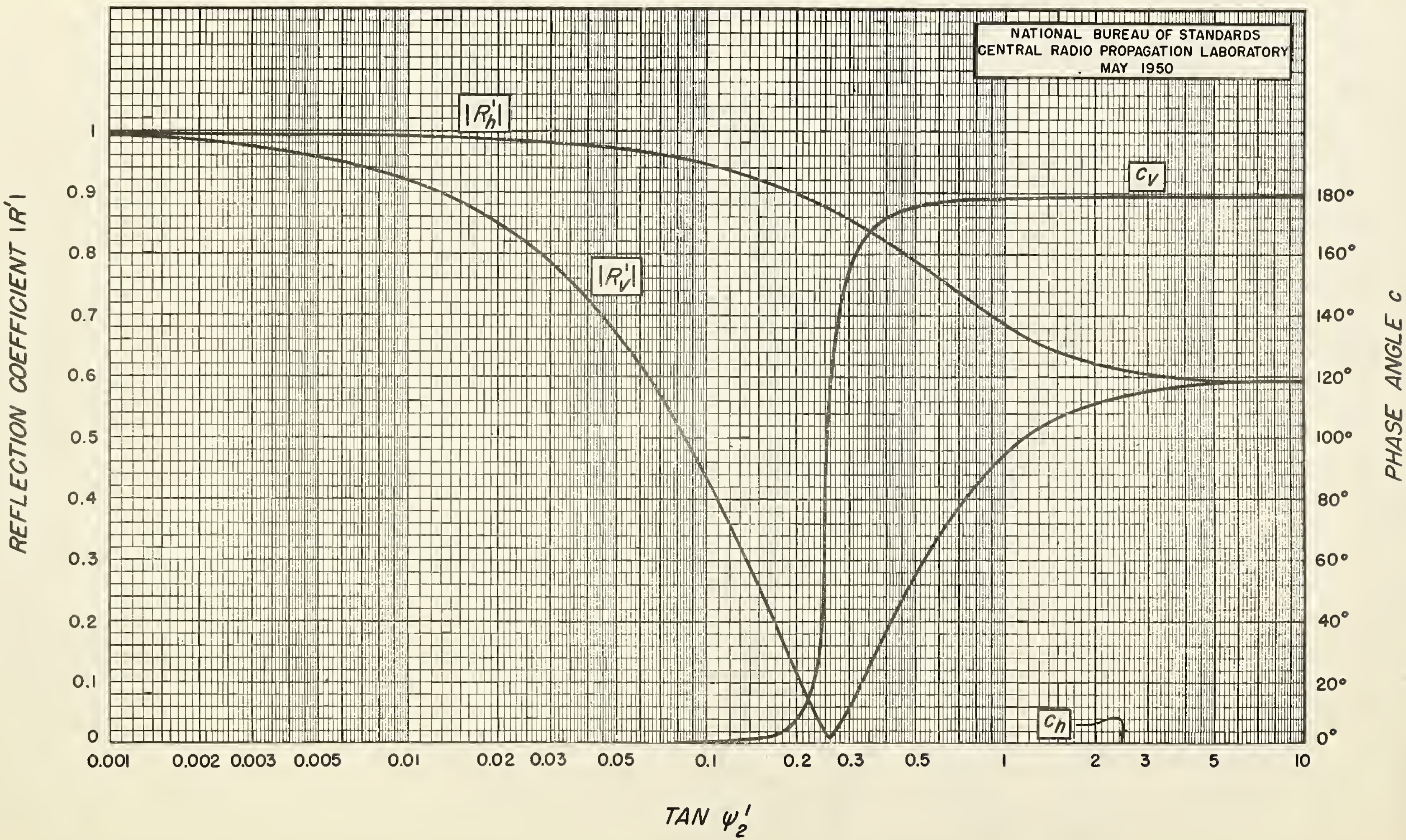


Figure 2

139 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

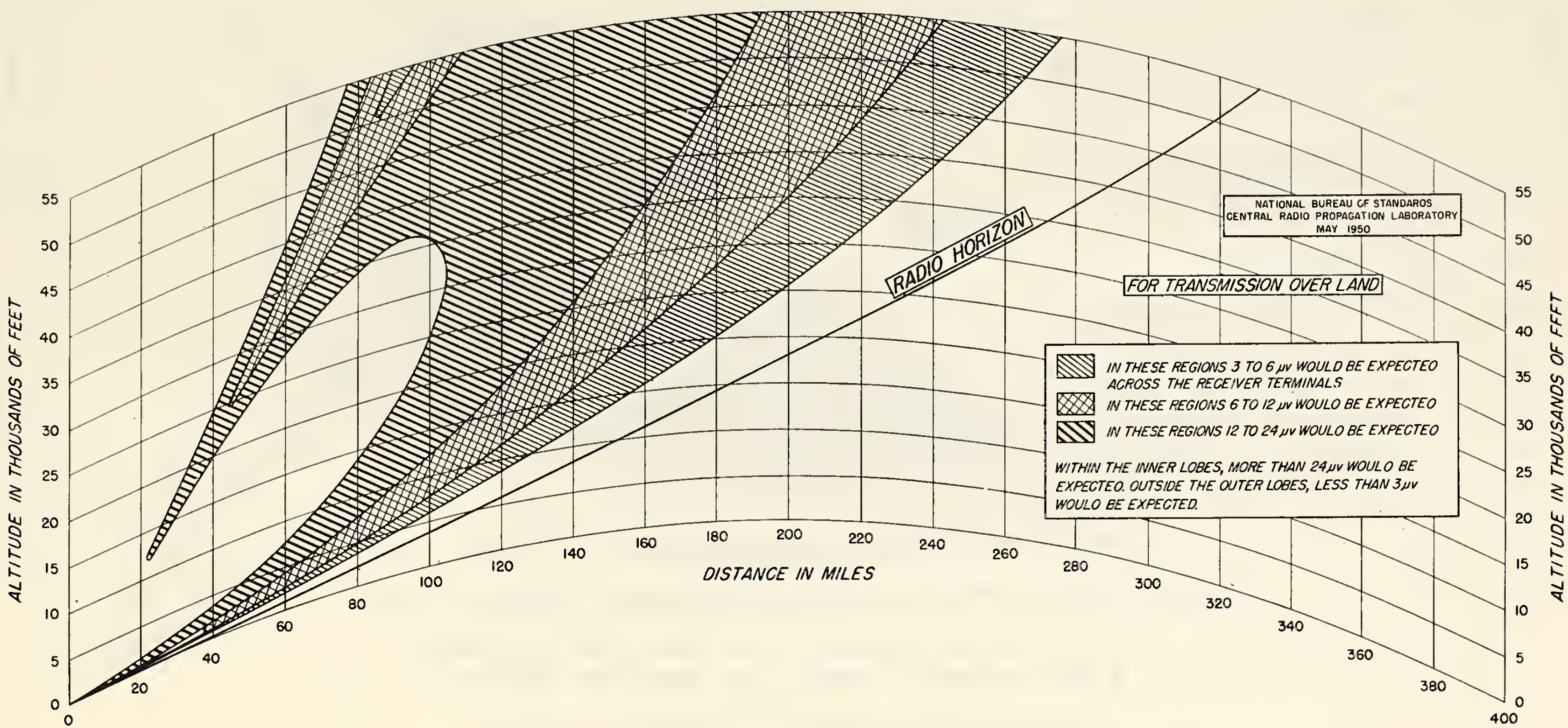


Figure 3

243 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION
OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

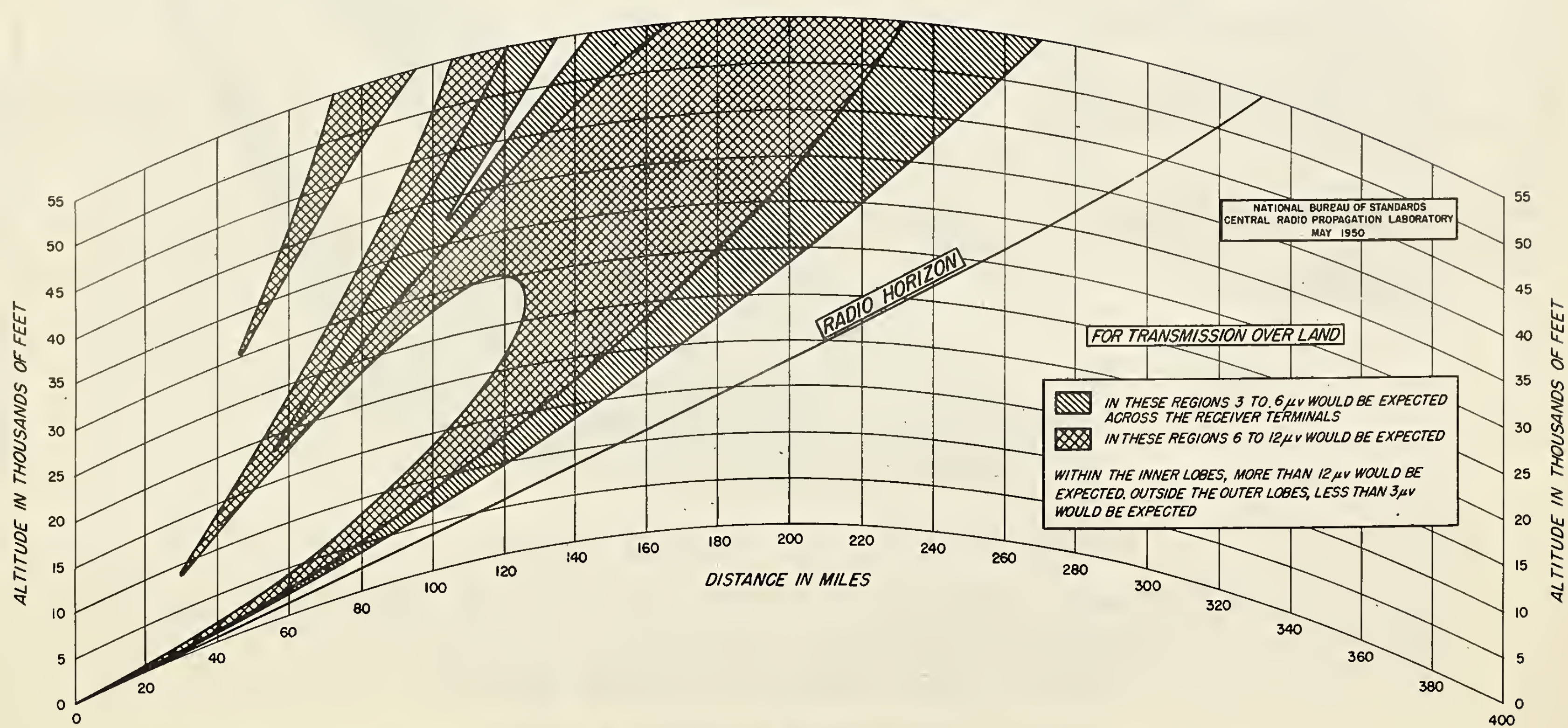


Figure 4

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

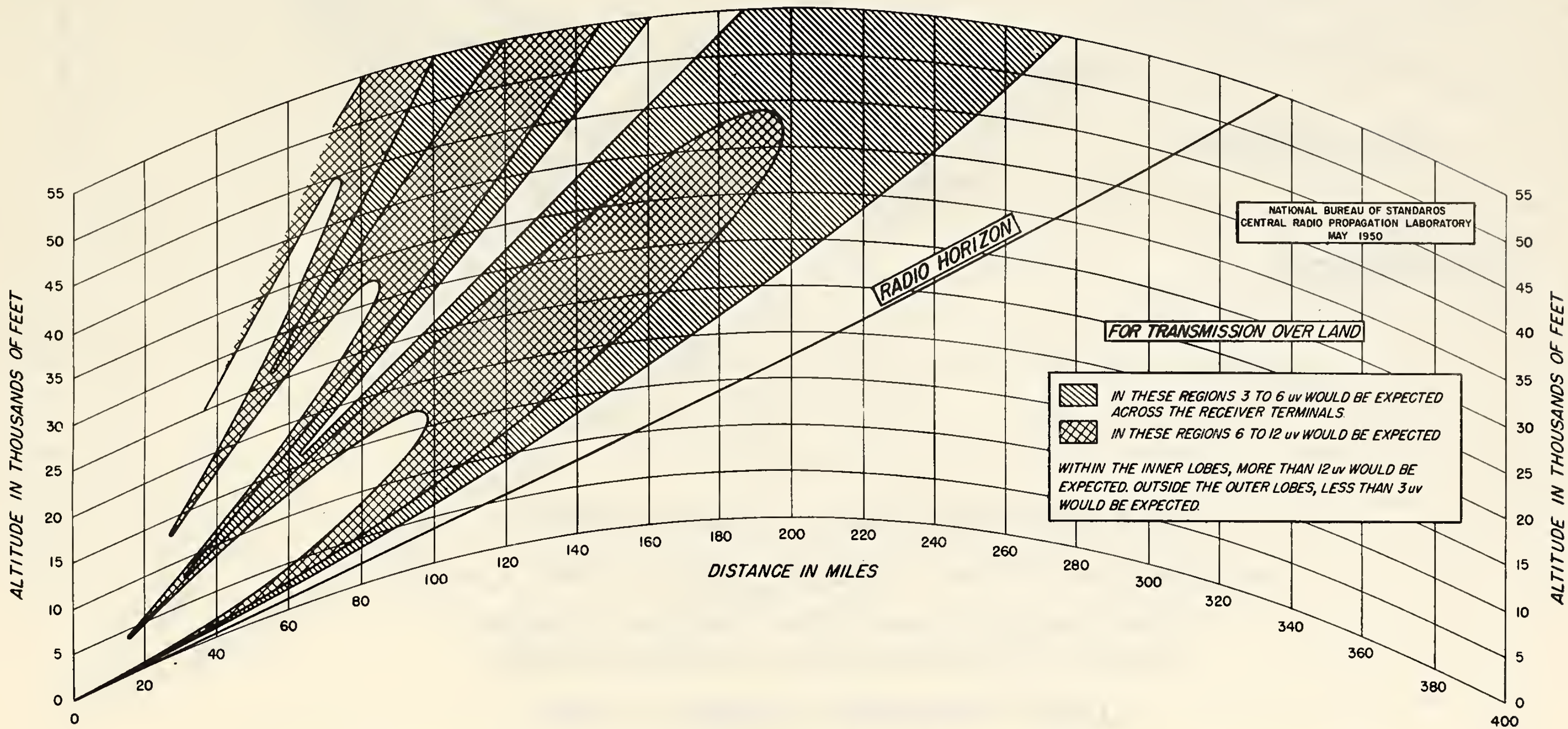


Figure 5

1,000 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

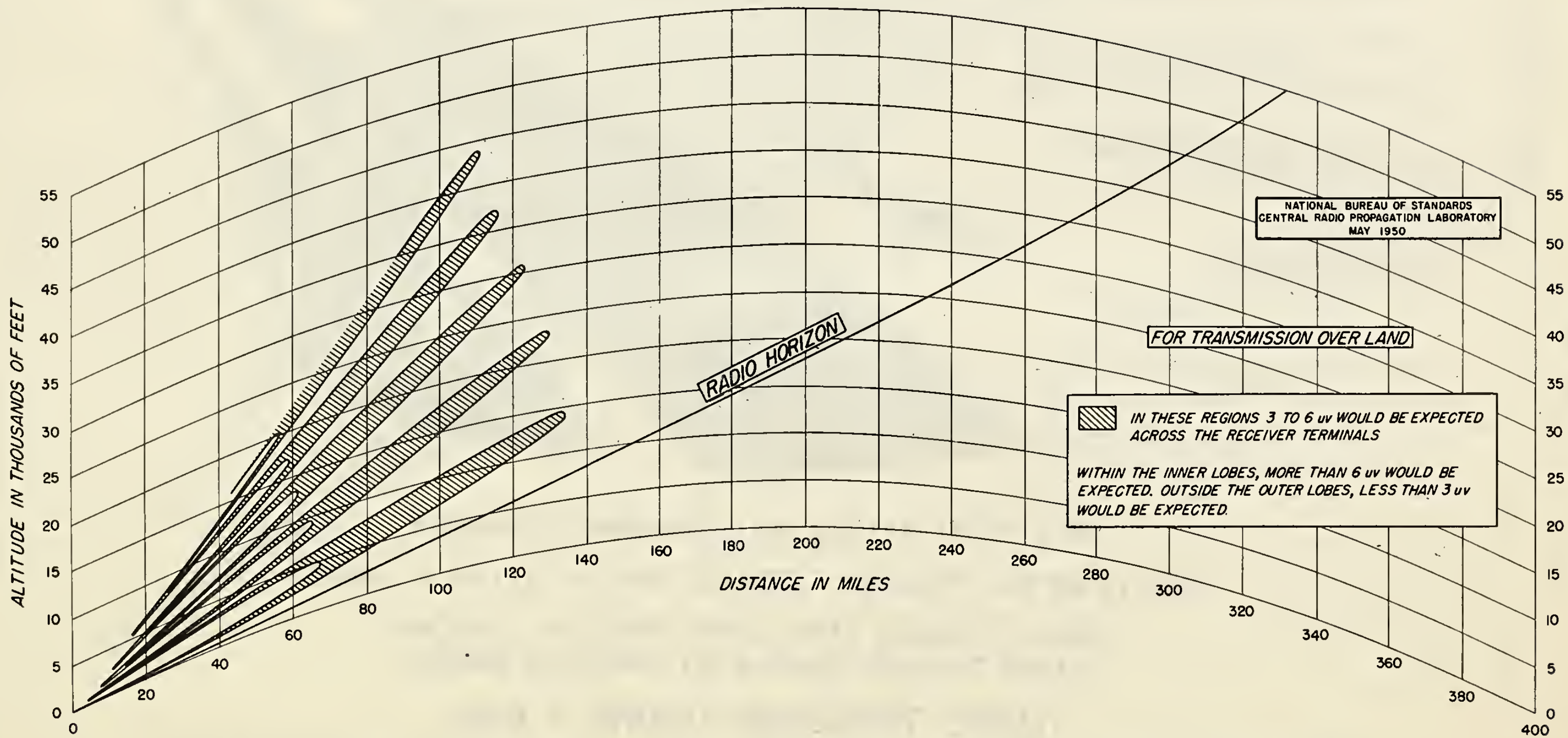


Figure 6

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE HORIZONTAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE HORIZONTAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; HORIZONTAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

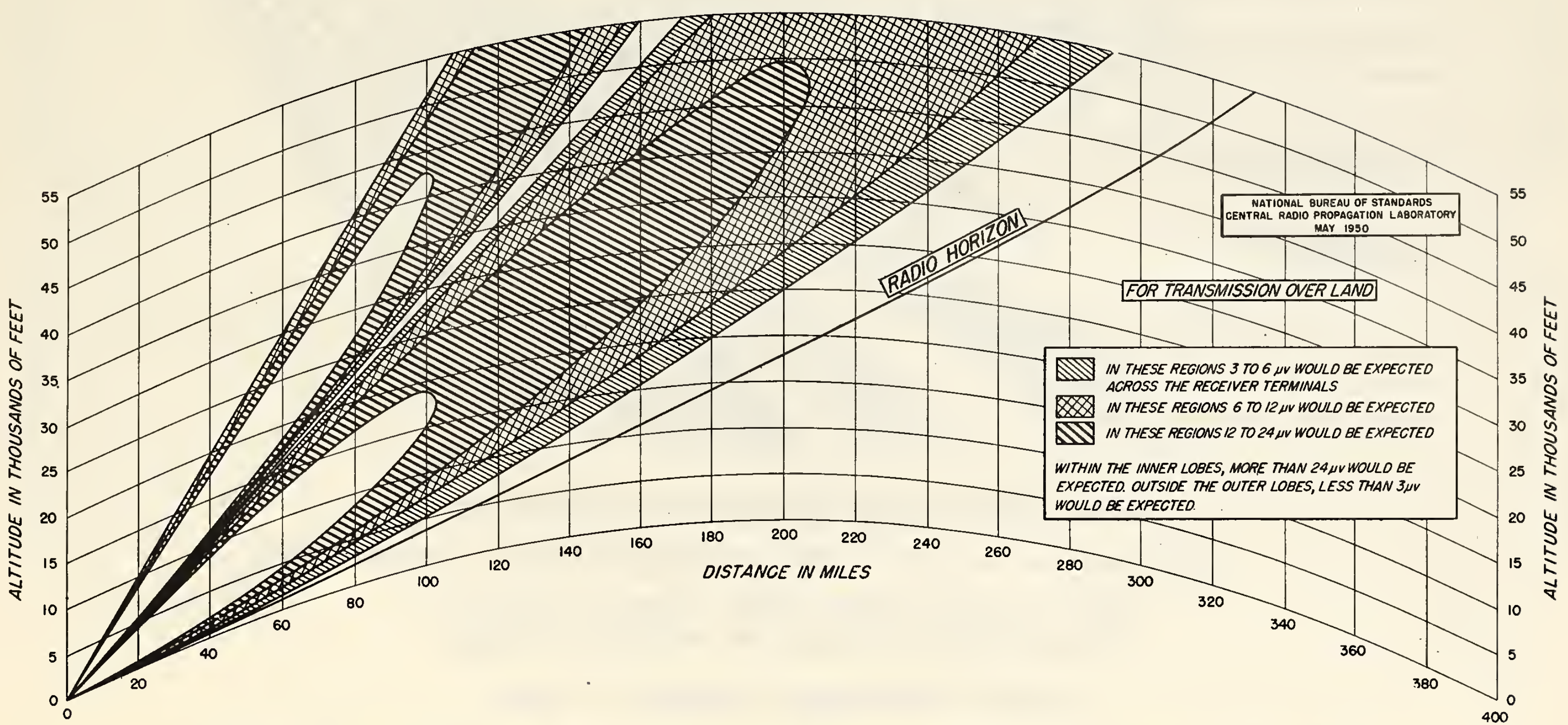


Figure 7

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 115 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

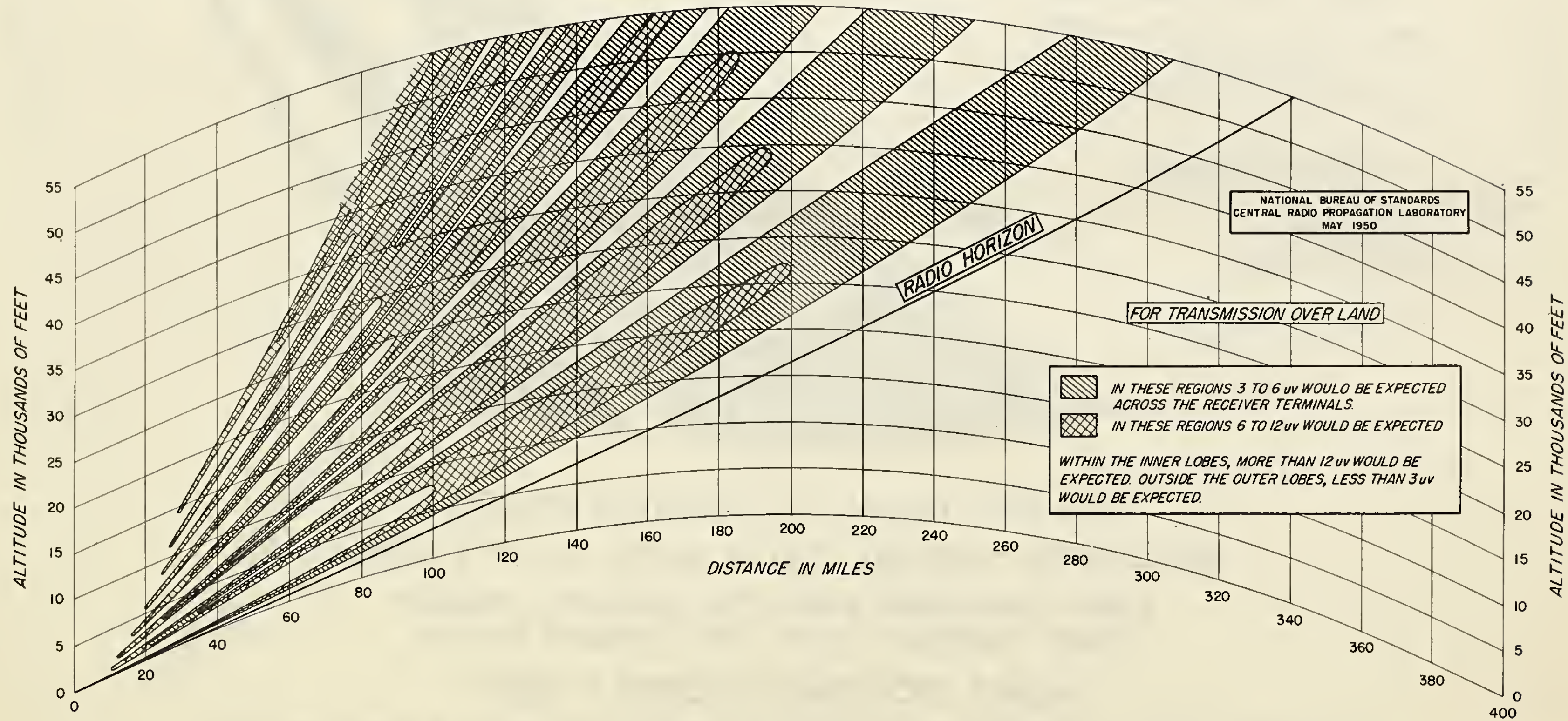


Figure 8

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: EIGHT ELEMENT COLINEAR ARRAY NOT TILTED
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

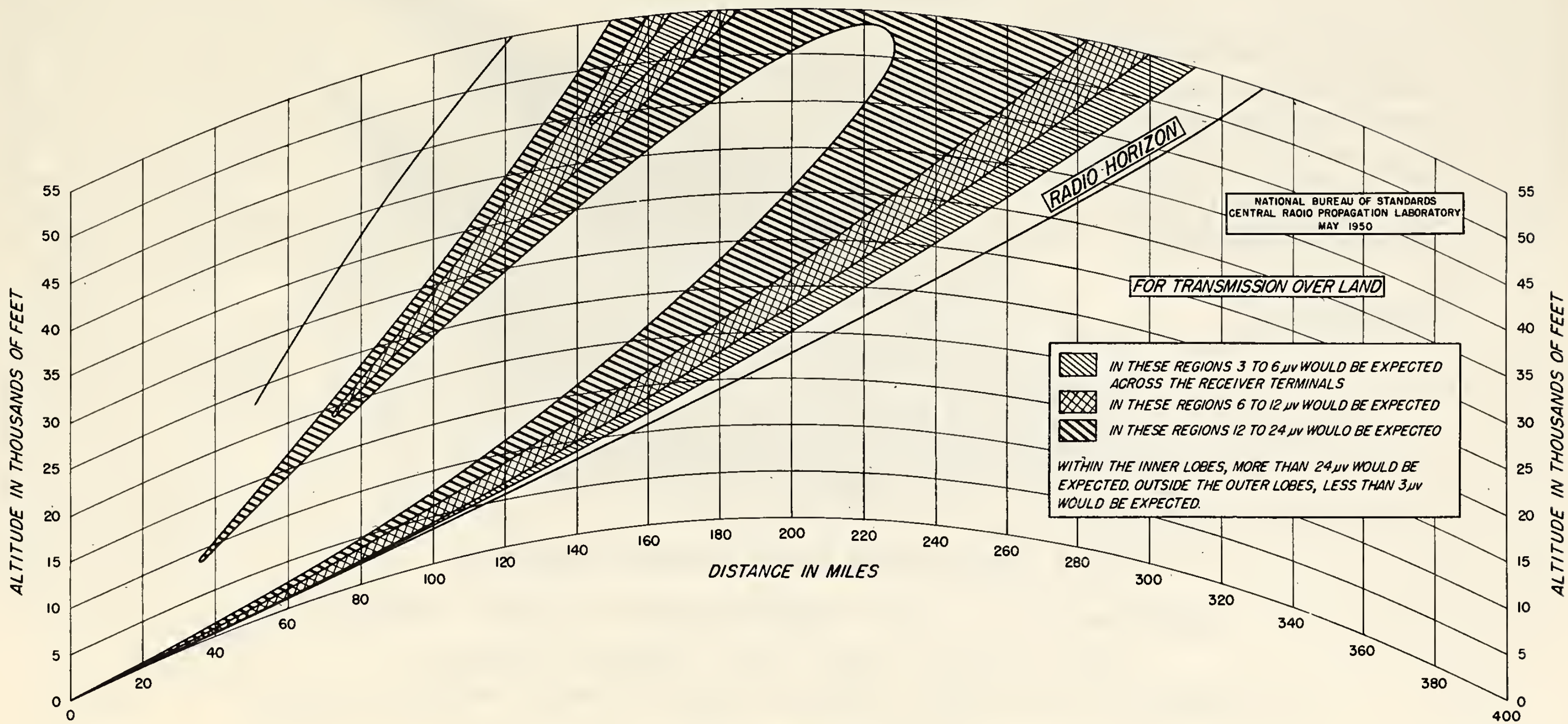


Figure 9

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: EIGHT ELEMENT COLINEAR ARRAY TILTED UPWARD 7.2°
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

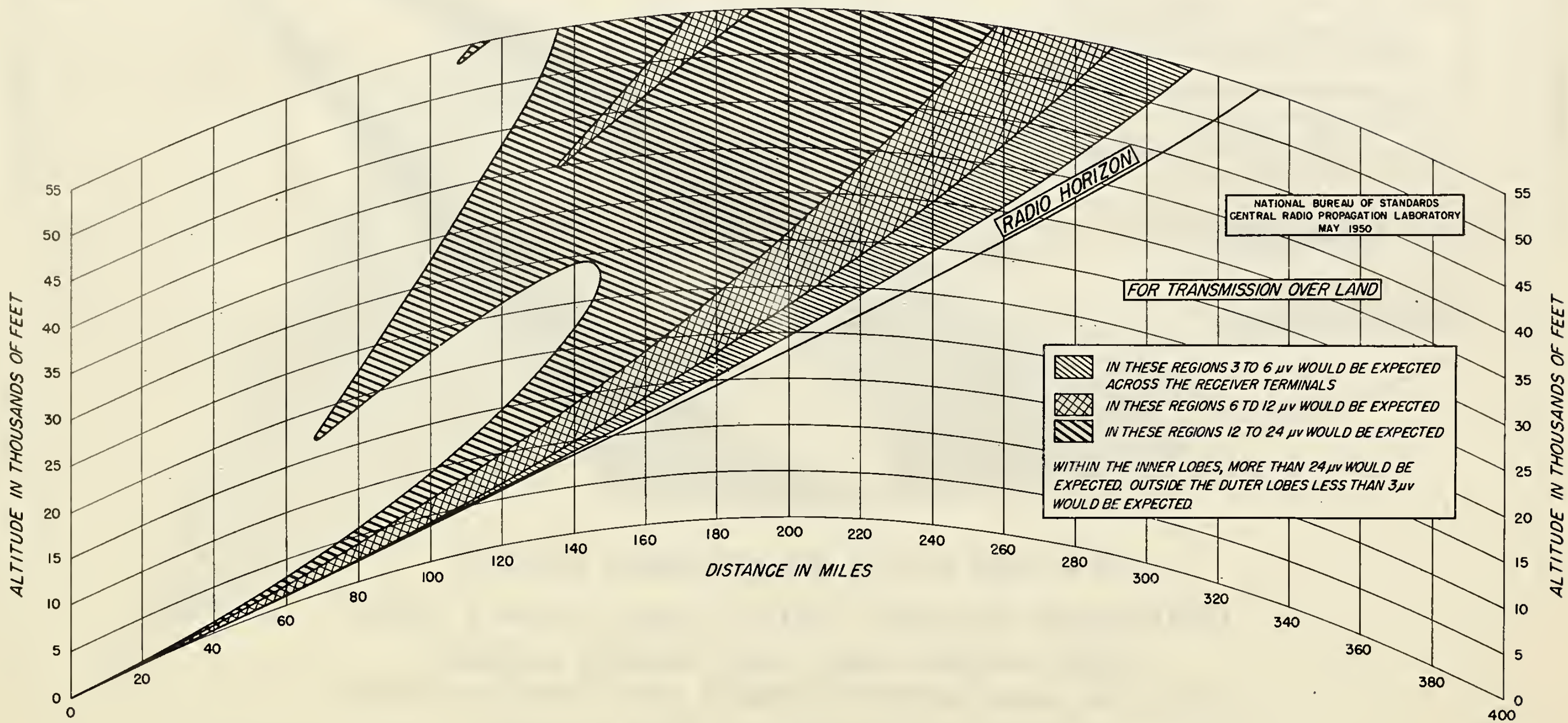


Figure 10

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE (HEIGHT DIVERSITY RECEPTION)
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER; 6 WATTS; HEIGHT: 35 AND 50 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

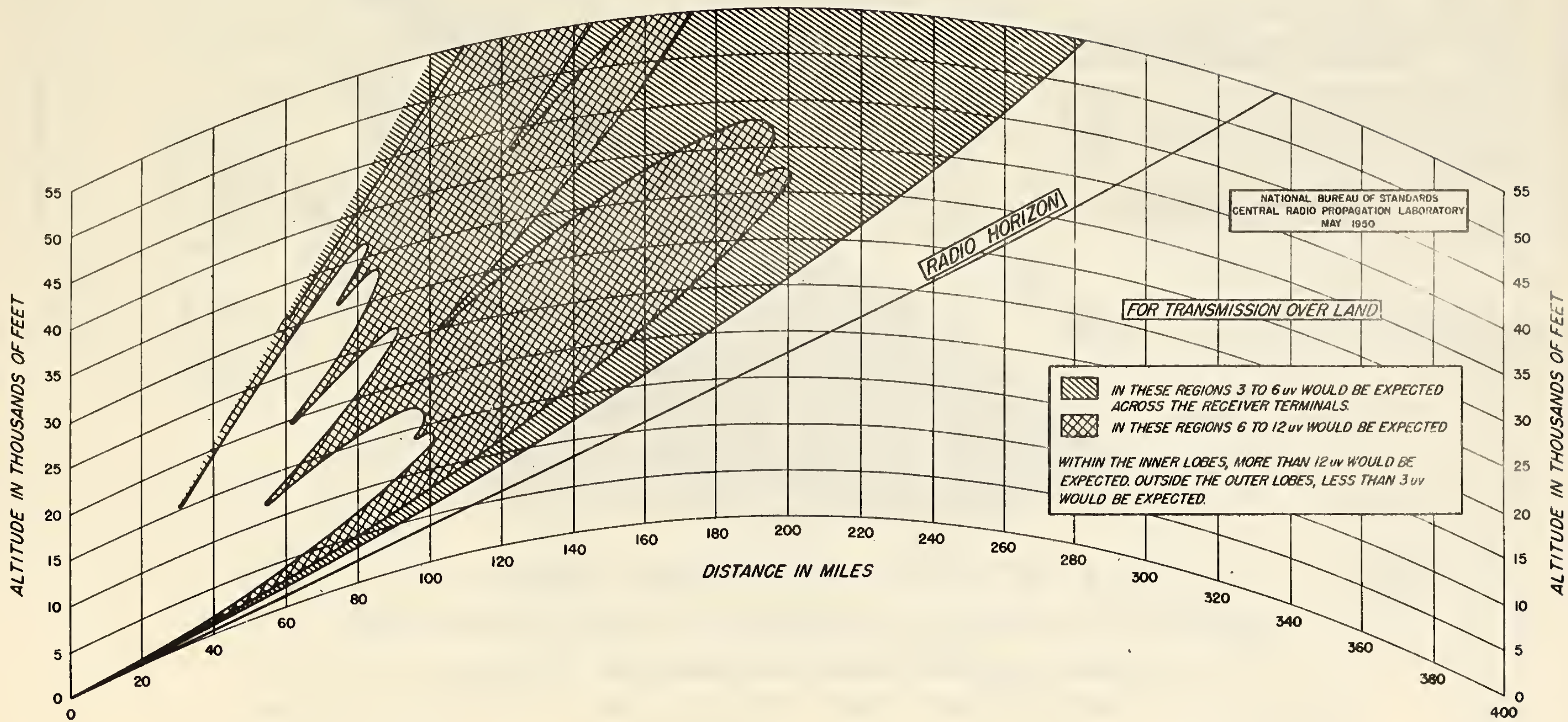


Figure II

328 Mc RADIATION PATTERN FOR AIR TO GROUND COMMUNICATION OVER A SMOOTH SPHERICAL EARTH

GROUND ANTENNA: HALF-WAVE VERTICAL DIPOLE (HEIGHT DIVERSITY TRANSMISSION)
AIRCRAFT ANTENNA: HALF-WAVE VERTICAL DIPOLE

POWER: 6 WATTS; HEIGHT: 35 AND 50 FEET; VERTICAL POLARIZATION

ASSUMED COMMUNICATION SYSTEM LOSS: 6 db

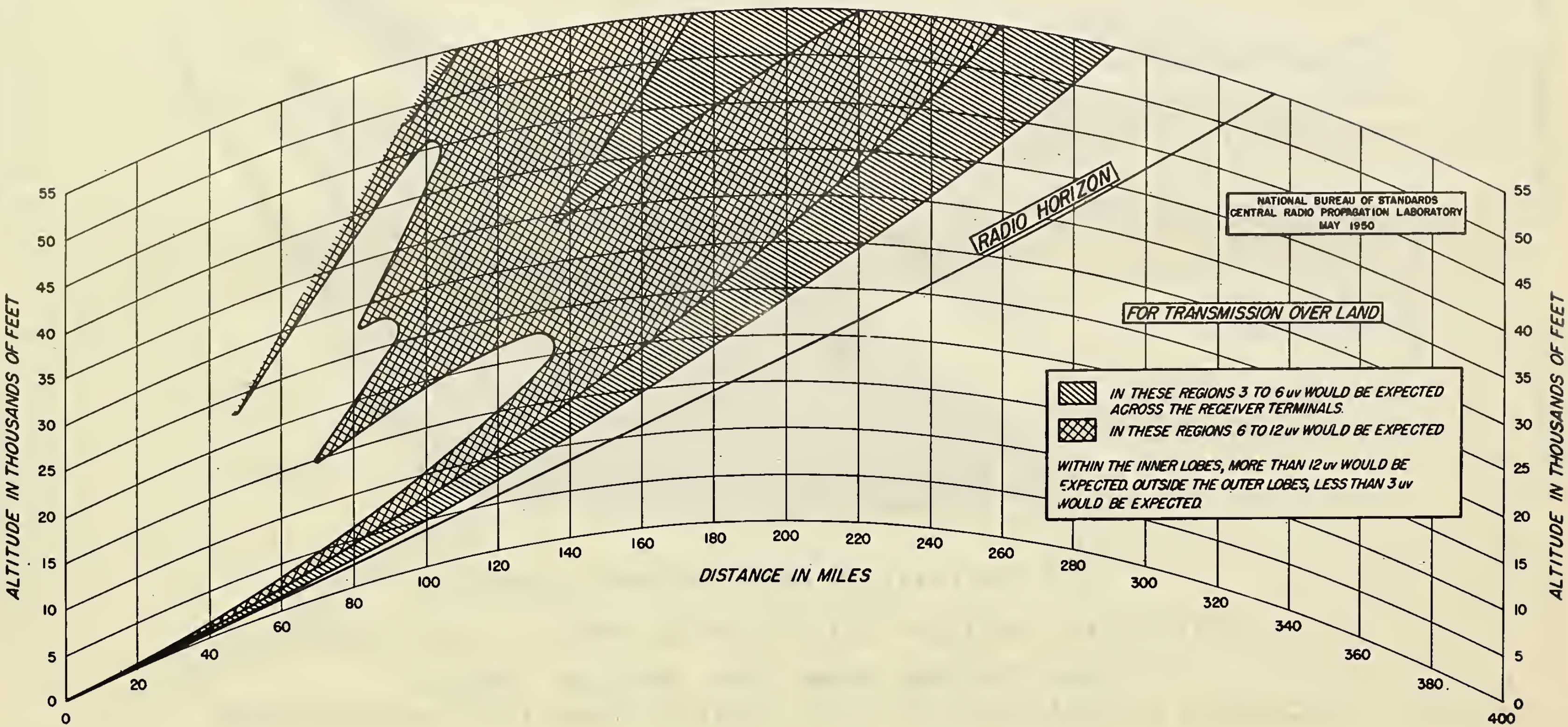


Figure 12

OBSERVED INPUT VOLTAGE VARIATION AT GROUND STATION RECEIVER FROM AN AIRCRAFT AT 10,000 FEET TRANSMITTING ON 328.2 MC/S

TRANSMITTER POWER: 6 WATTS; TRANSMITTING AND RECEIVING ANTENNA GAIN: 2.15 db (RELATIVE TO AN ISOTROPIC)
GROUND ANTENNA HEIGHT: 75 FEET; TRANSMISSION OVER WATER; 6 db COMMUNICATIONS SYSTEM LOSS ASSUMED FOR THEORETICAL CURVES

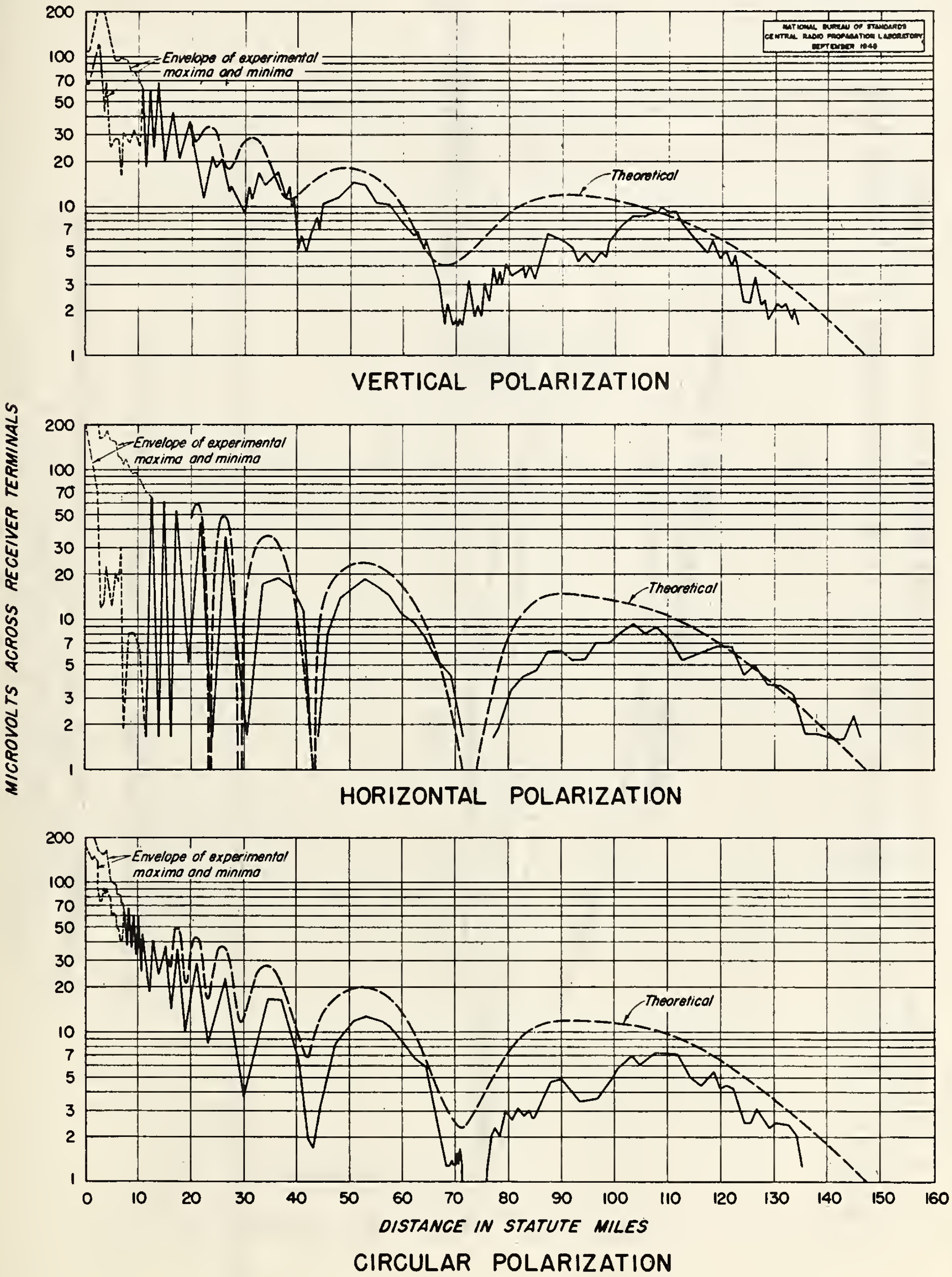
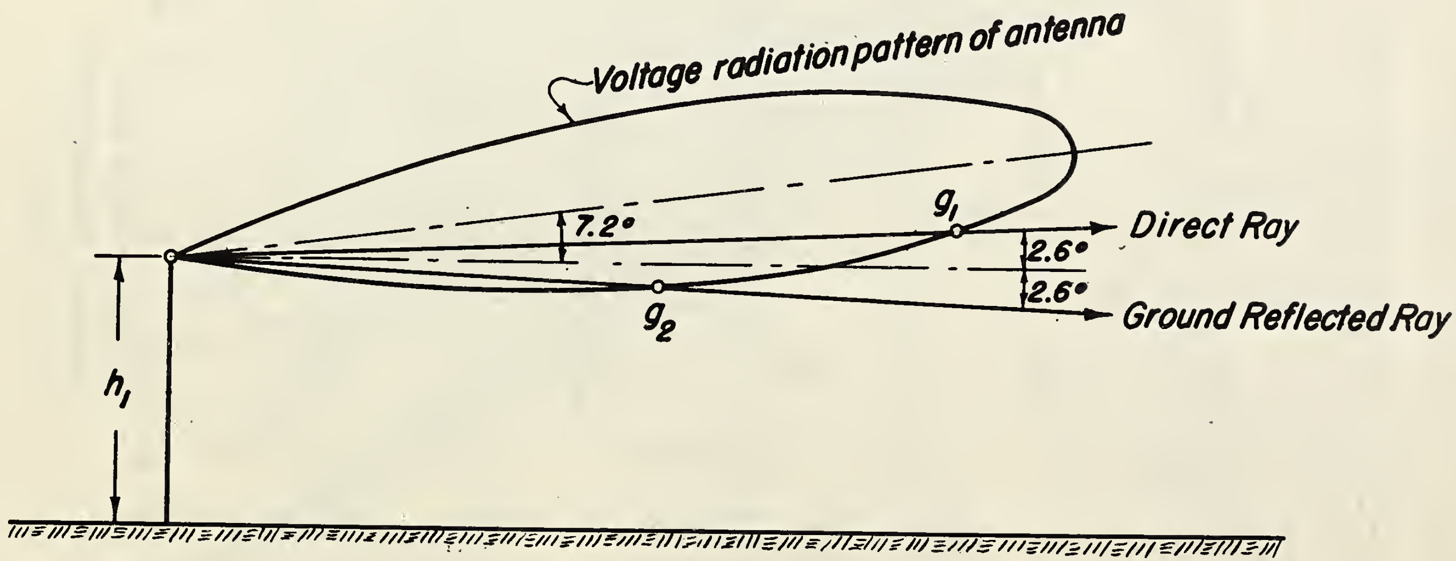


Figure 13

SUPPRESSION OF GROUND REFLECTED RAY OBTAINED BY USE OF HIGH-GAIN TILTED ARRAY

8 element colinear array phased to tilt pattern upward 7.2° in all directions

Null above first lobe occurs at an elevation of 2.6° with a ground antenna height of 35 feet and a frequency of 328 Mc



g_1 = antenna voltage gain factor for direct ray

g_2 = antenna voltage gain factor for ground reflected ray

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CENTRAL RADIO PROPAGATION LABORATORY
JUNE 1950

Figure 14

RELATIVE VOLTAGE IN THE NULL ABOVE THE FIRST LOBE AS A FUNCTION OF ANGLE OF TILT

Ground Antenna: 8 element colinear array 35 feet above ground
Frequency: 328 Mc; Null Elevation: 2.6° above radio horizon

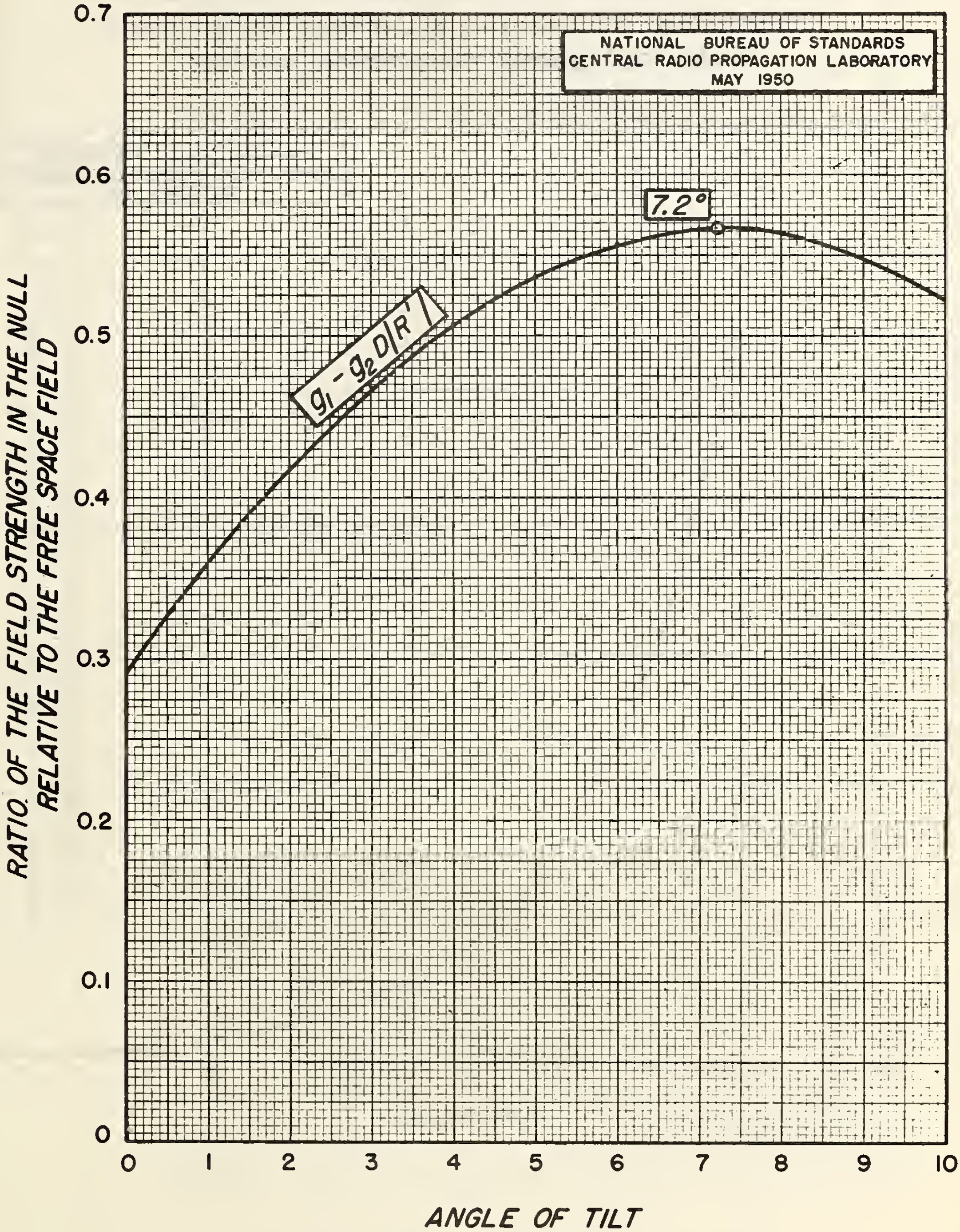


Figure 15

VARIATION OF RELATIVE PHASE BETWEEN DIRECT AND GROUND REFLECTED RAY WITH DISTANCE FROM GROUND ANTENNA TO GEOMETRIC RAY REFLECTION POINT

Frequency: 328 Mc; ground antenna height: 35 feet
Transmission path length: 100 miles; transmission over good ground; polarization: vertical

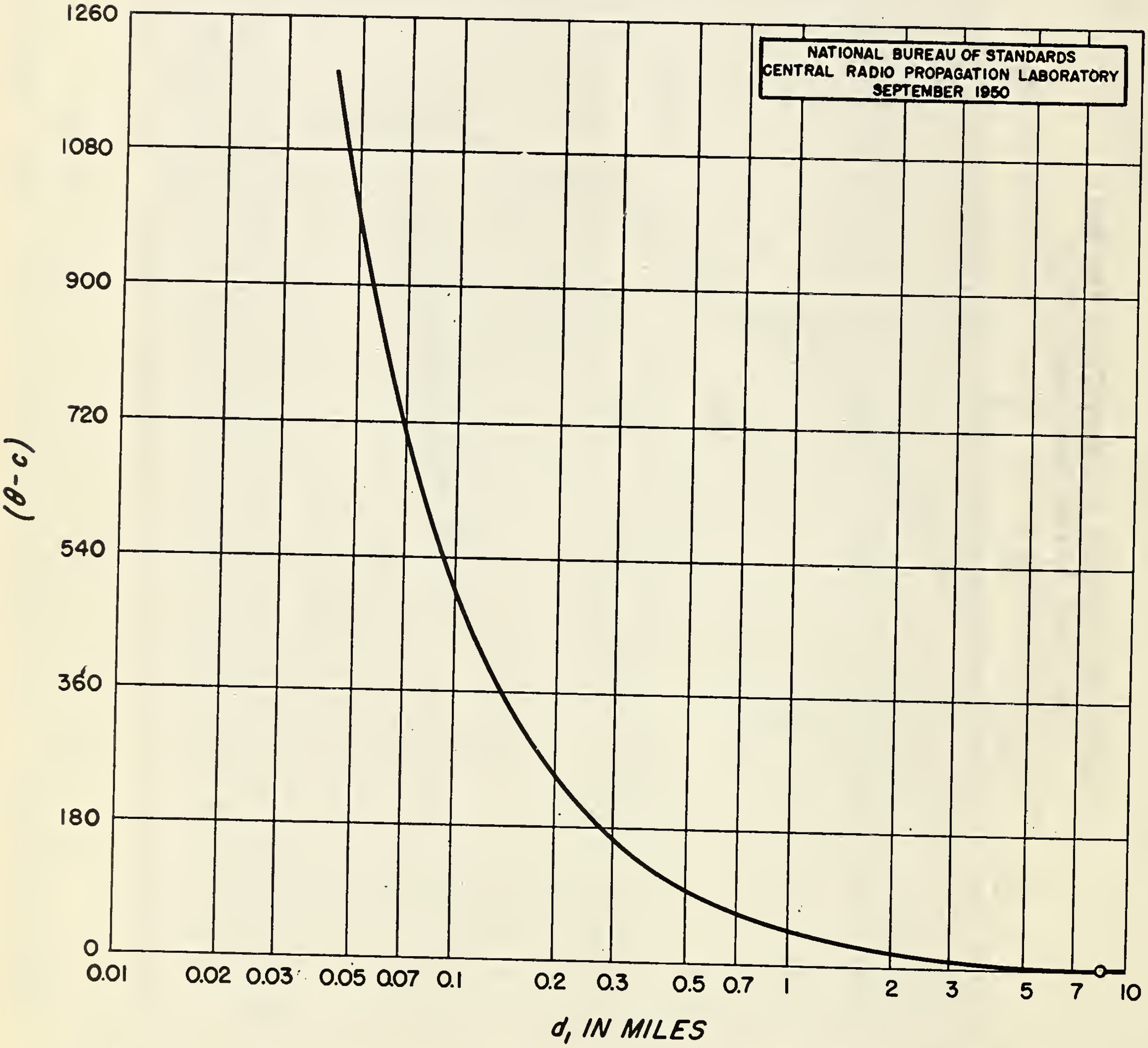


Figure 16

THE VARIATION OF FIELD STRENGTH WITH ALTITUDE OF AIRCRAFT AT A DISTANCE OF 100 MILES

Frequency: 328 Mc; ground antenna height: 35 feet
Transmission over good ground; polarization: vertical

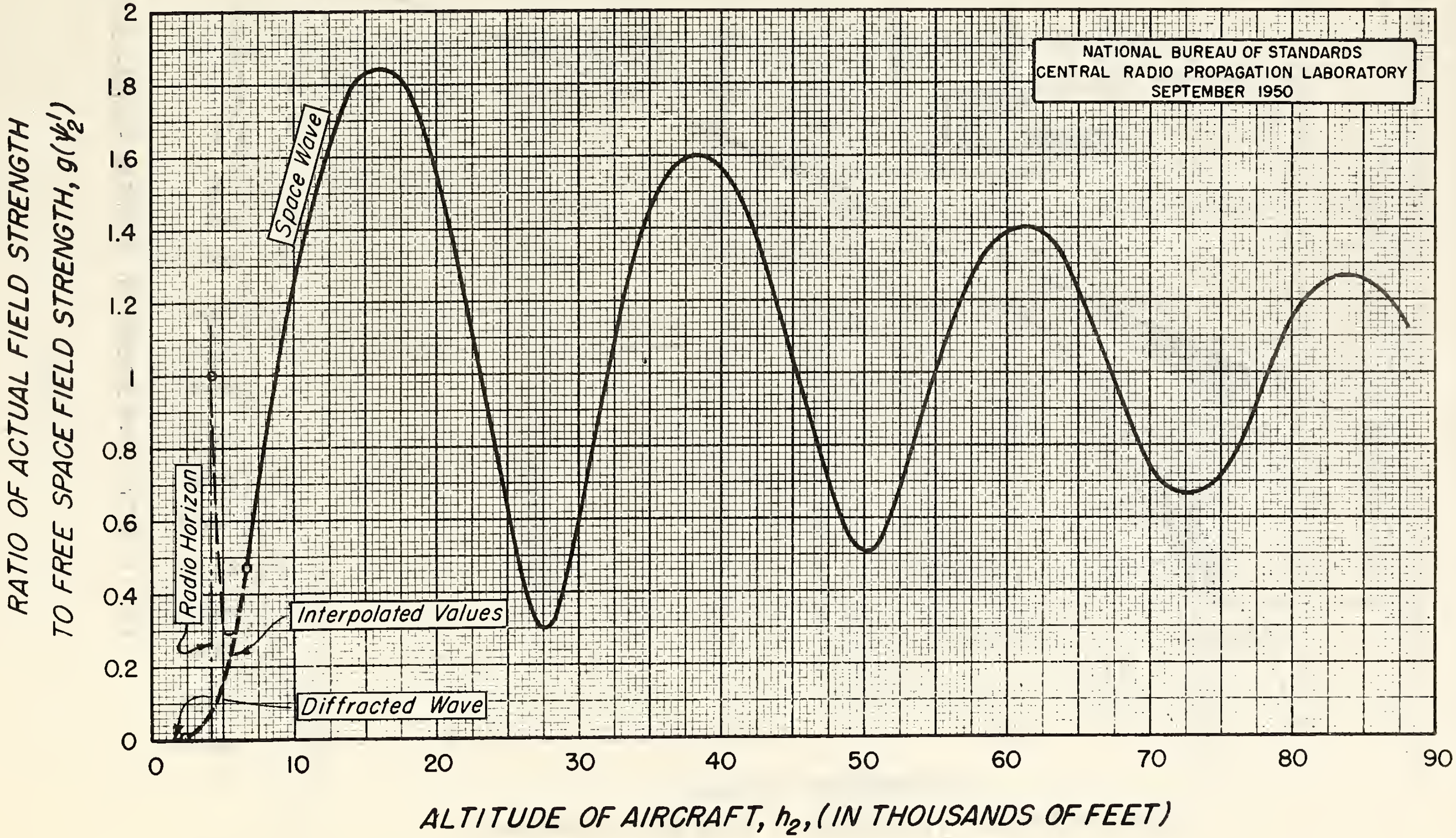
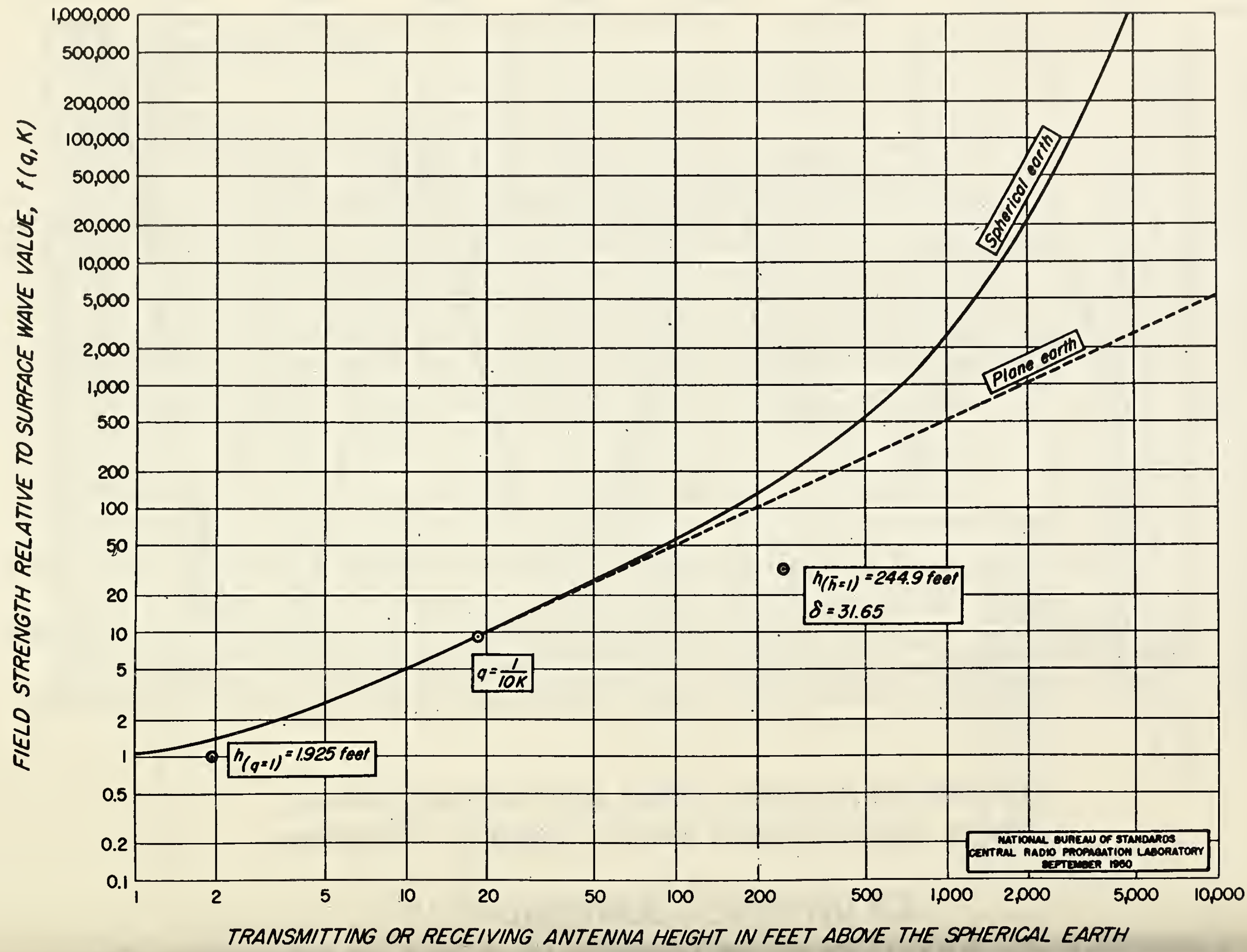


Figure 17

THE VARIATION OF FIELD STRENGTH WITH ANTENNA HEIGHT AT POINTS BELOW THE RADIO HORIZON

Frequency: 328 Mc; $\epsilon = 15$; $\sigma = 10^{-2}$ mhos per meter
Vertical polarization



THE VARIATION OF FIELD STRENGTH WITH ALTITUDE OF AIRCRAFT AT POINTS ABOVE AND BELOW THE HORIZON AT A DISTANCE OF 100 MILES

Frequency: 328 Mc; Ground antenna height: 35 feet
Transmission over good ground

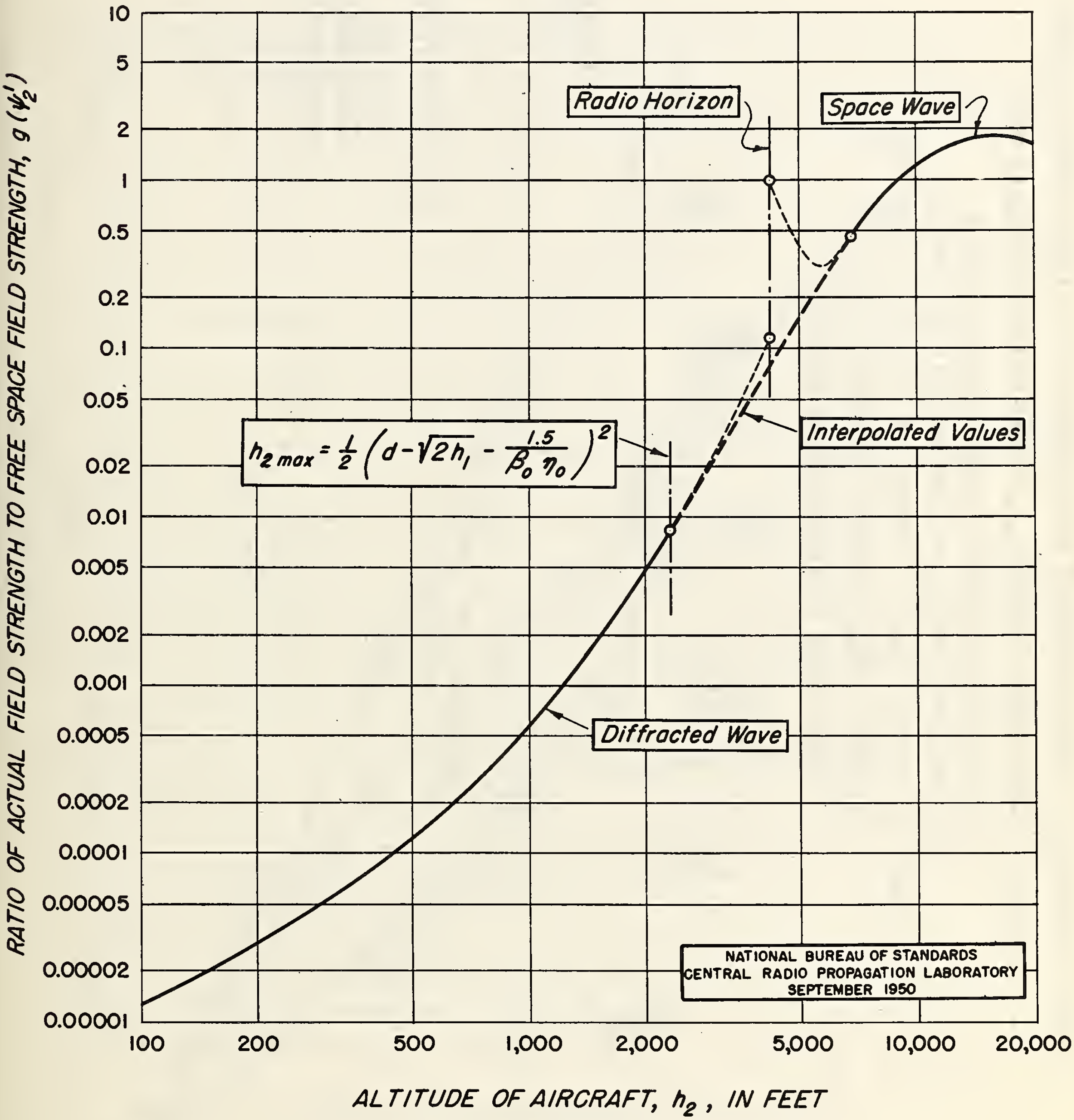


Figure 19