Effect of a Ground Discontinuity on a VOR

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EFFECT OF A GROUND DISCONTINUITY ON A VOR*

SUMMARY

Tests were conducted on top of a high bluff along the shore of Lake Michigan near Port Washington, Wisconsin, to determine the effect of an abrupt ground discontinuity on the course accuracy of a VHF omnirange. These tests indicated that satisfactory operation of a VOR located in proximity to a sharp ground discontinuity is attained when the antenna is located 4 feet above the terrain and not less than 63 feet from the ground discontinuity The tests also showed that the distance from the antenna to the ground discontinuity must be increased to 125 feet for satisfactory operation if the antenna is raised to a height of 14 feet above the terrain

Deep nulls were evident in the vertical plane-radiation patterns, and large variations of the course-deviation indicator and the TO-FROM indicator were observed in the nulls when the antenna was placed 13 feet from the discontinuity at a height of 14 feet These variations were greatly decreased as the antenna was lowered to 4 feet above the terrain and when the distance of 13 feet from the ground discontinuity was maintained When the antenna was moved away from the ground discontinuity, the nulls of the vertical radiation pattern were filled in and the variations of the course-deviation indicator were further decreased The surface of the lake was calm during the tests, and flight recordings failed to reveal any irregularities which might be attributed to changes in the surface conditions of the lake

Equations were derived which explain some of the phenomena observed during these tests The theoretical and measured positions of the lowest null were in close agreement

INTRODUCTION

In the past, very-high-frequency omnirange (VOR) sites have been chosen so that they are located far from large ground discontinuities Because this practice limits the choice of sites, it was deemed desirable to conduct tests near a large ground discontinuity to determine more precisely its effects on the accuracy of the VOR. This report presents the results of such tests which were conducted near Port Washington, Wisconsin, along the shore of Lake Michigan, where a reasonably straight length of shoreline presented an almost vertical drop of approximately 125 feet from ground to water level.

EQUIPMENT

A portable omnirange station, shown in Fig 1, was used It consisted of a 4-loop VOR antenna system, enclosed in a Masonite shelter for weather protection, and a 12-foot-diameter counterpoise, both mounted 14 feet above ground on top of a 2 1/2-ton truck The transmitter and associated VOR components were located in the enclosed van beneath the counterpoise A monitor, with the pickup supported slightly above counterpoise level in front of the truck by means of an aluminum support, was used to insure proper operation of the station during the tests Power was supplied to the equipment by an engine-driven generator in another truck 500 feet distant For tests at the ground level, the antenna and counterpoise were lowered to the ground and towed on flat skids by the transmitter truck See Fig 2 The distance between the antenna and the transmitter truck was maintained at 100 feet

SITE

A relatively flat site on a bluff on the shore of Lake Michigan at Port Washington, Wisconsin, was chosen for the tests The elevation of the site above the surface of Lake Michigan was approximately 125 feet The site was devoid of trees and other obstructions for approximately 1000 feet in all directions Approximately one-third of the site nearest the

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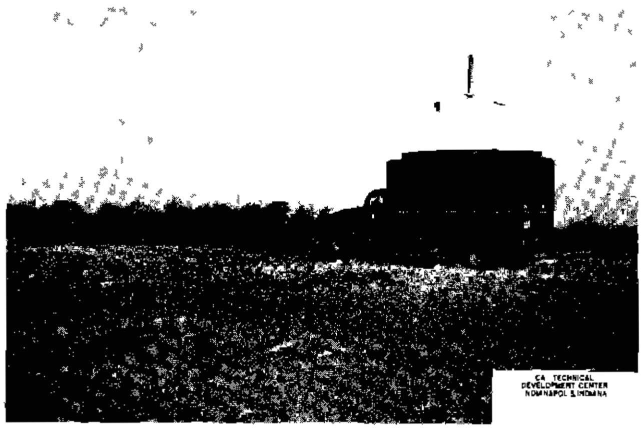

Fig 1 Portable VOR Equipment

edge of the lake bank was plowed ground and the remainder was in a natural state Figure 3 shows a general view of the site looking toward Lake Michigan, and Fig. 4 shows the ground discontinuity as viewed from approximately 80 feet down the steep slope The surface of the lake was calm during the tests

FLIGHT TESTS AND RESULTS

Flight tests were conducted with the omnirange at several locations as shown in Fig 5 Recordings of the course-deviation indicator (CDI), the TO-FROM indicator, and the electric field strength were made on radials of 45° and 90° with respect to the face of the ground discontinuity which had an average azimuth of 9° magnetic A theodolite calibration circle of approximately 10-mile radius also was recorded The first series of tests was made with the antenna and counterpoise mounted on top of the truck, which placed the antenna 14 feet above the terrain These tests were repeated with the antenna and counterpoise on the ground

Figure 6 shows a plot of the vertical plane patterns for the antenna at various heights and distances from the ground discontinuity Inability to repeat measurements of the field strength necessitated the selection of a reference point to permit direct comparisons of the lobular

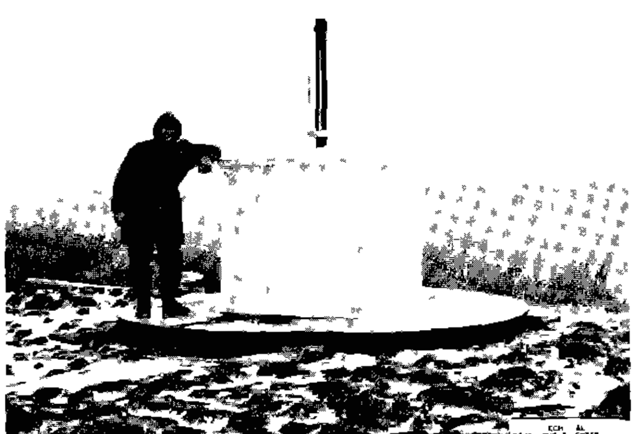

Fig 2 Counterpoise on Ground, 13 Feet from Bank Edge

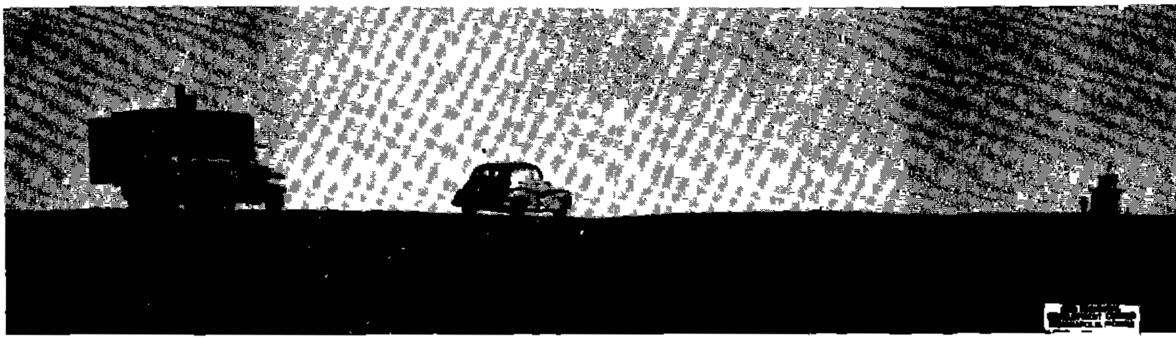

Fig. 3 General View of Test Site

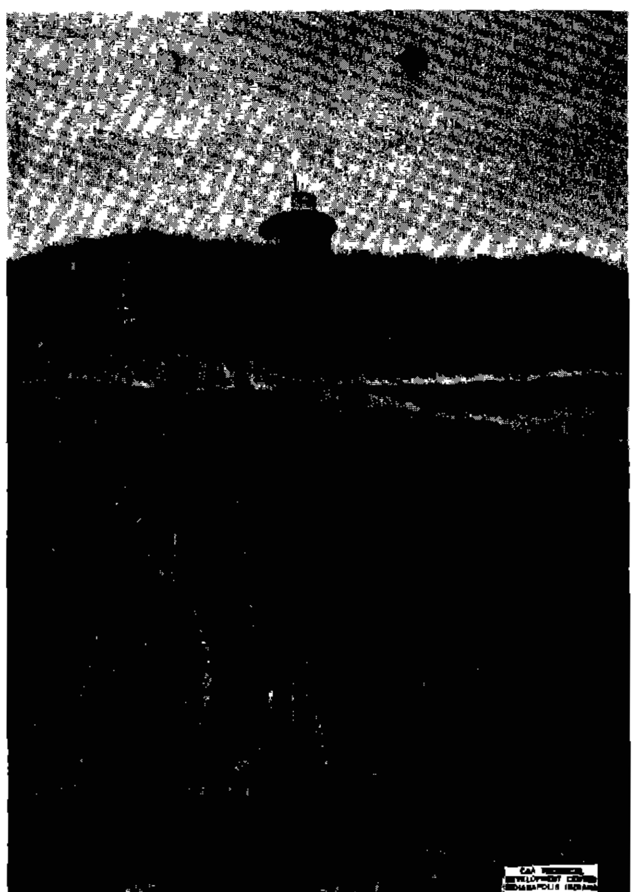

Fig 4 Bank Edge Viewed from Lower Level

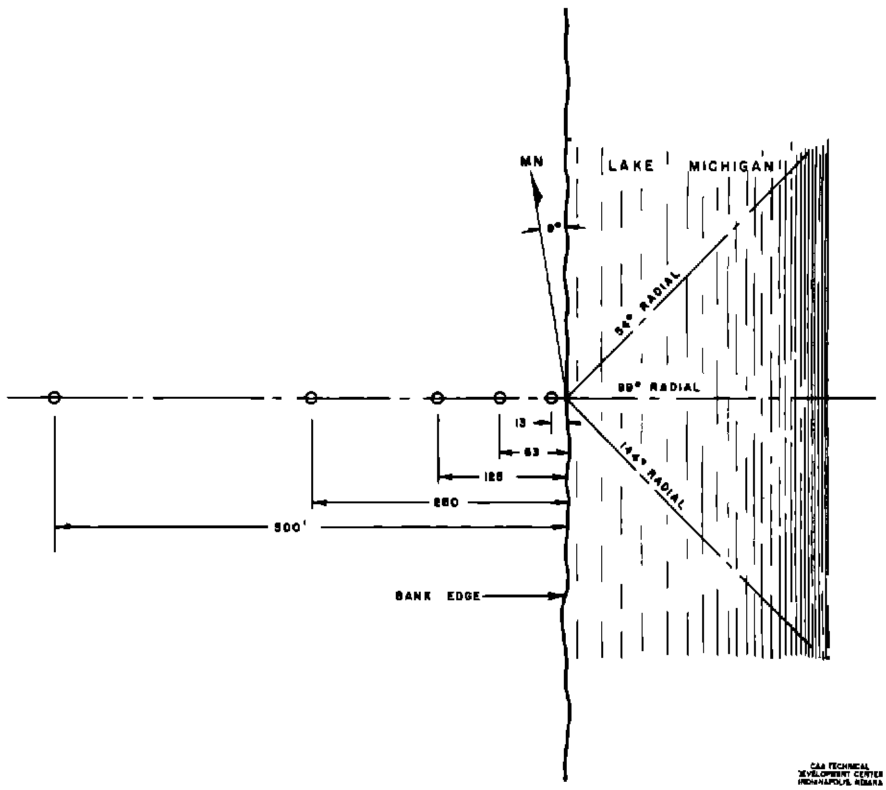

Fig 5 Chart of VOR Test Site

structure The maximum amplitude of the largest lobe (occurring between 25° and 35°) was made equal to a relative field strength of 6 4 units in all vertical plane patterns shown in Fig. 6 These relative field-strength units represent the number of millivolts which would be measured at the input to a modified Collins 51R2 receiver if the receiver were moved in the vertical plane between elevation angles of 0° and 90° along the circumference of a circle having a one-mile radius centered on the omnirange

The position of the lowest null was calculated to provide a comparison between theoretically ideal conditions and the type of ground discontinuity under test The theoretical null was computed to occur at 1.88°, and the measured null as recorded with the field-strength meter occurred at approximately 1 5°

A, B, and C on Fig 6 show the vertical plane patterns for the omnirange antenna and counterpoise mounted on top of the truck (antenna 14 feet above the ground) for locations of 13, 125, and 250 feet respectively from the edge of the ground discontinuity D, E, and F on this figure show the vertical plane patterns with the antenna and counterpoise on the skids (antenna 4 feet above the ground) for locations of 13, 63, and 125 feet respectively from the edge of the ground discontinuity Little change was noted in the size or shape of the vertical plane patterns above 17° elevation when the antenna was 14 feet above ground, or above 10° elevation when the antenna was 4 feet above ground At angles of elevation above approximately 10°, the shape of the pattern is primarily controlled by the size of the counterpoise and by the height of the antenna and counterpoise above ground.[1] Below approximately 10° elevation, multiple lobes were produced by reflections of the radio waves from the surface of the lake Since most operational flying is performed at elevation angles of a few degrees with respect to the omnirange station, a more detailed analysis was made for elevation angles of less than 10°.

[1] S. R Anderson and T. S. Wonnell, "The Development and Testing of the Terminal VHF Omnirange," CAA Technical Development Report No. 225, January 1954, Fig 37.

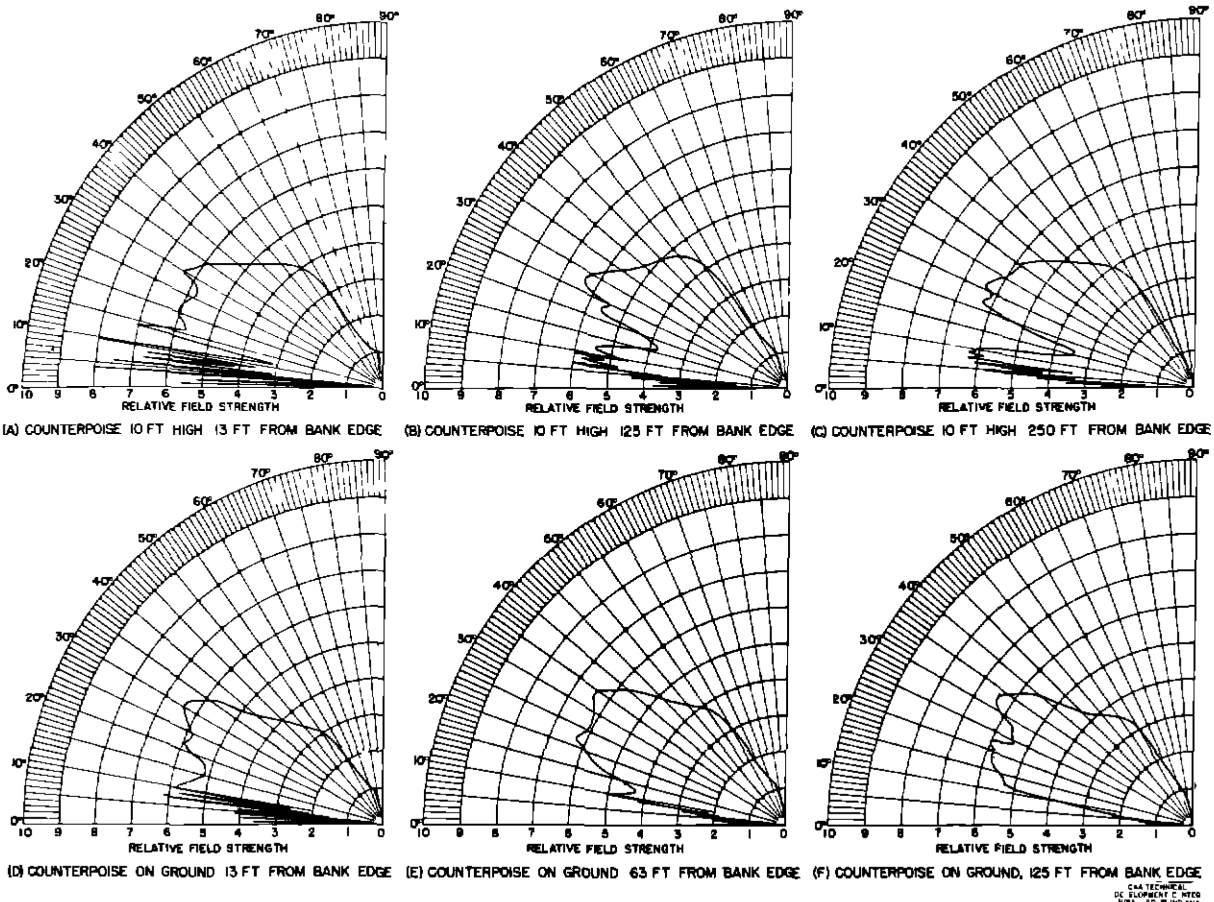

Fig 6 Vertical Plane Patterns

In A, B, C, and D on Fig 7, the vertical plane patterns below 10° elevation are plotted in rectangular co-ordinates The maximum amplitude of the fourth lobe above the horizontal has been made equal for all of the patterns to permit more direct comparisons Since the deepest nulls occurred when the antenna was 13 feet from the ground discontinuity and at either 4 or 14 feet above the terrain, the resulting vertical plane patterns are plotted with those corresponding antenna heights and at other distances from the ground discontinuity to illustrate the filling-in of the nulls

A and B on Fig 7 show the vertical plane patterns when the antenna was 14 feet above the terrain at distances of 125 and 250 feet respectively from the ground discontinuity C and D on Fig 7 show the vertical plane patterns when the antenna was 4 feet above the terrain at distances of 63 and 125 feet respectively from the ground discontinuity A study of these patterns shows the rate at which the nulls fill in as the antenna system is moved away from the ground discontinuity

Figures 8 and 9 are recordings of field strength, TO-FROM indicator, and CDI corresponding to the radiation patterns shown in Fig 7A Similarly, the recordings in Figs 10 and 11 correspond to the radiation patterns shown in Fig 7C Nulls in the vertical field pattern are evident as minimums in the field-strength recordings The effect of these minimums also is evident in the TO-FROM and CDI recordings A comparison of the recordings shown in Figs 8 and 10 shows that lowering the antenna from 14 feet to 4 feet greatly improved the performance of the VOR A greater improvement was attained either by moving the antenna to a distance of 125 feet from the ground discontinuity at the 14-foot height as shown in Fig 9, or by moving the antenna to a position 63 feet from the ground discontinuity at the 4-foot height as shown in Fig 11

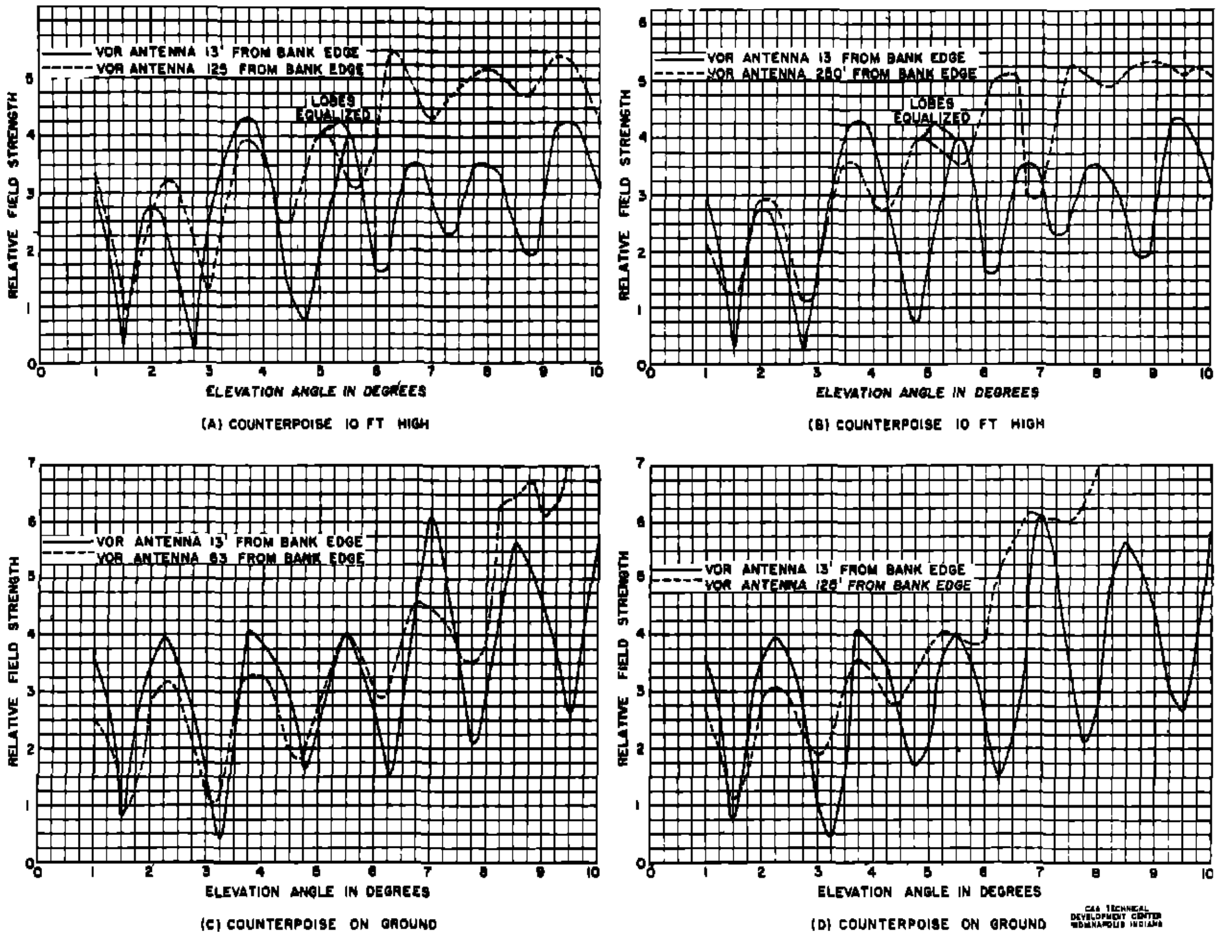

Fig 7 Vertical Plane Patterns

TABLE I

BEARING ERRORS MEASURED IN THE NULLS*

Distance of Antenna From Ground Discontinuity (feet)	Null Angle (degrees)	Antenna Height (feet)	Maximum Bearing Error in Null (±degrees)
13	1 5	14	7.0
13	3.0	14	2 5
13	4 5	14	5 0
13	6.0	14	2.5
13	1 5	4	0 25
13	3.0	4	0 375
13	4 5	4	0 5
13	6 0	4	0 5
125	1.5	14	0 25
125	3 0	14	0 00
63	1 5	4	0 25
63	3.0	4	0 00

*Altitude 1000 feet above ground

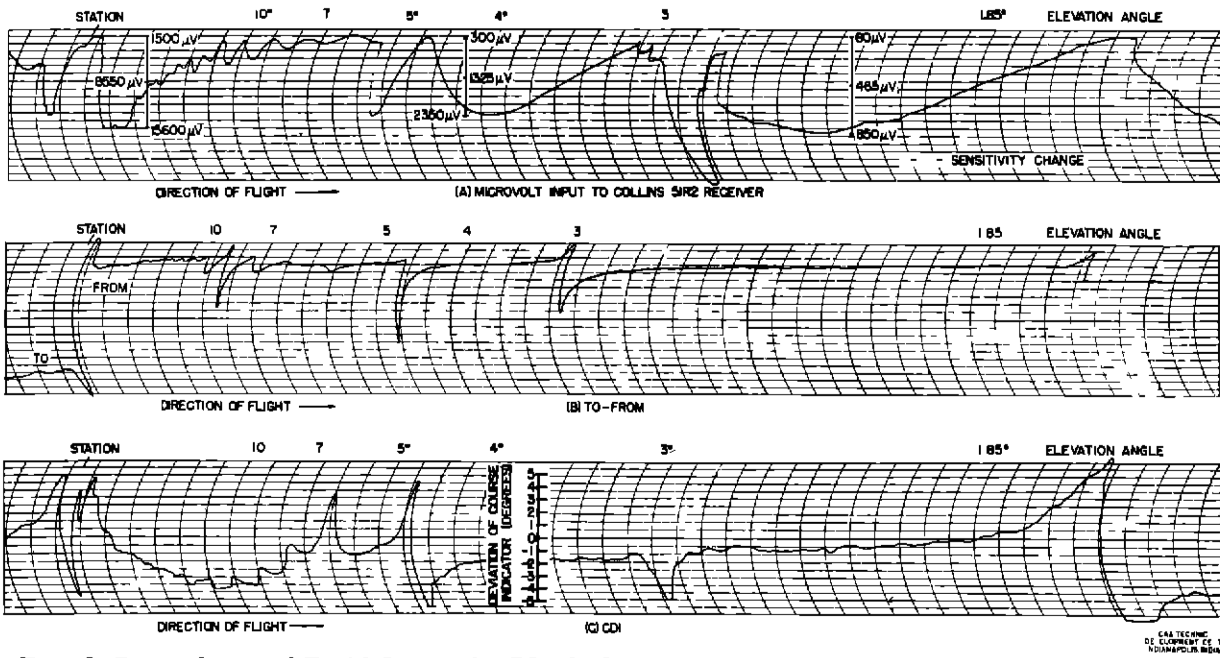

Fig 8 Recordings of Field Strength, TO-FROM Indicator, and Course-Deviation Indicator, Counterpoise 10 Feet High, 13 Feet from Bank Edge

During radial flights, CDI variations were observed to occur in the nulls of the vertical plane-radiation patterns The maximum bearing errors measured in the nulls along the radial normal to the face of the bluff are given in Table I

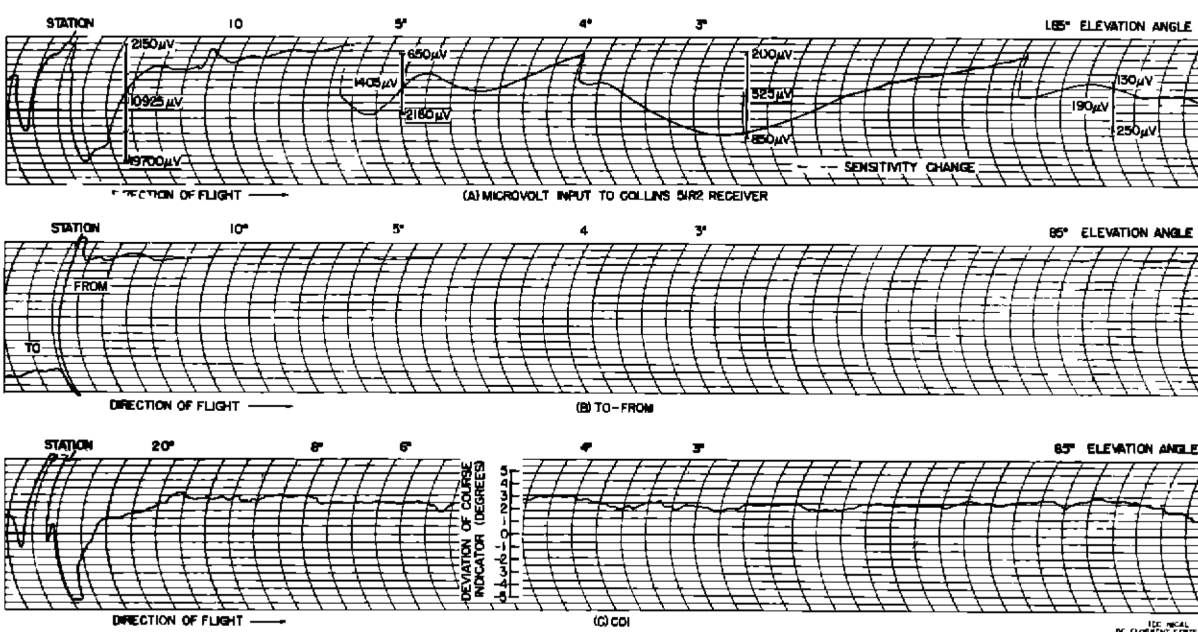

Fig 9 Recordings of Field Strength, TO-FROM Indicator, and Course-Deviation Indicator, Counterpoise 10 Feet High, 125 Feet from Bank Edge

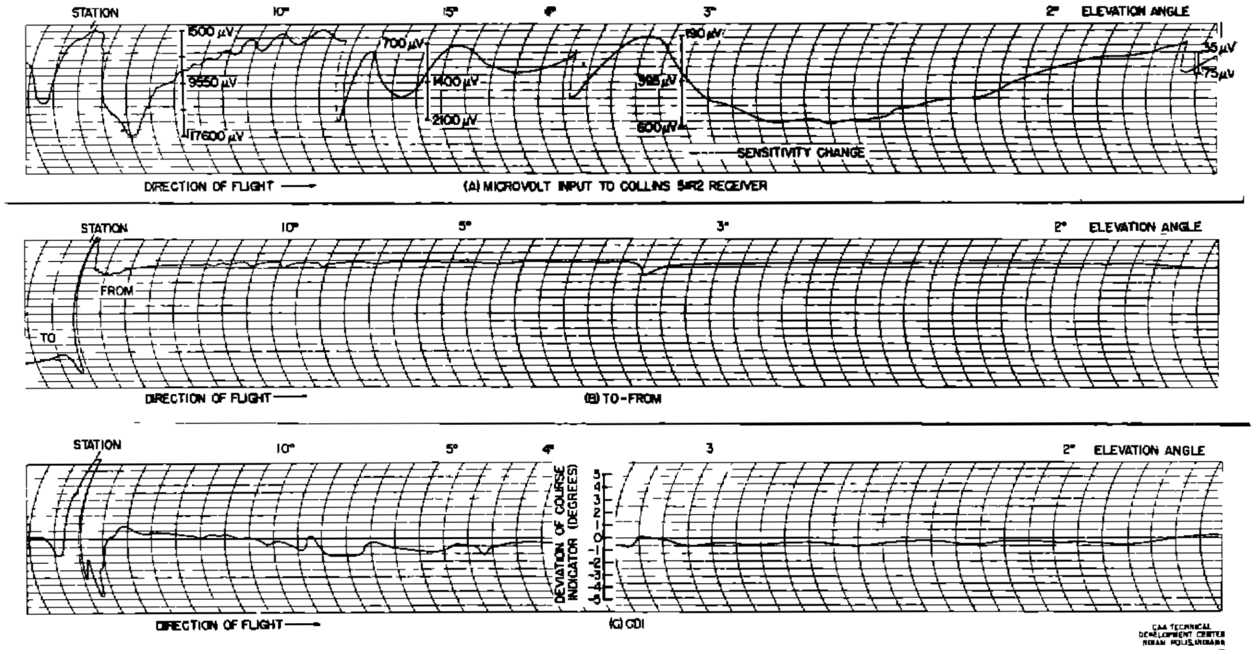

Fig 10 Recordings of Field Strength, TO-FROM Indicator, and Course-Deviation Indicator, Counterpoise on Ground, 13 Feet from Bank Edge

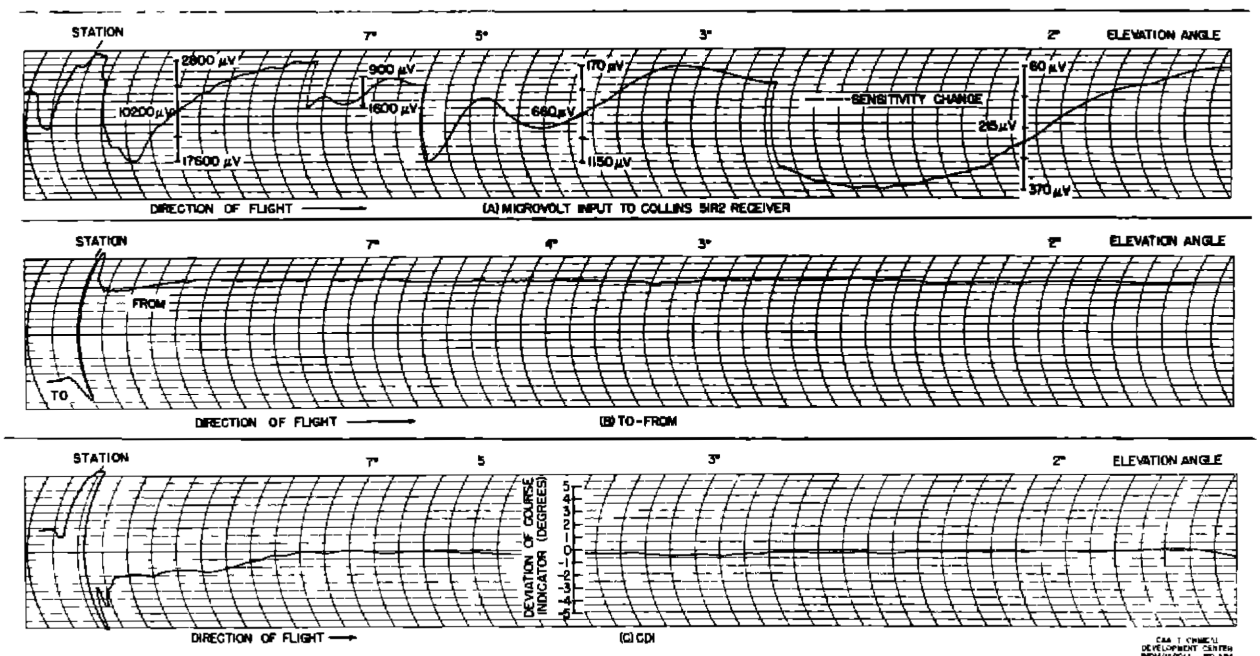

Fig 11 Recordings of Field Strength, TO-FROM Indicator, and Course-Deviation Indicator, Counterpoise on Ground, 63 Feet from Bank Edge

Additional effects associated with the nulls are shown in the TO-FROM indicator recordings in Figs 8B and 10B The excursions of the TO-FROM indicator from the normal position can be caused either by a phase shift between the reference- and variable-phase signals or by a severe loss of signal Since the signal level in the nulls was greater than that required for proper operation of the receiver, it was assumed that the displacement from normal was produced by a phase shift The TO-FROM indicator variations due to nulls decreased and finally disappeared as the antenna was moved away from the edge of the ground discontinuity, as evidenced in Figs 10B and 11B

Bearing-error curves obtained from recordings of theodolite calibration circles of 10-mile radius are shown in A and B on Fig 12, when the antenna was 14 feet high and located 13 feet and 125 feet respectively from the edge of the ground discontinuity The magnitude of course scalloping observed in certain sectors is indicated by shaded portions of the bearing-error curves A comparison of A and B on Fig, 12 shows the improvement which was attained by moving the antenna from a position 13 feet from the ground discontinuity to a position 125 feet from it By referring to C and D on Fig 12, similar comparisons can be made for an antenna height of 4 feet when the antenna was moved from a position 13 feet from the ground discontinuity to a position 63 feet from it As the height of the antenna was decreased from 14 feet to 4 feet at a fixed distance of 13 feet from the edge of the bluff, the scalloping amplitude decreased This may be seen by comparing A and C on Fig 12

During the analysis of the radial flight recordings shown in Fig 13, it was noted that the 54° and 144° radials (45° to the edge of the ground discontinuity), which were theodolite-controlled, had similar variations but were of opposite sensing This condition existed only when the antenna was 14 feet high and 13 feet from the ground discontinuity

THEORETICAL CONSIDERATIONS

A theoretical study of the effects on a VOR caused by a ground discontinuity was initiated by the use of applicable geometrical optics This approach will not produce exact results, but it will indicate approximately the nature of the phenomena involved

The type of ground discontinuity under consideration is displayed in Fig 14 It is a straight-line discontinuity formed by an abrupt drop in ground elevation down to water level The figure shows the direct and reflected waves directed to the aircraft at elevation angle θ, with the indirect wave reflected from the water surface When the reflected wave grazes the edge of the discontinuity, $\theta = \theta_c$ A further increase in θ results in a complete land reflection The following equation expresses θ_c in terms of the azimuth angle and the height and distance of the VOR antenna from the discontinuity

$$\theta_c = \arc \tan \left(\frac{h}{d} \sin \phi\right) \qquad (1)$$

Where

θ_c = elevation angle when the reflected wave grazes the edge of the discontinuity, in degrees

h = height of VOR antenna above the ground, in feet

d = the distance from the VOR antenna normal to the discontinuity, in feet

ϕ = azimuth angle, in degrees

Equation (1) is plotted in Fig 15 It will be noted that θ_c becomes smaller with changes in azimuth from 90° and with an increase in $\frac{d}{h}$ It is desirable to have θ_c as small as possible to reduce the number of nulls in the vertical plane-radiation pattern caused by reflections from the water Generally, the bearing information is adversely affected in the nulls by undesired signals because the field strength is small Reflections from the land would cause nulls in the vertical radiation pattern A counterpoise is used, however, to reduce the land reflections at high elevation angles and thereby suppress the high angle nulls The height of the VOR antenna above ground is chosen so that no nulls will result from land reflections at low elevation angles Figure 15 shows that the greatest number of nulls caused by reflections from the water would be expected at 90° azimuth and that the number of nulls will diminish with a departure from a direction normal to the bank

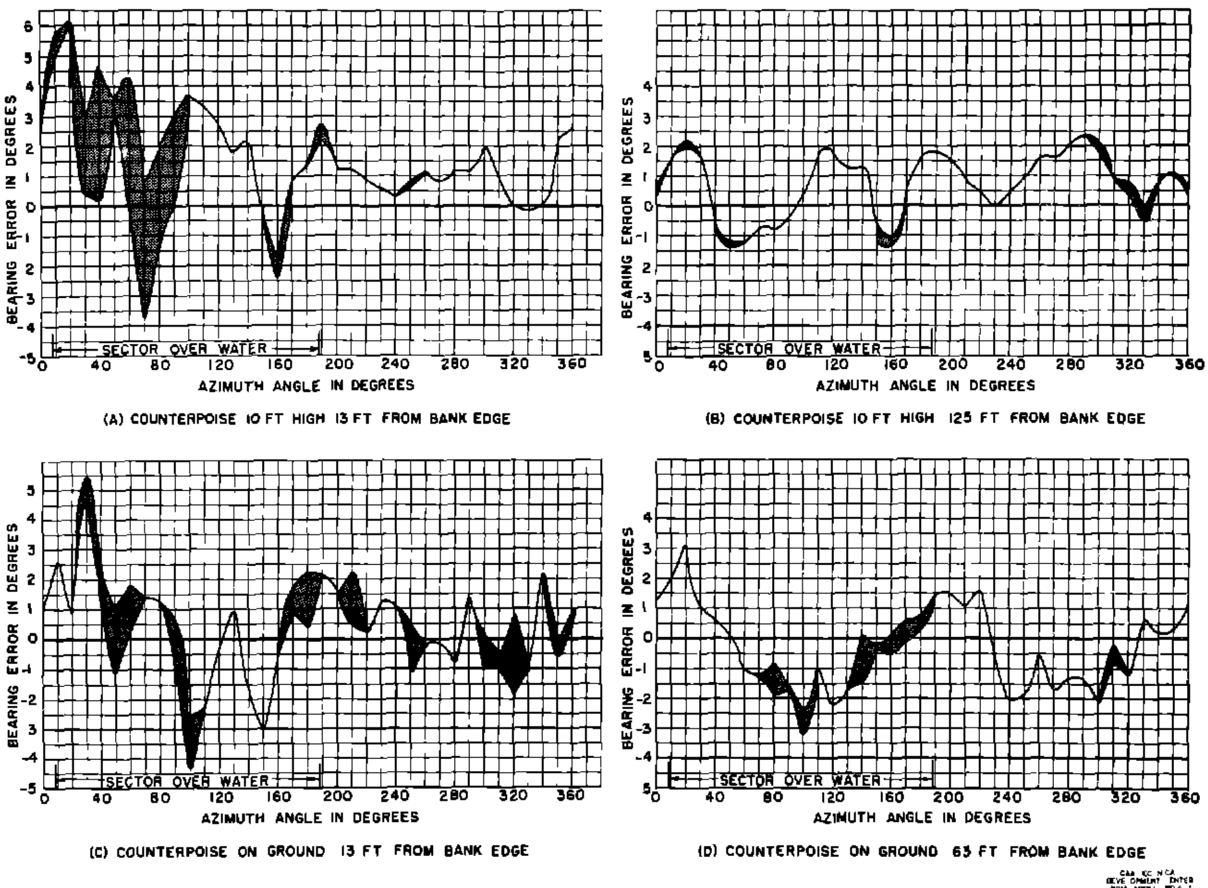

Fig 12 Theodolite Calibration of Test VOR, Port Washington, Wisconsin

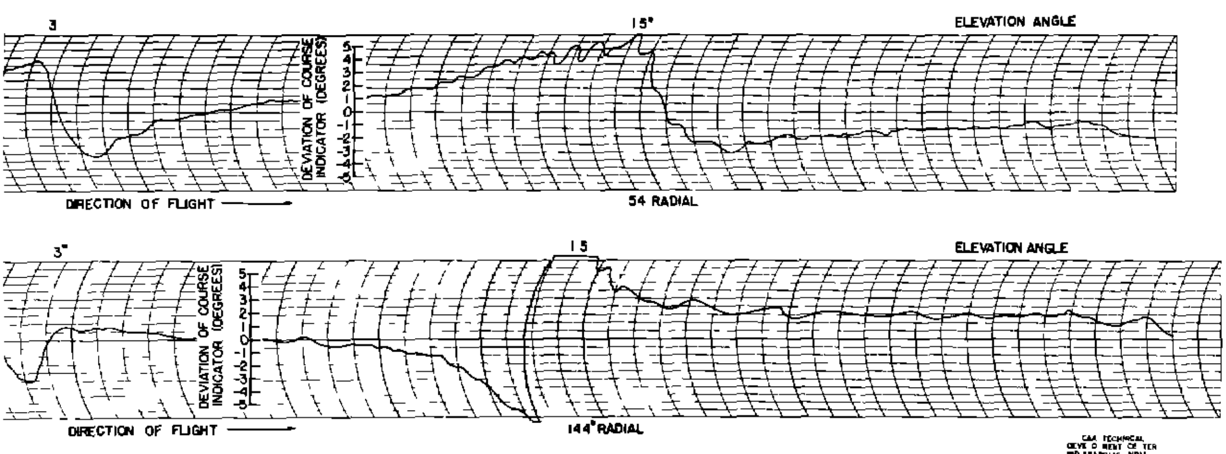

Fig 13 VOR Radials of 54° and 144°, Counterpoise 10 Feet High, 13 Feet from Bank Edge

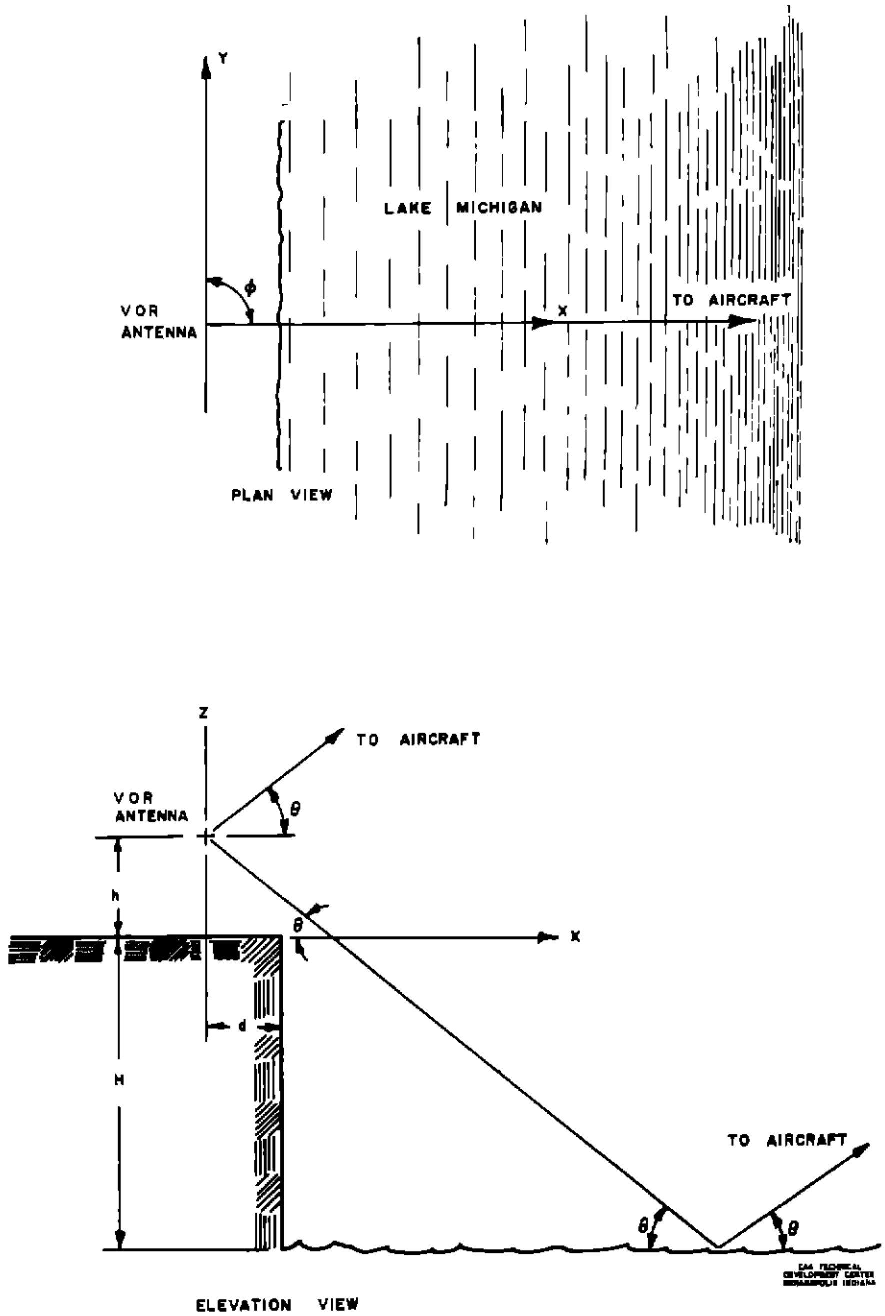

Fig 14 A VOR Located Near a Ground Discontinuity Formed by a Lake Bank

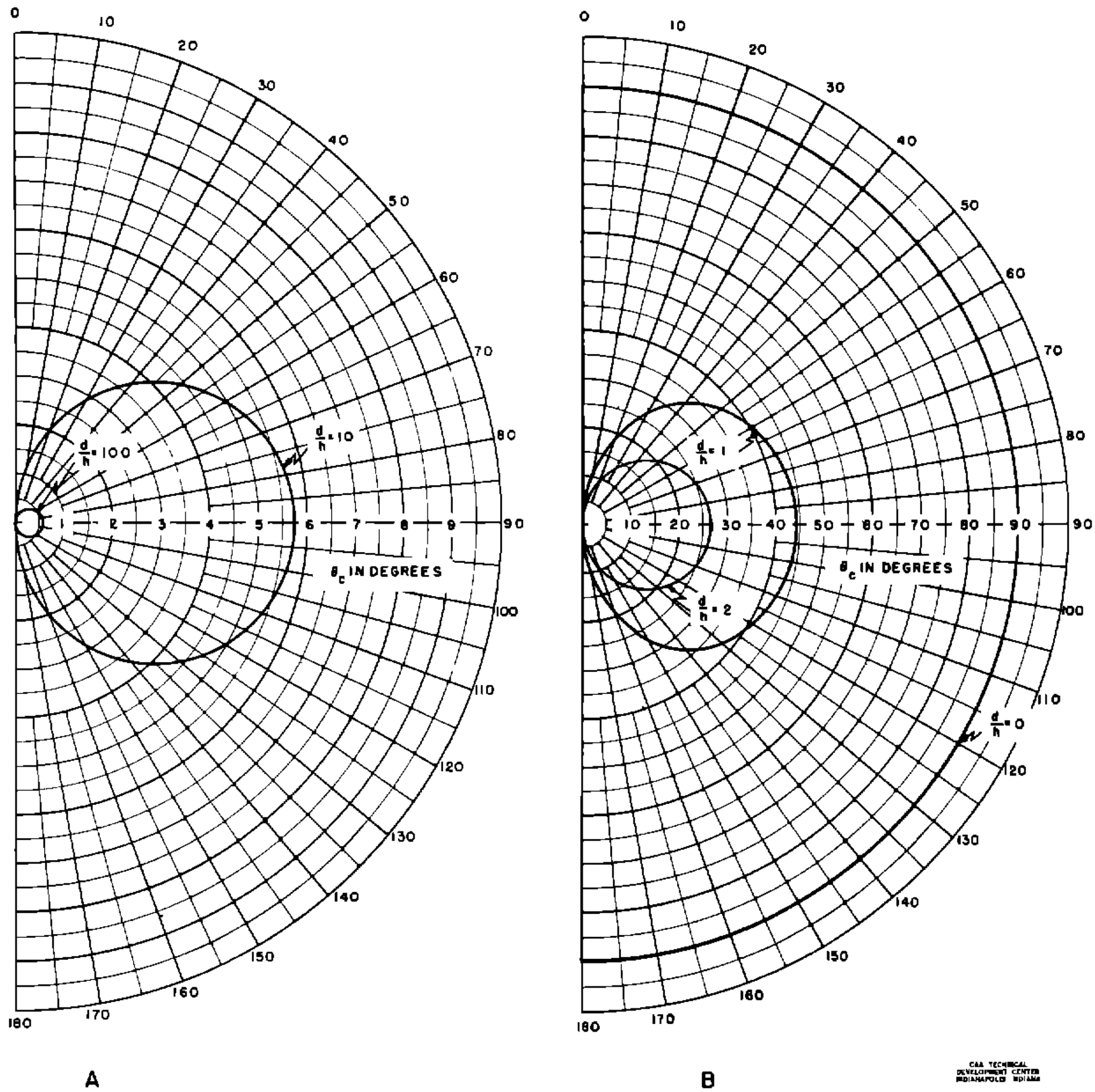

Fig 15 Plots Showing Values of θ_c Versus Azimuth Angle, With $\frac{d}{h}$ as the Parameter

The lowest null in the vertical plane pattern of the VOR antenna caused by reflections from the water is expressed by

$$\theta = \frac{28.65 \lambda}{H + h} \tag{2}$$

Where

θ = elevation angle, in degrees

H = height of ground discontinuity, in feet

λ = wavelength, in feet

Combining Equations (1) and (2), letting $\theta = \theta_c$, and then solving for d,

$$d = \frac{h}{\tan\left(\frac{245.5^\circ}{H + h}\right)} \qquad (3)$$

Equation (3) is plotted in Fig 16 for the two parameters tested, h = 4 feet and h = 14 feet. The curves on Fig 16 indicate that the higher the lake bank H, the further the VOR antenna must be placed from the discontinuity. Also, these curves show that decreasing the antenna height h decreases appreciably the distance d that the VOR antenna must be placed from the edge of the discontinuity. Theoretically, if the conditions of Equation (3) or Fig 16 are met, the nulls in the vertical plane pattern caused by reflections from the water are suppressed to some extent by the shielding effect of the lake bank. The lowest null is filled in the least, with more filling in attained with each successive higher angle null.

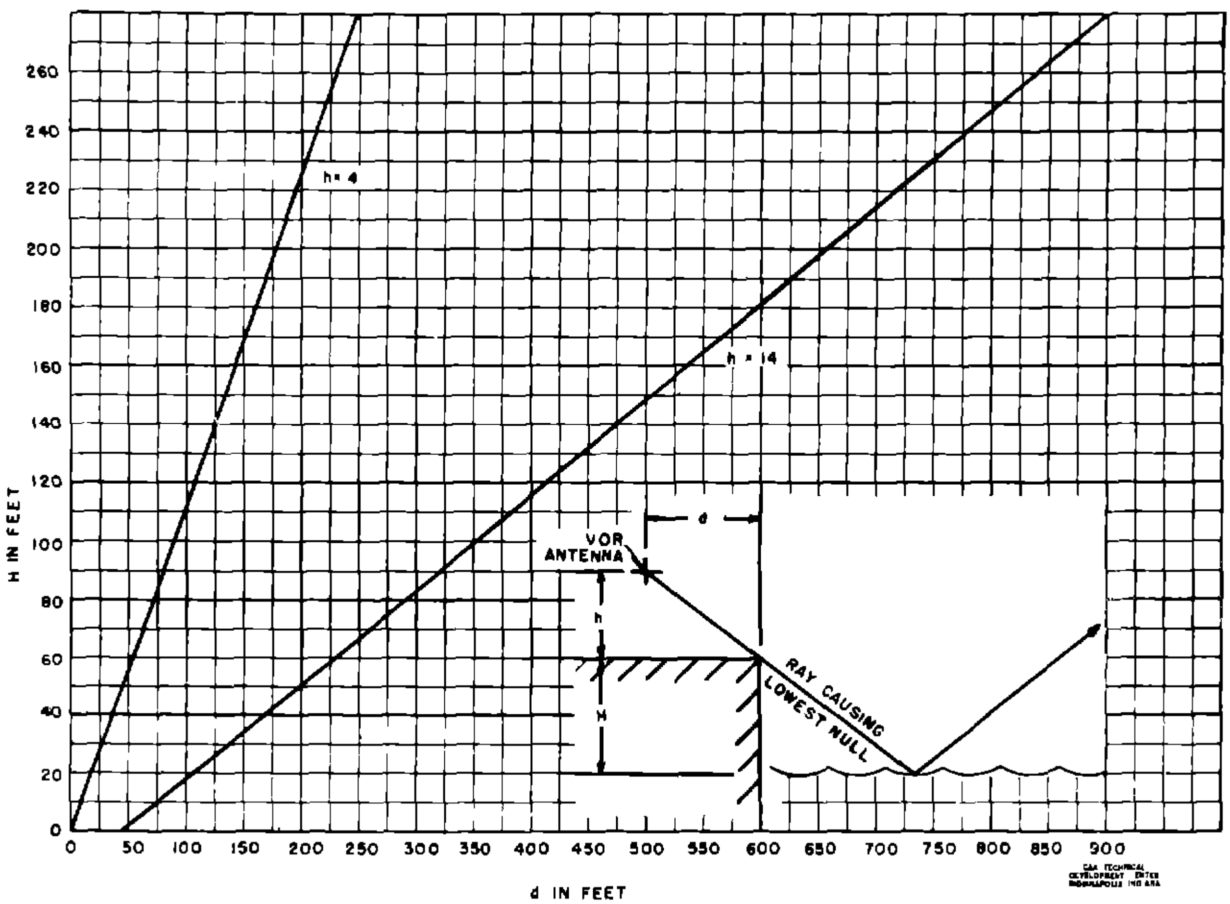

Fig 16 Conditions Required for the Ray Producing the Lowest Null Just to Graze the Edge of the Lake Bank

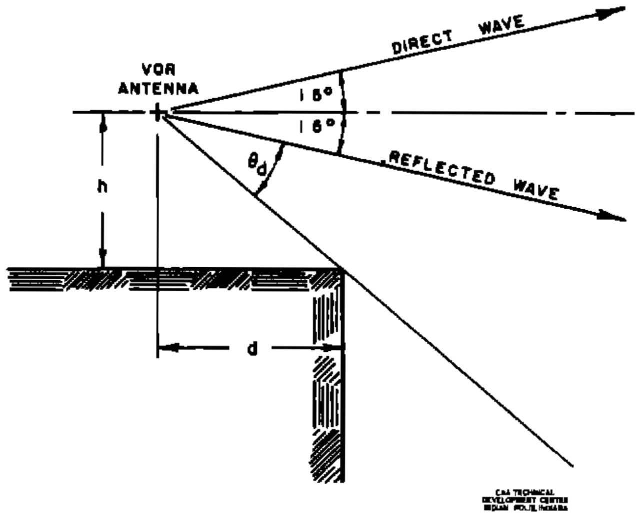

Fig 17 A Cross-Sectional View of the VOR Antenna and Bank Edge

As stated previously, a large reduction in CDI fluctuations in the nulls occurred when the VOR antenna was lowered from the 14-foot to the 4-foot height above ground with the antenna located 13 feet from the ground discontinuity This improvement is believed to be caused by filling-in of the nulls which results from diffraction over the edge of the ground discontinuity. The following derivation supports this belief

The example chosen is for the 1 5° null because (1) the CDI fluctuations in this null were appreciably reduced by lowering the antenna from 14 feet to 4 feet above ground, and (2) the direct-wave and reflected-wave components producing the null at 1.5° passed well above the diffraction edge, that is, the ground discontinuity did not obstruct either wave.

Referring to Fig. 17, it is required to find the reflected wave (before reflection from the water) and the direct wave as functions of the height above ground h, by taking into account the diffraction caused by the ground discontinuity This may be done by applying Fresnel straight-edge diffraction theory[2] as follows

$$\frac{E_n}{E_o} = Z_n \, e^{-j\zeta_n} \tag{4}$$

Where

n = 1, refers to the reflected wave

n = 2, refers to the direct wave

E_n = the diffracted field at the receiver

E_o = the free space field at the receiver

Z_n and ζ_n are determined by means of a function v and curves plotted in a published source [3]

[2]Chas R Burrows and Stephen S Attwood, "Radio Wave Propagation," Academic Press, Inc , New York, 1949

[3]Ibid

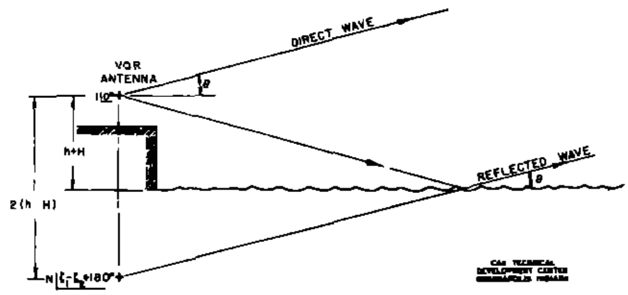

Fig 18 The VOR Antenna and Its Image Relative to a Lake-Surface Reflection

Also,

$$v = \frac{\theta_d}{57.3\sqrt{\frac{\lambda}{2d}}} \tag{5}$$

Where

θ_d = an angle shown in Fig 17

d = antenna distance from edge of discontinuity, in feet

λ = wavelength, in feet.

Also, $\theta_d = \arc\tan \frac{h}{d} - 1.5°$ for the reflected wave

$\theta_d = \arc\tan \frac{h}{d} + 1.5°$ for the direct wave

Figure 18 shows how the problem is treated The VOR antenna transmits a direct wave to the receiver while the image antenna transmits the reflected wave. The relative amplitude of the resultant field at the receiver (direct wave plus reflected wave) is expressed

$$|E| = \sqrt{1 + N^2 - 2N\cos[\zeta_1 - \zeta_2 - 2K(H + h)\sin\theta]} \tag{6}$$

Where

$$N = \frac{rZ_1}{Z_2}$$

r = magnitude of reflection coefficient

$$K = \frac{2\pi}{\lambda}$$

Since N varies slowly with θ, the minimum field in the vicinity of the aircraft occurs when $\cos[\zeta_1 - \zeta_2 - 2K(H + h)\sin\theta] = 1$ Therefore, the minimum field is

$$|E_{min}| = \sqrt{1 + N^2 - 2N} \tag{7}$$

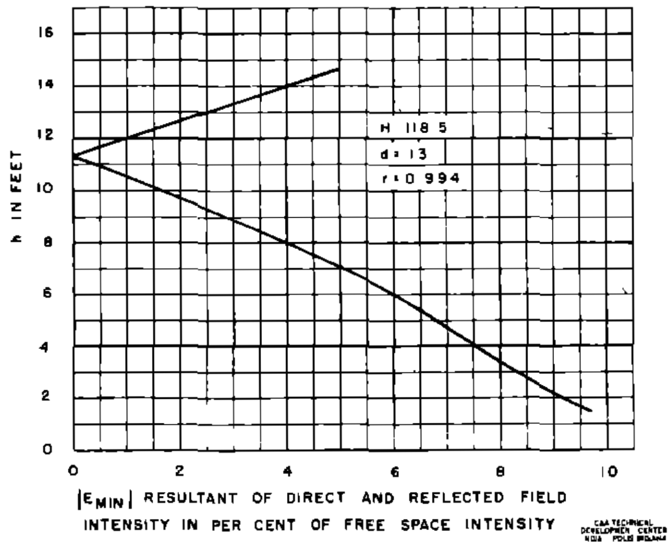

Fig 19 Theoretical Field Intensity of the Null at 1 5° Elevation Angle Versus VOR Antenna Height Above Ground

Figure 19 is a plot of Equation (7) for the conditions prevailing at the Port Washington, Wisconsin, site, that is, h = 14 feet or 4 feet. The curve shows that the null in the vicinity of 1 5° varies in depth with the antenna height and that the null fills in as the antenna is lowered, reducing the CDI variations It also shows that lowering the antenna from 14 feet to 4 feet

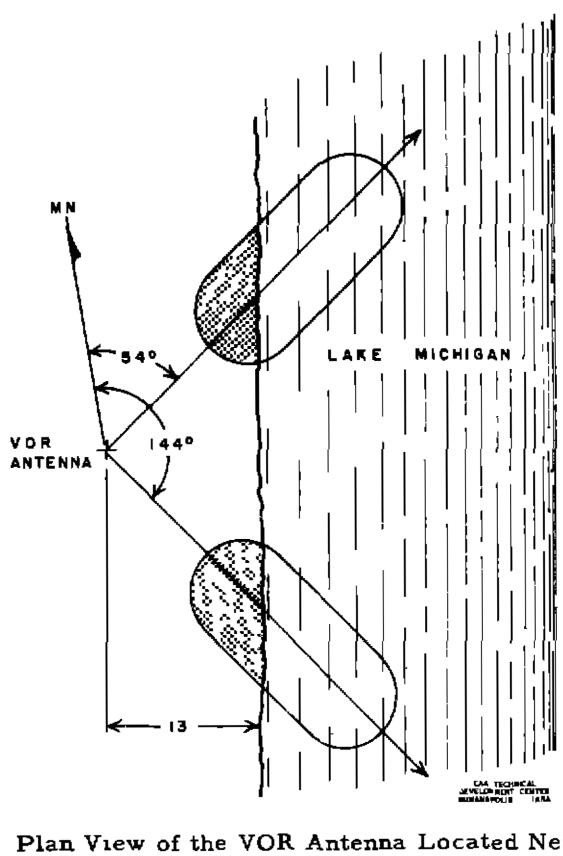

Fig 20 Plan View of the VOR Antenna Located Near the Bank Edge Showing the Fresnel Zones

increases the field strength in the null 1 89 times It is interesting to note that the null would be 0 6 per cent of free-space intensity if the diffraction edge were removed, thereby placing the VOR antenna above the lake surface

The approximate locations of the nulls may be found from Equation (6) by equating

$$\zeta_1 - \zeta_2 - 2K\,(H + h)\sin\theta = 360^\circ n \tag{8}$$

Where n = 0, 1, 2, and so forth,

$$\sin\theta = \frac{360^\circ n - \zeta_1 - \zeta_2}{2K\,(H + h)} \tag{9}$$

For small values of θ, in degrees,

$$\theta = \left| \frac{28\ 6n\,\lambda}{H + h} - \frac{(\zeta_1 - \zeta_2)\,\lambda}{6\ 29\,(H + h)} \right| \tag{10}$$

The second term in Equation (10) accounts for the effect of the ground discontinuity on the location of the nulls When $(H + h) = 133\ 5$ feet, $n = 1$, $\lambda = 8\ 76$ feet, and $\zeta_1 = \zeta_2 = 3^\circ$, then $\theta = 1\ 88^\circ$ The measured null location occurred at $1\ 5^\circ$

It was pointed out earlier that when the VOR antenna was located 14 feet above ground and 13 feet from the ground discontinuity, similar CDI variations occurred on the 54° and 144° radials but were of opposite sensing This may be explained by reference to Fig. 20 which shows that the ground discontinuity modifies the Fresnel zones, but with opposite sensing. The Fresnel zones are those which would be present in their entirety if the ground discontinuity were nonexistent

CONCLUSIONS

1 The errors caused by the ground discontinuity were small when (a) the VOR antenna was placed 14 feet above ground and 125 feet from the discontinuity, and (b) the VOR antenna was 4 feet above ground and 63 feet from the discontinuity

2 The magnitude of the bearing error or scalloping becomes greater as the depth of the nulls in the vertical plane-radiation pattern increases

3 A close correlation was found between calculated and observed location of the lowest null in the vertical plane-radiation pattern.

4 The vertical plane-radiation patterns show that the effect of the ground discontinuity appears as a multiple-lobe structure superimposed on the normal pattern between elevation angles of approximately 0° to 10°

5. The depth of the lowest null decreases slowly with an increase in the distance between the VOR antenna and a ground discontinuity

6 Higher angle nulls produced by the ground discontinuity filled in rapidly as the VOR antenna was moved from the ground discontinuity.