THE DEVELOPMENT AND TESTING OF THE TERMINAL VHF OMNIRANGE

By

S R Anderson

and

T. S Wonnell

Electronics Division

Technical Development Report No 225

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA

April 1954

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary

CIVIL AERONAUTICS ADMINISTRATION
F. B. Lee, Administrator
D. M. Stuart, Director, Technical Development and Evaluation Center

TABLE OF CONTENTS

This is a technical information report and does not necessarily represent CAA policy in all respects.

THE DEVELOPMENT AND TESTING OF THE TERMINAL VHF OMNIRANGE

SUMMARY

This report describes the development of the terminal VHF omnirange which was first started in 1950 at the Technical Development and Evaluation Center of the Civil Aeronautics Administration at Indianapolis, Indiana. The performance of terminal VHF omnirange installations at Indianapolis, Indiana, Traverse City, Michigan, Augusta, Maine, Oklahoma City, Oklahoma, Toledo, Ohio, and Washington, D. C , airports are discussed with special emphasis on the effect of nearby hangars and of other large obstructions

The results of extensive tests which used a large surface to simulate a hangar face are presented and are compared with predicted results, based on wave-reflection theory, in order to explain the characteristics of such surfaces as a source of omnirange-course scalloping

It is concluded that the terminal VHF omnirange can be extremely useful as an aid for obtaining an accurate fix, as a holding aid, or in the guidance of aircraft to or from an airport during low approaches to the field for landing.

INTRODUCTION

The operational experience obtained from the use of the very-high-frequency omnirange (VOR) has resulted in the growing conviction that there are potentially many advantages to be realized by installing VOR facilities on or adjacent to the airports. Such an omnirange installation has been designated as a terminal VHF omnirange, or TVOR.

The distinct advantages of TVOR installations fall into several categories. Many airports having low traffic density are now being operated only under visual-flight-rule (VFR) conditions because of the lack of nearby aircraft navigational facilities. The installation of a TVOR at these airports would be of tremendous aid in the completion of flights under instrument-flight-rule (IFR) conditions with lowered minima. The TVOR in yet another category has many possible uses at airports in areas of heavy traffic density. When the TVOR facility is located at the airport, air traffic controllers have at hand a facility with many traffic-control possibilities in conjunction with radar plan-position-indicator (PPI) approaches and departures, routing, and holding procedures. Considerations of the probable benefits which would be derived from an omnirange located at an airport resulted in the establishment of a project at this Center to develop and evaluate a terminal VHF omnirange.

This is a report of the results obtained from a detailed investigation conducted to establish criteria with respect to TVOR siting, transmitter power, and counterpoise size and height, and to study the effects of nearby hangars on course stability and accuracy. The flight-test results obtained on TVOR installations at the Indianapolis, Indiana; Traverse City, Michigan, Augusta, Maine, Oklahoma City, Oklahoma, Toledo, Ohio, and Washington, D. C., airports are described.

TERMINAL-OMNIRANGE EQUIPMENT

The first TVOR installed at the Indianapolis Weir Cook Municipal Airport was housed in a building approximately six feet square and seven feet high. This space was sufficient to house the major components of the TVOR equipment. With the addition of other components, it was necessary to increase the size of the building to six feet by eight feet by seven feet for the installations at the Augusta, Toledo, Traverse City, Oklahoma City, and Washington, D. C., airports. The building was constructed of wood and masonite and was supported by skids which provided a space of approximately four inches between the floor of the building and the ground. Ventilation was provided by screened openings near the top and the bottom on opposite sides of the building. See Fig. 1.

The TVOR equipment, shown diagrammatically in Fig. 2, was essentially the same, with the exception of the transmitter, as that used in a standard VOR airways facility. A self-contained Type TUQ transmitter having a rated output of 50 watts provided the main source of r-f power to the antenna. The unit was crystal-controlled and had a tunable range from 111 to 127 Mc with provision for operation by remote control The r-f and the audio components, the d-c plate and filament power supplies are assembled on an aluminum chassis which is housed in a steel cabinet. The audio and the modulator components are capable of producing 90 per cent modulation of the r-f carrier at audio frequencies up to and including the 10-kc subcarrier with an input level to the transmitter of -20 db.

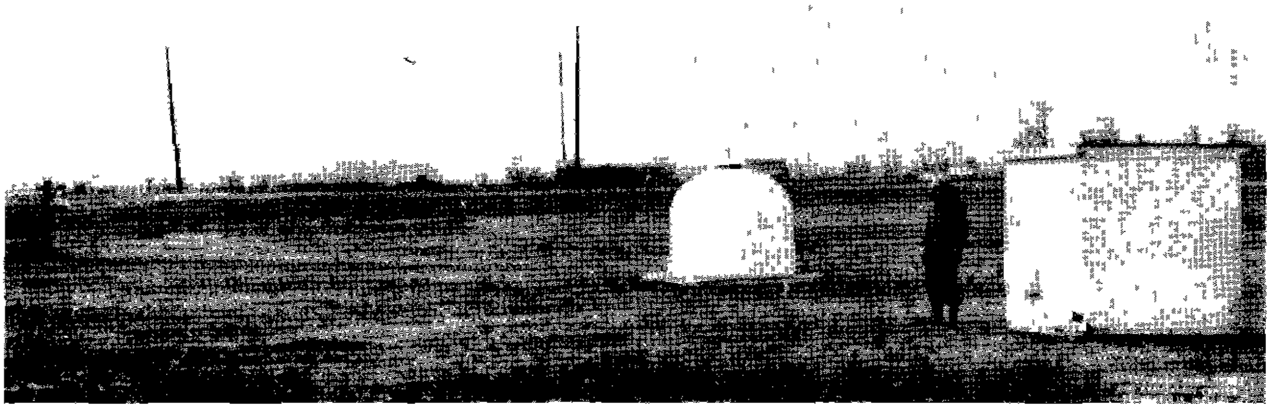


Fig. 1 Location of the TVOR With Respect to the Simulated Hangar Face

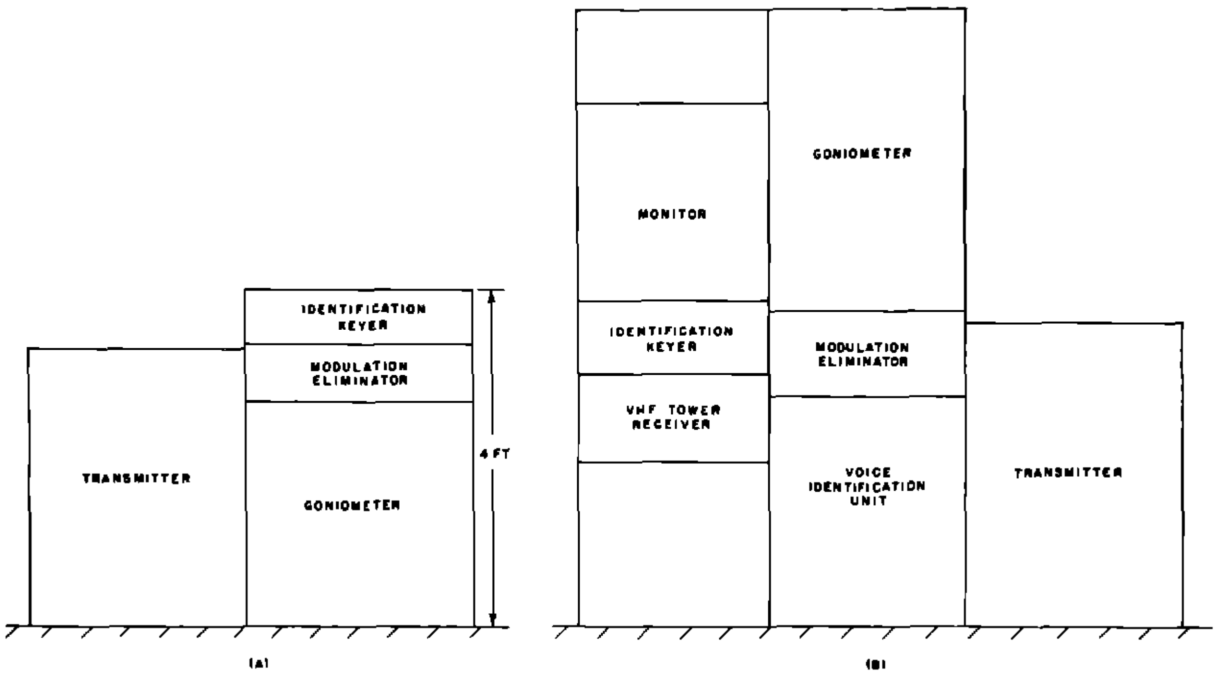


Fig. 2 TVOR Transmitting Equipment

Some modifications in the audio-amplifier stages were necessary to provide for three separate modulations of the r-f carrier. The maximum d-c operating potential in the unit was approximately 600 volts, and the r-f output circuit was designed to feed a 52-ohm load This transmitter was primarily designed for communication purposes, but it has proved quite satisfactory for TVOR operation

THE ANTENNA SYSTEM

The original experimental TVOR installation at Indianapolis was designed for a four-loop antenna array [1] The antenna was sheltered in a Fiberglas house anchored to a nine-foot-square wooden base supported on four-inch skids at ground level. The top of the wooden base was covered with a galvanized metal sheet nine feet in diameter The four-loop pedestals were mounted on a galvanized steel base plate which was bolted to the wooden base and was 0 25 inch thick and 44 inches in diameter The standard loop height of 48 inches above the base plate was maintained

The standard VOR five-loop array has been used at several TVOR installations. It's configuration is well known[2] and needs no description here The performance of this array is

---

[1] Sterling R Anderson, Hugh F. Keary, and William L Wright, "The Four-Loop VOR Antenna," CAA Technical Development Report No 210, June 1953

[2] H. C Hurley, S R Anderson, and H. F Keary, "The CAA VHF Omnirange," CAA Technical Development Report No. 113, June 1950.

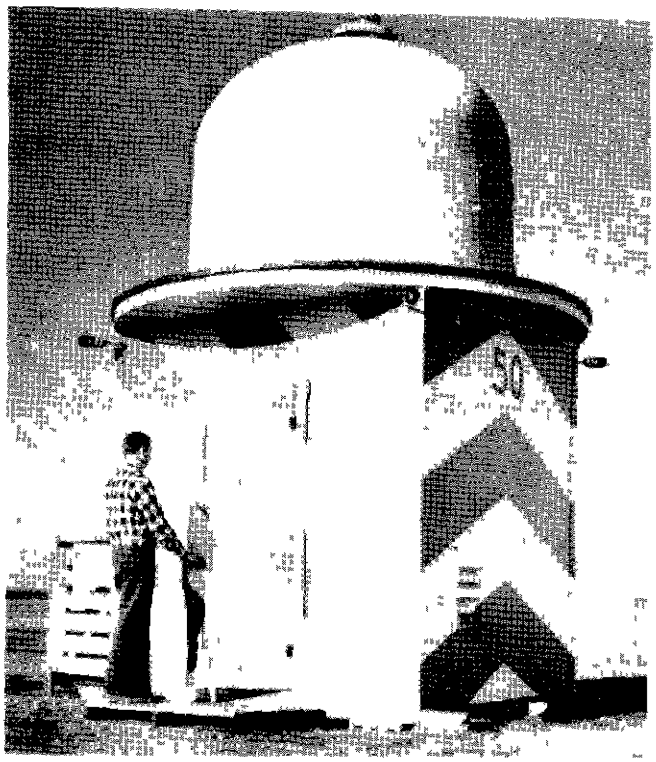


Fig. 3 Indianapolis TVOR, Counterpoise 12 Feet in Diameter, 10 Feet High

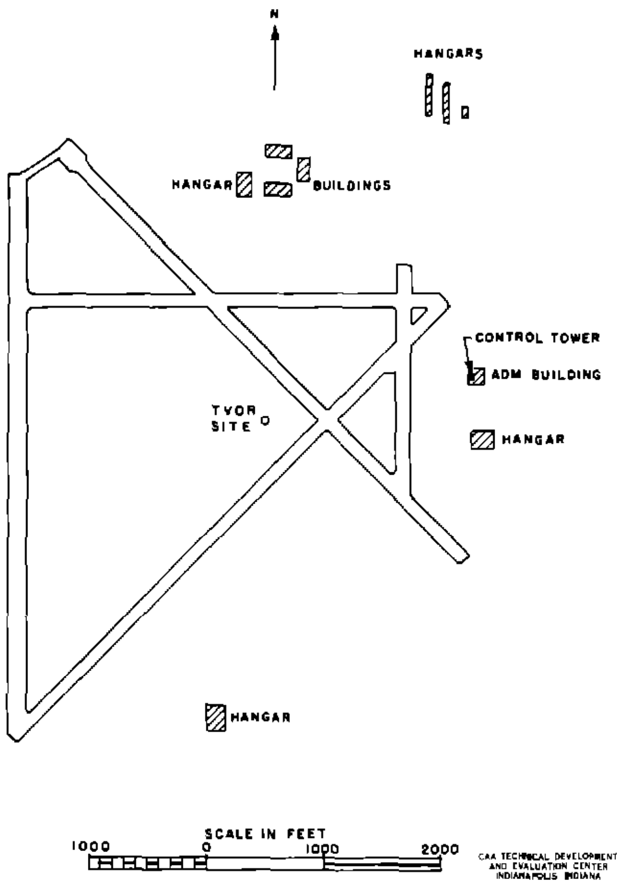


Fig. 4 Indianapolis Airport

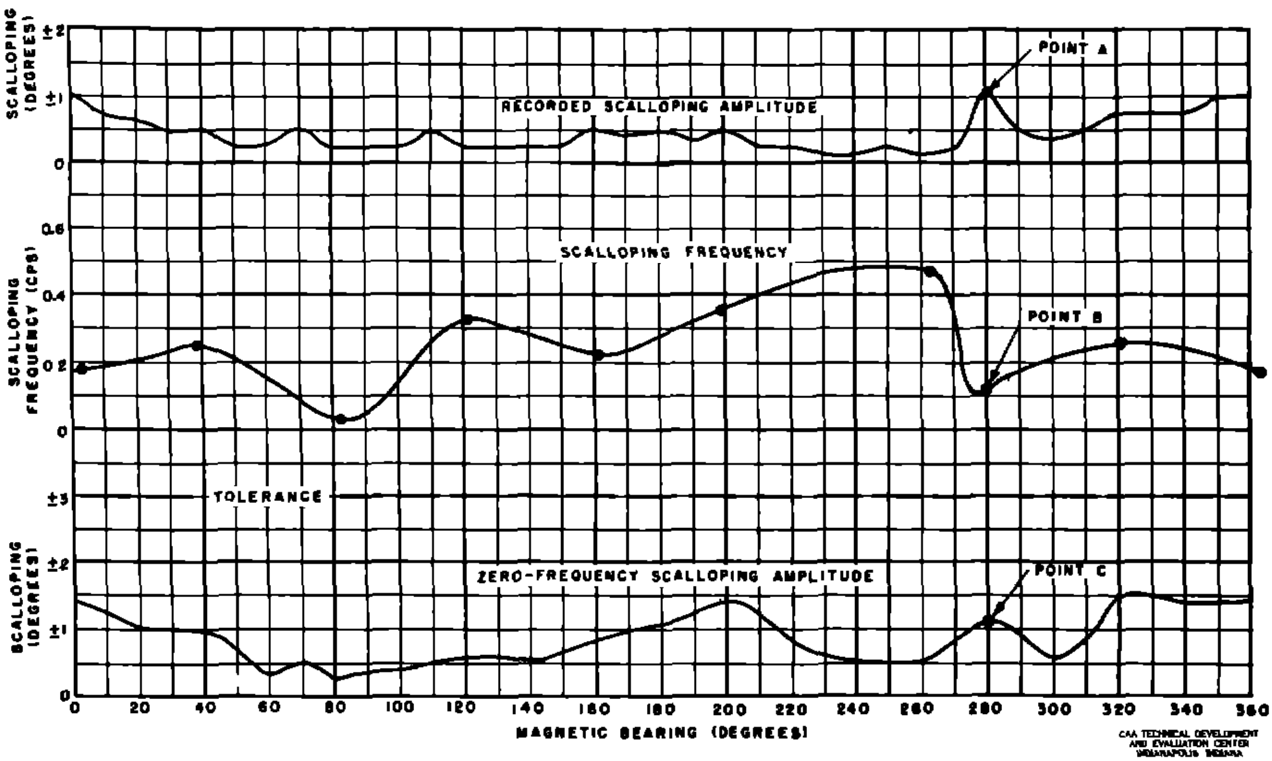


Fig. 5 Indianapolis TVOR 30-Mile-Radius Scalloping Graph

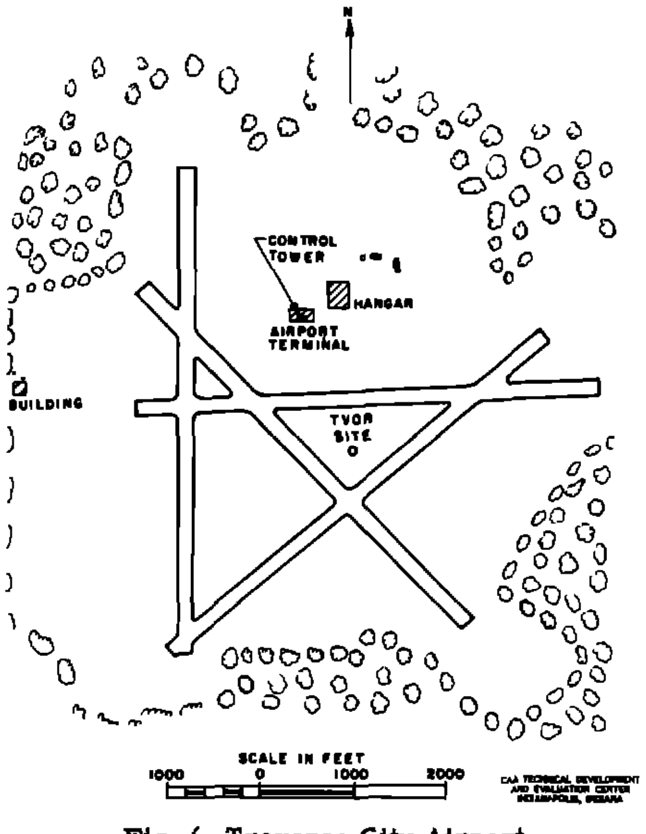


Fig. 6 Traverse City Airport

essentially the same, either on the ground or on a 10-foot high counterpoise, with respect to bearing information and distance range as that of the four-loop array, but the cone characteristics are inferior to those obtained with the four-loop array.

The antenna is usually located on a line due north of the transmitter building and approximately 50 feet from it. This spacing is governed by the height of the equipment above ground. The height of the equipment, as determined from previous tests, should not exceed 48 inches. This requirement is discussed later in this report. The location of the antenna on the ground provides a simple installation, since it dispenses with a tower. Although the usable distance range is reduced, it is still quite satisfactory for the intended purpose. The polarization effects are similar to those obtained with the antenna elevated above the ground, although the cone characteristics are superior to those of the elevated antenna

In later tests at Indianapolis, the TVOR installation was modified. The roof of the transmitter building was adapted to a counterpoise 12 feet in diameter with the antenna array mounted thereon and housed in the Fiberglas shelter. The counterpoise was approximately ten feet above ground. This arrangement allowed a compact and efficient installation with an increase in the usable distance range of approximately 30 per cent over that obtained when the array was on the ground. Also, the shortened coaxial feed lines provided a more efficient transfer of r-f power from the transmitter to the antenna and were completely protected from extreme weather conditions. Aside from the improvements noted, the performance of the facility under these conditions was similar to that observed when the array was at ground level. A view of the installation is shown in Fig. 3.

FLIGHT TESTS

The first TVOR was constructed and installed at Weir Cook Municipal Airport, Indianapolis, Indiana, in September 1950. The equipment consisted of a 50-watt transmitter with a four-loop antenna array situated on the ground 50 feet from the transmitter. After the completion of the preliminary tests, this TVOR was operationally evaluated jointly by personnel of TDEC and of the Office of Federal Airways. The results of the evaluation revealed that the TVOR was very satisfactory and was potentially a valuable aid to air navigation.

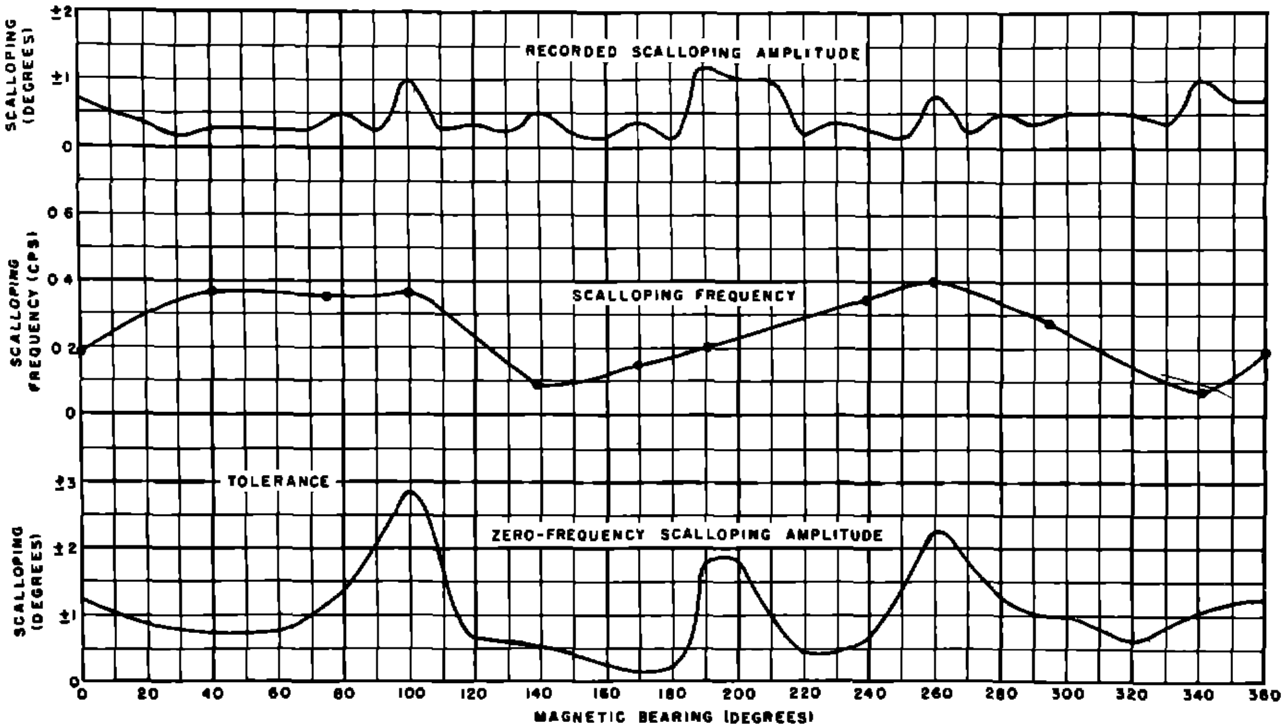


Fig. 7 Traverse City TVOR 30-Mile-Radius Scalloping Graph

When the flight tests on the TVOR at Indianapolis had been completed, it was desired to obtain data relating to the nature and the extent of the reflected energy which might be encountered at installations on airports of different sizes and having varying numbers, sizes, or shapes of adjacent buildings such as hangars and administration buildings. The presence of these buildings and their proximity to the TVOR is the fundamental difference between the siting of a TVOR and that of an en route VOR. Although such buildings may be as much as 2,000 feet from the TVOR, they present themselves as plane-surface reflectors of a height which may exceed 50 feet. The airports selected for trial TVOR installations were located at Traverse City, Augusta, Washington, D. C., Oklahoma City, and Toledo. When the installation and tuneup of the TVOR at each of these airports were completed, flight tests were conducted to obtain the following data

1. Theodolite flight calibration at five-mile radius.
2. Twenty- or thirty-mile-radius calibration.
3. Cone measurements
4. Airways radial-flight checks.
5. Polarization checks.

Approximately 12 hours of flying time were required in flight-testing each installation. Since these installations were similar, the flight-test data were repetitious but were necessary to provide scientific proof that the TVOR was in proper operation and that any differences in operational performance were functions of siting and not of equipment.

The flight-test data which proved to be most important included the amplitude, the frequency, and the azimuth of course scalloping as they were determined from the recordings obtained on the 20- and 30-mile-radius calibration flights The data provided information about the extent of "airport effect" and about the objects responsible for the reflection of TVOR energy. The scalloping recorded on the large-radius calibration circles varied from a simple sine-wave type of scalloping to a very complex type of scalloping. The reflecting surface may be quite accurately located from the simple type of scalloping, but the complex type of scalloping indicates that a number of objects are contributing to the interference of the direct signal.

The six airports selected for testing represented different types in respect to sizes, types, and numbers of buildings around the airport and in respect to different kinds of terrain in the immediate vicinity of the airport The flight tests revealed that the Augusta and the Indianapolis airports provided very satisfactory sites. The Toledo and Oklahoma City installations proved to be cases in which one simple source of reflection predominated. The Traverse City TVOR site was marginal inasmuch as it had three directions of large-amplitude scalloping, one direction being just under the tolerance. Flight tests at Washington, D C , indicated that this airport was not suitable as a site for good TVOR performance in all sectors A discussion of the tests at the six airports follows.

The layout of the Indianapolis airport is shown in Fig. 4 The 20-mile-radius scalloping characteristics are shown in Fig. 5 This is an example of an acceptable airport site on flat terrain and based on an arbitrarily selected maximum acceptable scalloping of ± 3° The curves labeled "recorded-scalloping amplitude" and "scalloping-frequency" were obtained from the flight-test data The curve labeled "zero-frequency, scalloping-amplitude" was obtained from the two afore-mentioned curves with the aid of Fig. 22.[3] For example, point A shown on Fig 5 has a value of ± 1.0° and point B has a value of 0.12 cps. Both of these figures were originally obtained from the course-deviation-indicator (CDI) recording made during a flight of 20 miles in radius. In reference to Fig 22, 0.12 cps corresponds to an ordinate of 88 per cent of scalloping amplitude. The zero-frequency scalloping amplitude, point C, is then obtained by $\frac{\pm 1.0°}{0.88} = \pm 1.14°$.

The significance of the zero-frequency scalloping amplitude is that during a very particular type of flight (namely, one that deviates 1° or less from a radial flight) a very slow scalloping frequency, even zero, will be experienced[4] It is at such a time that the CDI errors will equal the zero-frequency scalloping amplitude.

---

[3]The derivation of Fig. 22 is treated in more detail under the section of this report entitled "Tests of a Simulated Hangar Face "

[4]S. R Anderson and H F. Keary, "VHF Omnirange Wave Reflections From Wires," CAA Technical Development Report No. 126, May 1952, pp. 14 and 15

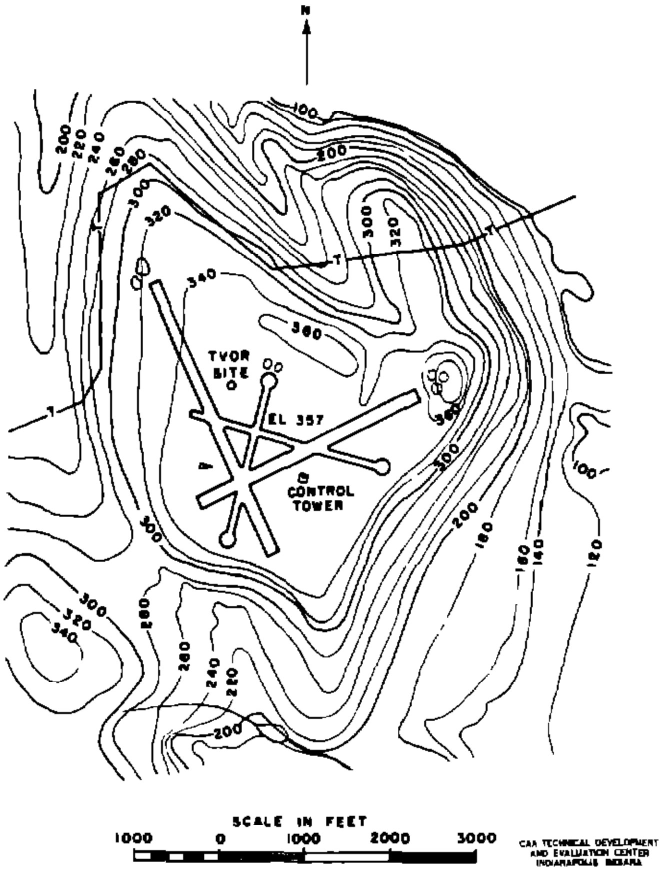


Fig 8 Augusta Airport

The installation and the flight-testing of the TVOR at Traverse City, Michigan, were completed in March 1951 This TVOR was not affected by the heavy snow which had just accumulated. The location of reflecting objects may be seen in Fig 6, and the associated scalloping characteristics are presented in Fig 7. The terrain at Traverse City Airport is flat with rising land four to six miles away. Results of flight tests revealed this to be a satisfactory site. The maximum at 190° to 200° azimuth zero-frequency scalloping amplitude, Fig 7, is believed to be due to reflections from the south face of the control-tower building north of the TVOR. The sources causing the large scalloping at 100° and at 260° azimuth are unknown, but it is indicated by the data that both scalloping sectors may be caused by one source. The three maxima are of such amplitude that radial-flight tests might well be in order to determine the accuracies that exist in practice in the three sectors The zero-frequency-amplitude curve indicates that the tolerance is met in all directions It will be noted that high-frequency scalloping causes small recorded scalloping amplitudes to increase to large zero-frequency scalloping amplitudes For example, compare the scalloping amplitudes at 100° and at 260° azimuth

The airport at Augusta, Maine, is located on a hilltop with the land declining sharply from the airport proper This was expected to produce some irregularities in the cone or in the courses, although none were observed during the limited flying period and satisfactory TVOR performance was obtained A plan view of the site is shown in Fig 8 The course-scalloping characteristics are given in Fig 9.

Oklahoma City Will Rogers Field has a site similar to the one at Indianapolis in that the terrain is flat. See Fig. 10. Buildings are the source of scalloping Fig 11 shows the resulting scalloping characteristics The zero-frequency, scalloping-amplitude curve maxima at 60° and at 280° azimuth are believed to be caused by reflections from hangar No. 50 and from the terminal building, respectively. The sources of other maxima are not known The sharp peak at 122° azimuth is so narrow that from the practical standpoint it may be neglected.

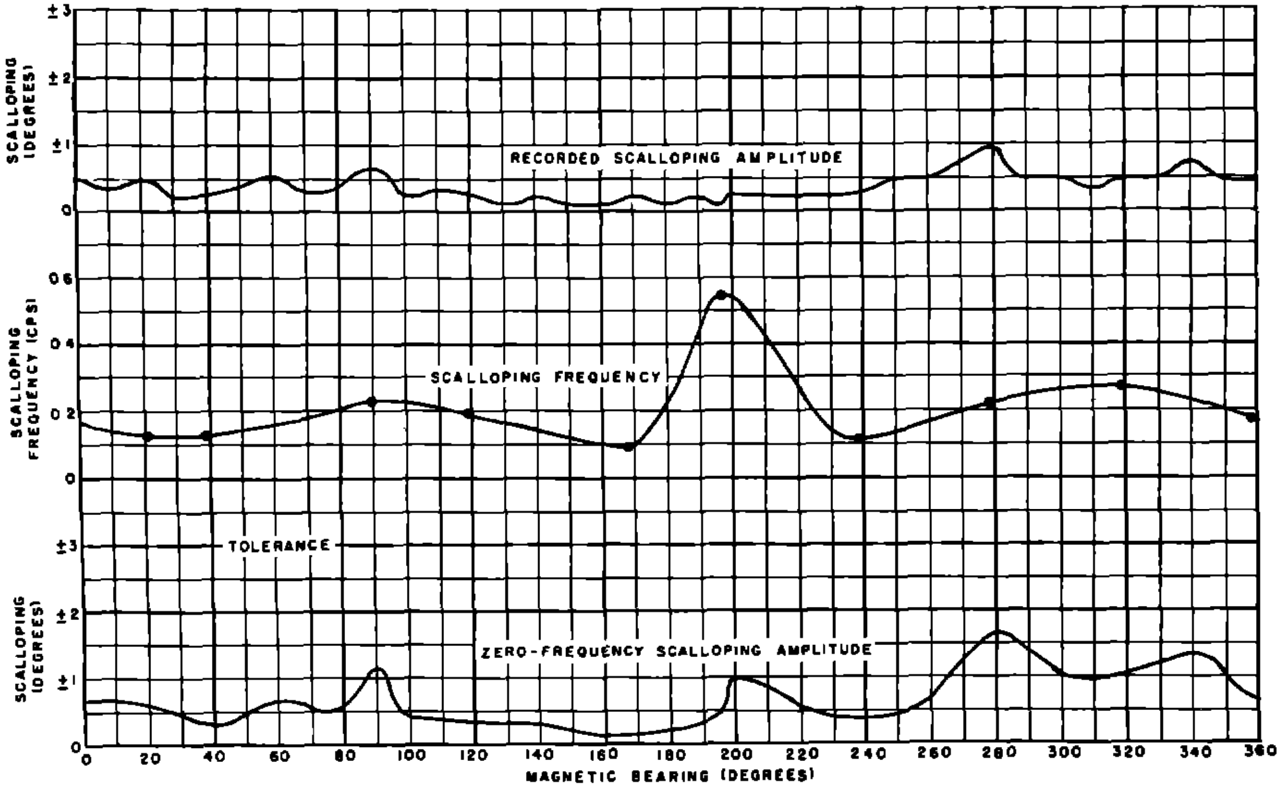


Fig. 9 Augusta TVOR 30-Mile-Radius Scalloping Graph

This airport is considered an acceptable TVOR site for service in all directions except the sector of 55° to 65° azimuth, where the scalloping approaches the maximum acceptable value.

At the Toledo Municipal Airport, the TVOR was installed with the antenna placed on a standard counterpoise 35 feet in diameter and ten feet above ground After the flight tests, the counterpoise and its supporting structure were removed, the antenna was placed on the ground, and the flight tests were repeated These tests revealed that the ratio of reflected-to-direct radiated signal is not changed when the antenna is elevated above ground. The performance for both cases was excellent throughout 351° of azimuth, but excessive scalloping was encountered in a 9° sector centering approximately at azimuth 277°. An analysis of the recordings revealed that the reflecting object was a hangar 45 feet high and 1,900 feet from the TVOR and that the near end of it was acting as a metal plane reflector with an angle of incidence of approximately 45° Upon reference to Fig. 12, Site No 1 was selected to provide the maximum approach service to all runways on the airport and to provide the greatest distance between the TVOR and potential reflection sources.

In an attempt to reduce the reflection of energy from the one large hangar on the field, three additional sites (Nos 2, 3, and 4 in Fig. 12) were selected. The installations with the antennas on the ground were in turn made at these three sites, and flight tests were conducted in each case

Fig 13A presents the condensed flight-test data pertinent and distinct to the Toledo, Ohio, siting problem From the recordings obtained on the 30-mile-radius calibration flight, the maximum over-all scalloping recorded on each 10° sector is plotted. Table I is a tabulation of the azimuth and of the amplitude of the maximum scalloping recorded when a radial was flown in an area of scalloping.

From Fig 13A and Table I, it can be seen that Sites Nos. 2 and 3 were inferior to Sites Nos 1 and 4 Site No 2 proved to be the least desirable of the four sites tested because of its proximity to a railroad switchyard and its associated lighting towers and power-transmission lines.

TABLE I

TOLEDO, OHIO TVOR FLIGHT-TEST DATA

Site	30-Mile-Radius Flight Test		Radial-Flight Data	
	Area of Heavy Scalloping (Degrees)	Amplitude of Maximum Scalloping (Degrees)	Radial Flown (Degrees)	Amplitude of Maximum Scalloping (Degrees)
1**	281 - 272	5 05	276	6 14
1A*	283 - 274	5 4	276	9 5
2	290 - 270	4 0	280	6 2
3	330 - 290	2 8	313	4 6
4	284 - 278	3 9	280	6 2

** Antenna on ground

* 10-foot-high counterpoise

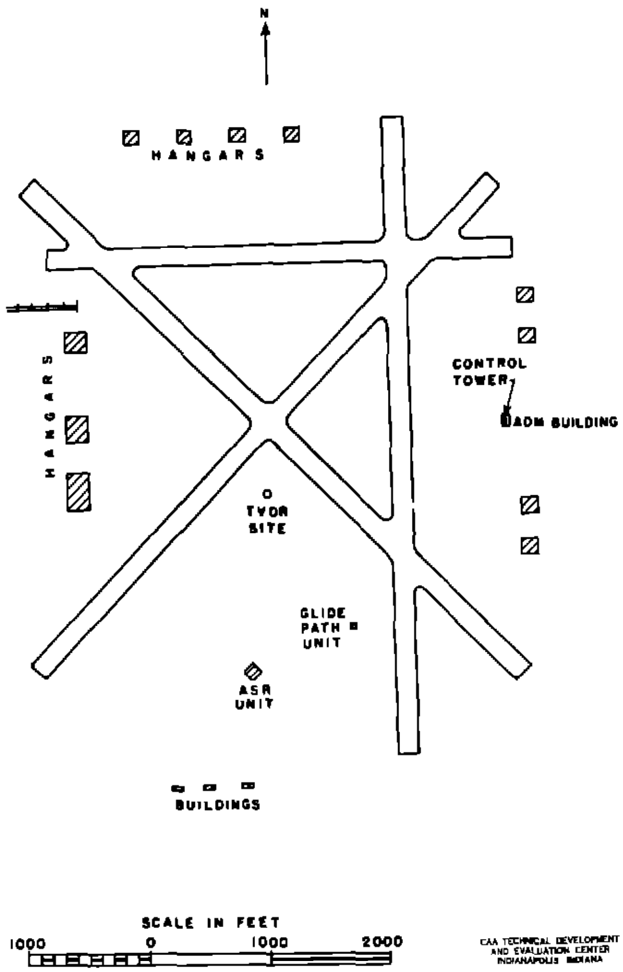


Fig 10 Will Rogers Field, Oklahoma City

The selection of a site for the Toledo TVOR then became a choice of either Site No 1 or Site No 4 Site No 4 was selected to provide approximately the same angle with respect to the large hangar on the field as Site No 1 and yet to provide a greater distance separation between the TVOR and the reflecting surface Site No 4 gave improved performance over Site No 1, but it still had a 6° sector in which out-of-tolerance scalloping occurred Since Site No 4 appeared to be the best location available on the airport, a more thorough analysis was made of its scalloping data than was made of the data of the other sites Fig 13B presents the results The zero-frequency, scalloping-amplitude curve clearly indicates that the scalloping caused by the afore-mentioned hangar face exceeds the tolerance at 280° azimuth

The Washington National Airport is an example of an airport where a good TVOR site could not be found The hangars and buildings on the south and west edges of the field made it impossible to locate the TVOR so that the wave incident to the faces of all the buildings did not cause scalloping See Fig 14 The Potomac River bounding the north, east, and south edges of the field makes it impossible to move the TVOR far enough away from the airport buildings to reduce the scalloping from approximately ± 7° to a desired value of ± 3° or less The scalloping characteristics for Site No 2 are presented in Fig 15 The maximum scalloping at 170° azimuth on the zero-frequency, scalloping-amplitude curve is believed to be a result of reflections from the southwest faces of hangars Nos 1 through 7 The large scalloping at 310° azimuth is from an unknown source, however, the large frequency of scalloping is evidence that the reflecting object is 4,600 feet or more from the TVOR The tests conducted at Sites Nos 1, 2, and 3 and the theoretical analysis made of the airport indicate that by moving the TVOR on the field the sector or sectors of large scalloping may be directed to other azimuths These same tests indicate that the amplitude of maximum scalloping is little changed Therefore, if certain azimuths are of less importance than others in air navigation, the direction of maximum scalloping may be so located

TESTS OF A SIMULATED HANGAR FACE

During the tests conducted at the various airports, large scalloping was experienced because of reflections from some hangars While reflections from objects had been investigated theoretically[5] and had been observed during previous flight tests of omniranges, little had been done to investigate thoroughly the scalloping caused by a real or simulated hangar face The following is a description of a series of tests conducted on a simulated hangar face

A vertical plane surface consisting of 27 horizontal No. 12 copper conductors, each approximately 146 feet long, spaced 22 inches apart, and stretched between two poles, simulated a hangar face The surface extended from ground level to a height of 50 feet It was erected in such a way that it could be tilted from the vertical position to a 60° angle of elevation with the horizontal and could readily be lowered to the ground A view of this reflecting surface is shown in Fig 16

A four-loop TVOR with the antenna at ground level was moved about as required with respect to the simulated hangar face A C-47 type of aircraft equipped with a navigation receiver and a tail V receiving antenna was used to measure the scalloping caused by the hangar face.

[5] Ibid.

Fig. 11 Oklahoma City TVOR 30-Mile-Radius Scalloping Graph

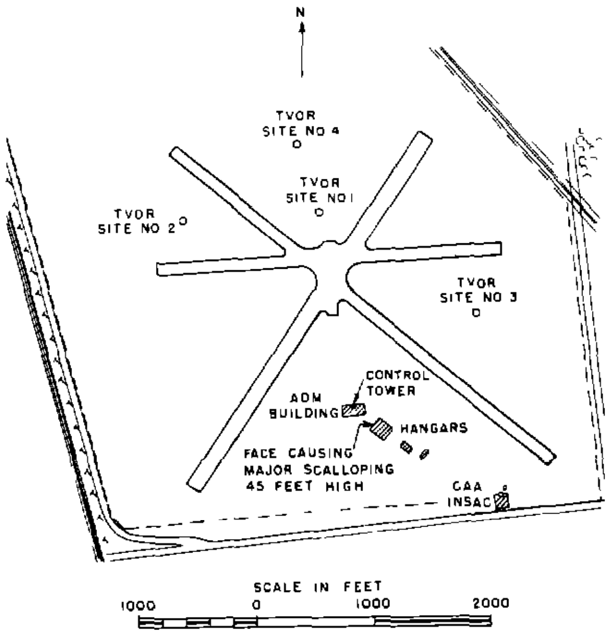


Fig 12 Toledo Municipal Airport

The plan diagram, Fig. 17, shows the location of the antenna with respect to the reflecting surface Fig 18 shows the manner in which the amplitude of scalloping caused by the simulated hangar varies with the azimuth of the aircraft for various angles of the reflected wave α_c The distance between the reflecting sheet and the antenna was 500 feet in each case The aircraft was flown in a six-mile-radius circle around the TVOR and at an altitude of 1,500 feet above ground Fig. 18A, for example, was taken with the angle $\alpha_c = 15°$ Maximum scalloping occurred at 165°, indicating that the angle of incidence to the center of the face is equal to the angle of reflection, as would be expected from optical theory The frequency of the scalloping was 0 244 cps, measured at and near the direction of maximum amplitude, and the half-power beam width was 8°. Figs 18B through 18F present similar information for $\alpha_c = 30°$, $= 45°$, $= 60°$, $= 75°$, and $= 90°$, respectively The angle of incidence to the center of the face and the angle of reflection, as determined by the azimuth of the center of the beam for all cases, are nearly equal except in Fig 18F Fig 18F represents a special case, since the wave striking the center of the face would reflect at an azimuth of 90° and would produce aircraft-bearing information of the same phase or in phase opposition to that transmitted directly to the aircraft This would not cause an error in the received bearing Waves reflected from the reflecting surface at angles of 83° and of 87° caused scalloping In one test performed in this series, α_c was 0° and d was 500 feet No scalloping or other effects due to the simulated hangar face were noted

The theoretical frequency of the scalloping versus the complement of the angle of incidence has been plotted in Fig 19 Measured points from Fig. 18 show reasonable agreement with the calculated curve The measured points cannot be expected to fall exactly on the theoretical curve[6] since the ground speed of the aircraft was not accurately known, therefore, the indicated speed of the aircraft, 150 mph, was used as the ground speed Fig 20 shows how much the complement of the angle of incidence over the simulated hangar face may vary for the 500-foot spacing between reflecting surface and the TVOR antenna.

The widths of the scalloping patterns shown in Fig 18 are plotted in Fig 21 The points $\alpha = 83°$ and $= 87°$ were taken from Fig. 18F, where it was assumed that the angles of incidence and reflection were equal for the directions of maximum scalloping

[6] Ibid., Appendices I, II, and III

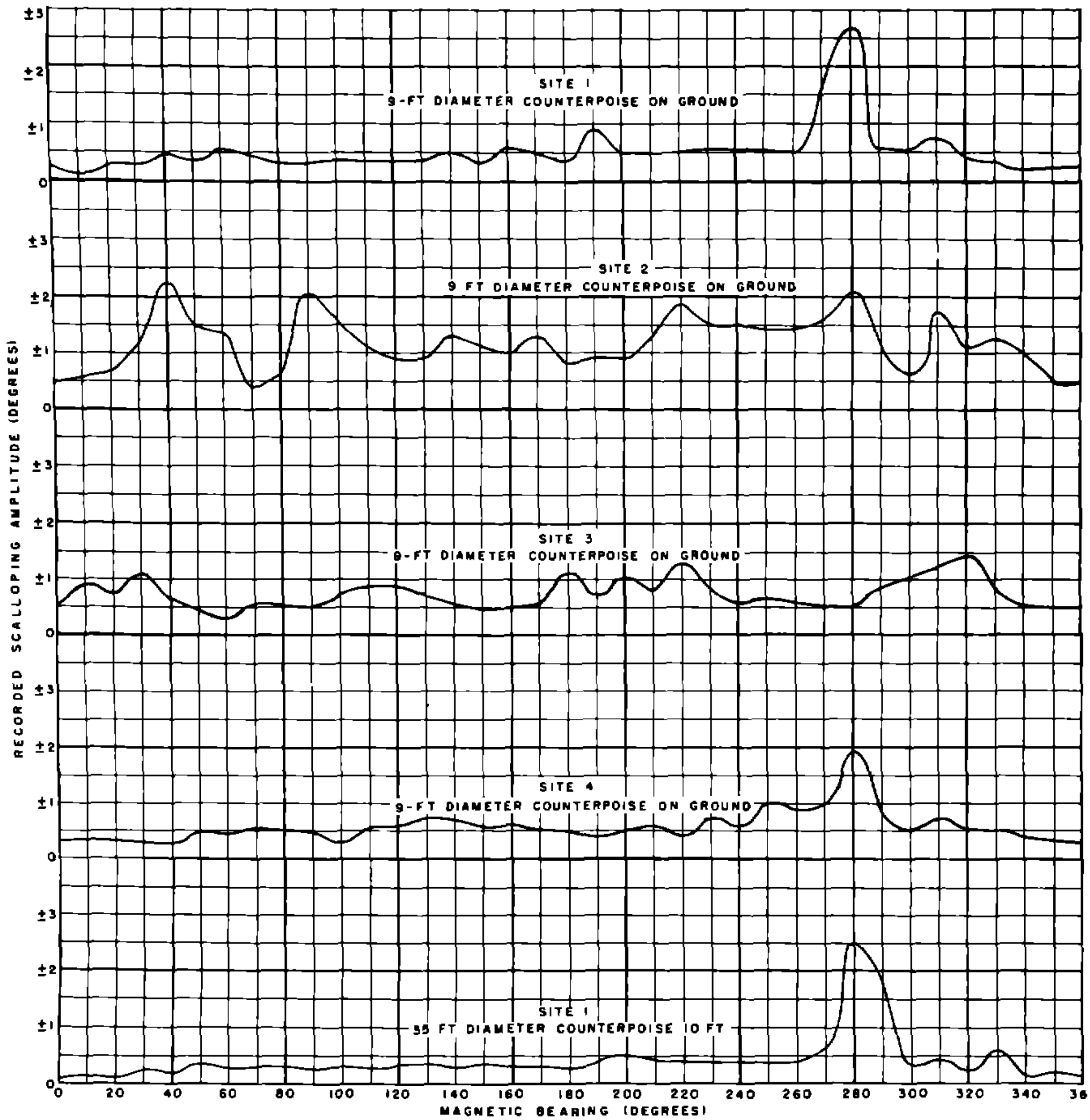


Fig 13A Toledo TVOR 30-Mile-Radius Scalloping Graph

The curve in Fig. 22 shows how the CDI responds to scalloping It is seen that the indicated scalloping amplitude is a function of the scalloping frequency The curve represents the average of a large number of points obtained in actual flight tests Therefore, the curve can be considered to be a plot of nominal values The arbitrarily selected maximum acceptable scalloping is ± 3° Since the indicated amplitude is a function of the scalloping frequency and since the 0-cps, 100-per-cent scalloping-amplitude point of Fig. 22 corresponds to ± 3°, higher scalloping frequencies will have correspondingly smaller amplitudes. This is graphically expressed in Fig. 23

The maxima of the scalloping pattern shown in Fig 18, with the values corrected to a

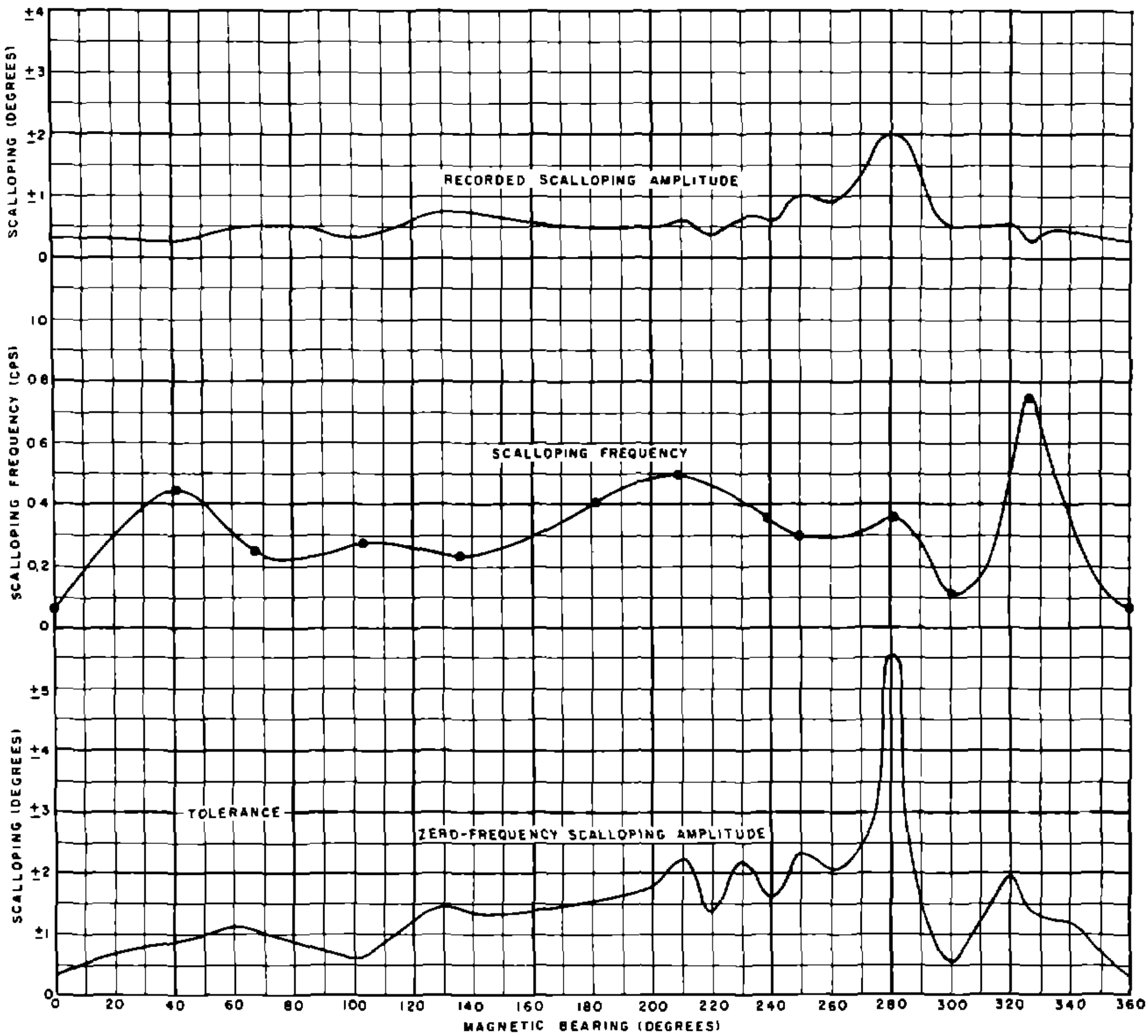


Fig 13B Toledo TVOR Detailed Analysis of Site 4 Scalloping Graph

scalloping frequency of 0 cps, are plotted in Fig 24 to show the agreement with the theoretical curve [7] The amplitude of scalloping may appear to be large or small, depending on its frequency All amplitudes were corrected to values corresponding to a common frequency by use of the curve of Fig 22 to compensate for this change Fig 25 illustrates the effect of the distance between the simulated hangar face and the TVOR antenna on scalloping In each case, a_c was held constant at 45° The aircraft was flown in circles with radii of 6 miles for a spacing of 500 feet between the TVOR and the reflecting surface, of 12 miles for 1,000 feet, of 18 miles for 1,500 feet, and of 24 miles for 2,000 feet The reason for flying the aircraft in circles of different radii was to hold the scalloping frequency constant The altitude of the aircraft above ground was held at 1,500 feet

The amplitude of scalloping caused by a horizontal wire, as given by Anderson,[8] is shown in Equation (1)

---

[7] Ibid , Fig 14, p 8

[8] Ibid

$$S = \frac{K_3 D_2 f(\alpha) \sin\left(\frac{2\pi}{\lambda} \frac{h_0 h_1}{D}\right) \sin\left(\frac{2\pi}{\lambda} h_1 \sin\theta\right)}{D_1 D \sin\left(\frac{2\pi}{\lambda} h_0 \sin\theta\right)} \qquad (1)$$

where

D = distance between the VOR array and the reflecting wire

D_1 = distance from the reflector to the aircraft

D_2 = distance from the VOR to the aircraft

K_3 = a constant depending upon the reflector size and other parameters

$f(\alpha)$= a factor accounting for the change in scalloping amplitude because of a change in α

α = angle of incidence to the vertical plane surface containing horizontal wires

λ = wavelength

h_0 = height of the VOR array above the ground

h_1 = height of the reflecting wire above the ground

θ = elevation angle of the aircraft above the horizontal

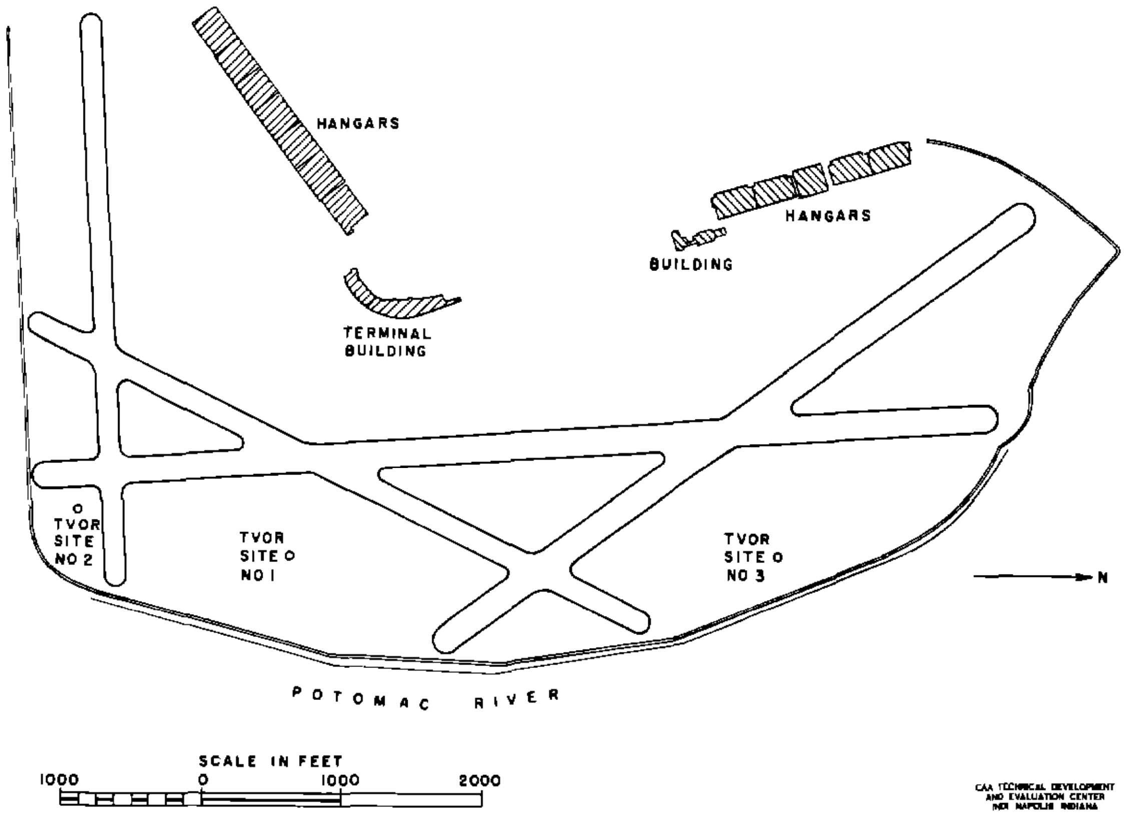


Fig 14 Washington, D. C , National Airport

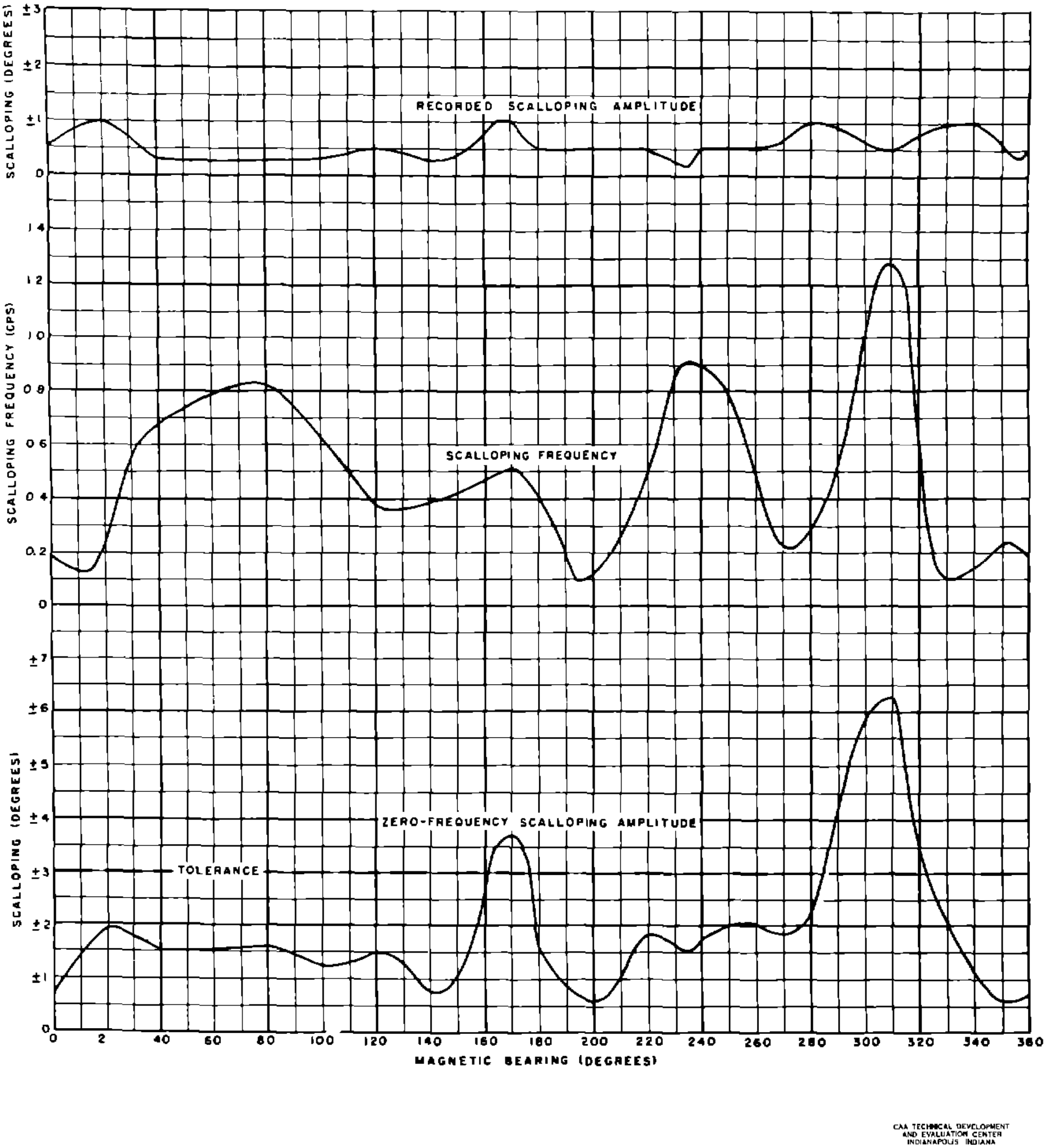


Fig 15 Washington, D C , TVOR 30-Mile-Radius Scalloping Graph

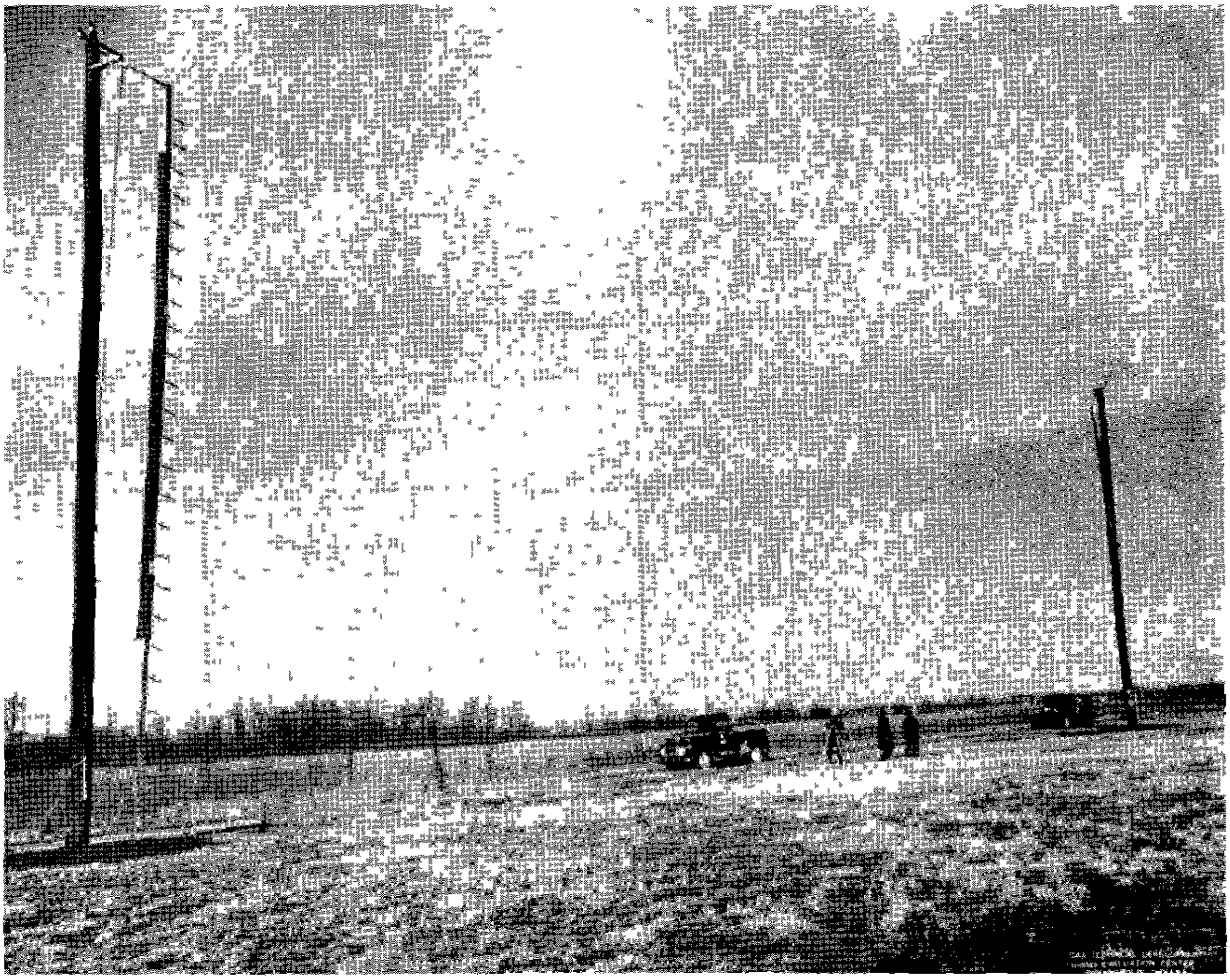


Fig. 16 Simulated Hangar Face

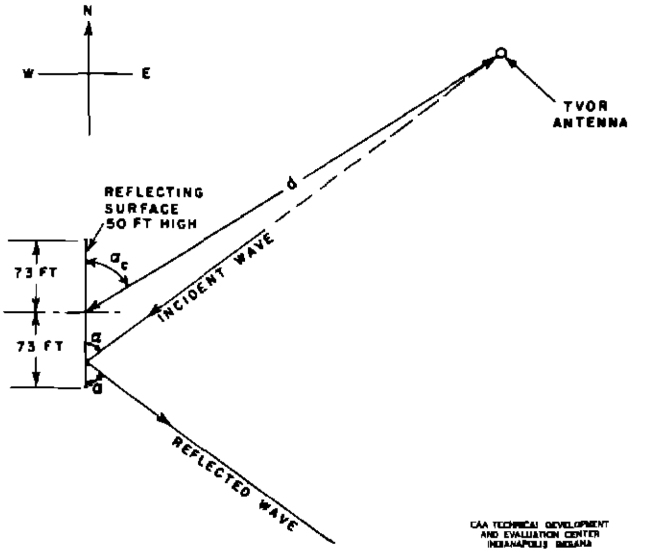


Fig. 17 TVOR Antennas and Simulated Hangar Face

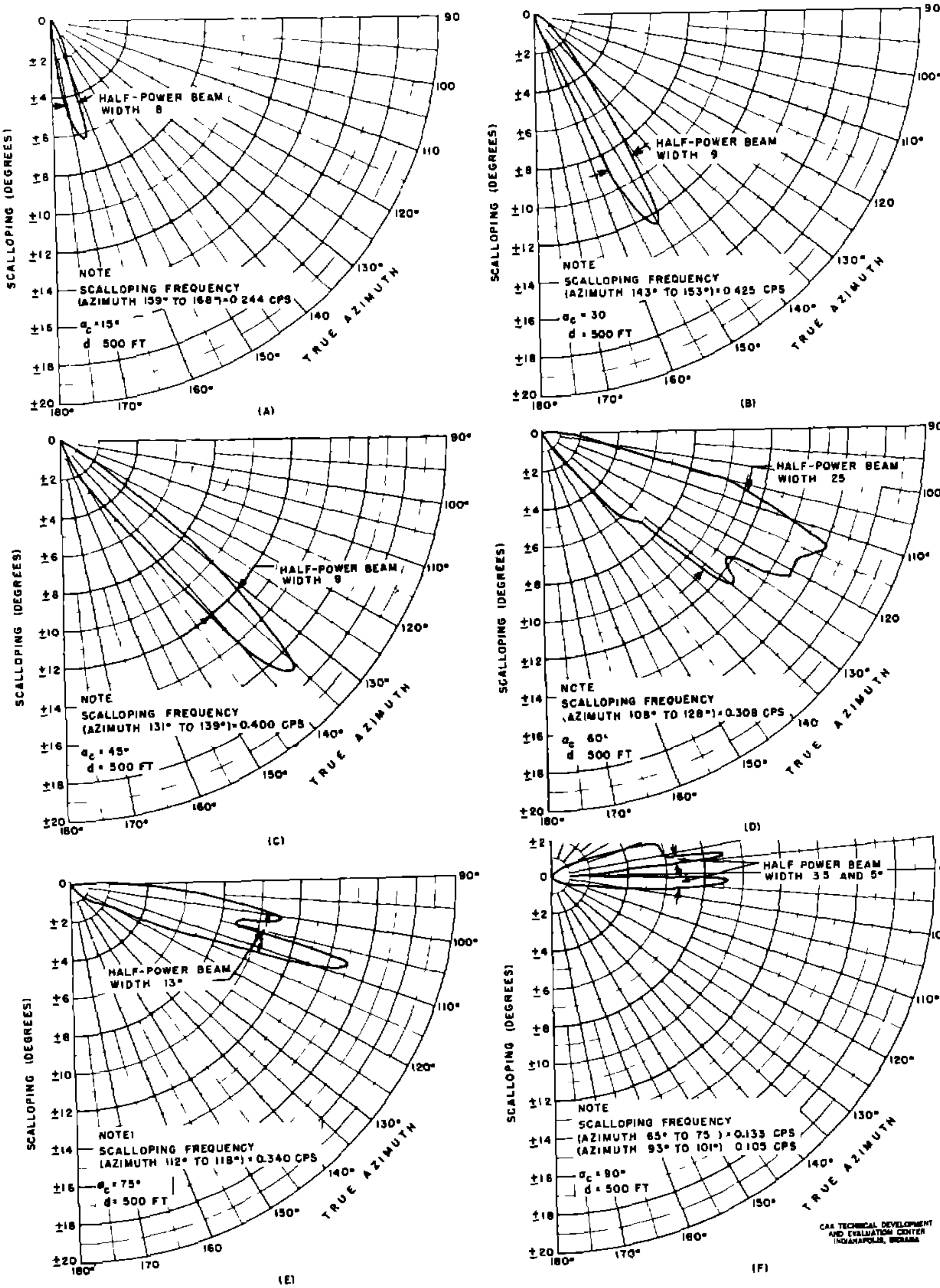


Fig. 18 Polar Plots of Course Scalloping

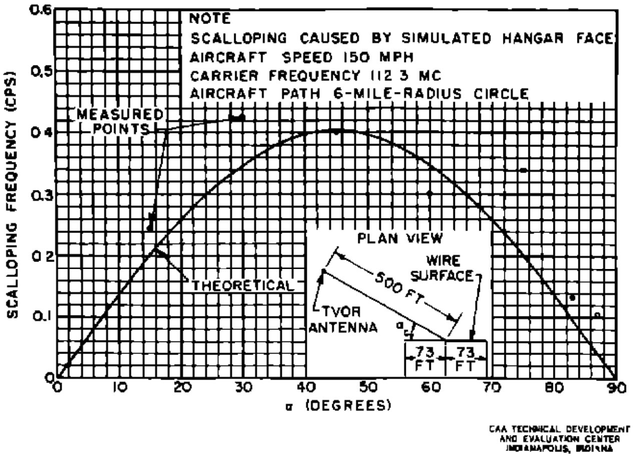


Fig 19 Measured and Calculated Course-Scalloping Frequency Versus Angle of Incidence

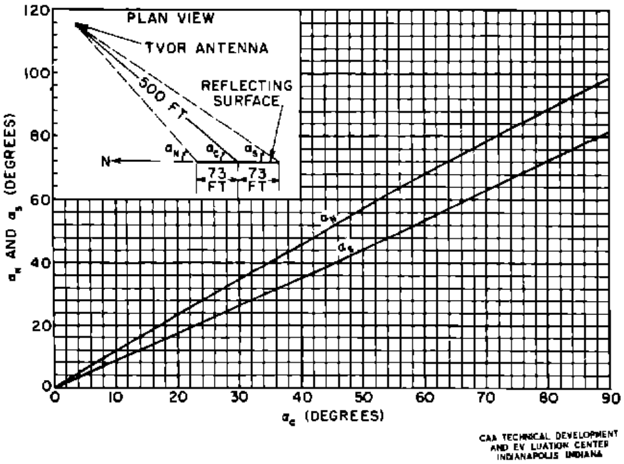


Fig 20 Angles of Incidence at the Ends of the Simulated Hangar Face As a Function of the Incidence Angle to the Center

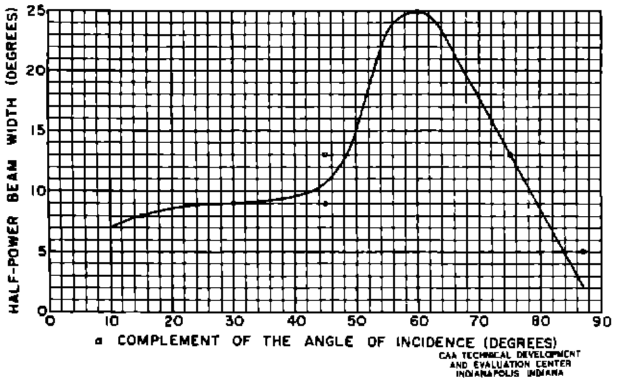


Fig 21 Course-Scalloping Pattern Width Versus Angle of Incidence

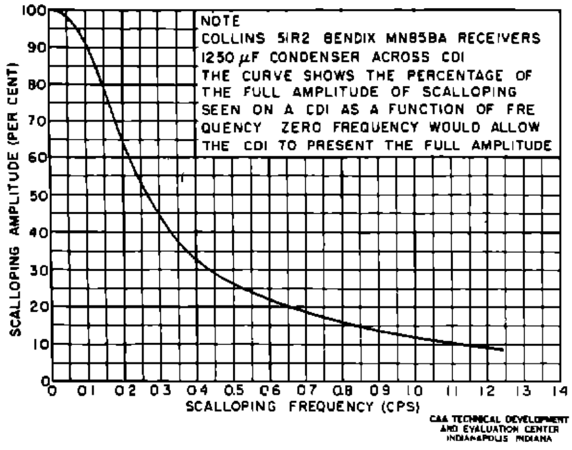


Fig 22 Scalloping Characteristics of Navigational Type Receivers

To obtain an expression for the scalloping produced by one conductor which is h_1 feet above ground, equation (1) can be simplified under the following conditions

$f(\alpha)$ = a constant, since $\alpha_c = 45°$,

$D_1 \approx D_2$, because D is small compared with D_1 and D_2 and because of the location of the aircraft when on a maximum,

$$\sin\left(\frac{2\pi h_0 h_1}{\lambda D}\right) \approx \frac{2\pi h_0 h_1}{\lambda D}, \text{ because } \frac{2\pi h_0 h_1}{\lambda D} \leq 16.9°$$

and

$$\sin\left(\frac{2\pi h_0 \sin\theta}{\lambda}\right) \approx \frac{2\pi h_0 \sin\theta}{\lambda}, \quad \text{since } \frac{2\pi h_0 \sin\theta}{\lambda} \leq 7.96°$$

when h_0 = 4 feet and λ = 8.56 feet, Equation (1) becomes

$$S = \frac{K_4 h_1 \sin\left(\frac{2\pi h_1}{\lambda} \sin\theta\right)}{D^2 \sin\theta} \qquad (2)$$

As seen in Fig 26, curve A is a plot of Equation (2) on which are indicated measured points representing maxima of scalloping patterns shown in Fig 25. The simulated hangar face consisted of a number of wires, one above the other, forming a plane surface. By adding the fields produced by each conductor from ground level to height h_2, the scalloping produced by the surface may be obtained [9]

Thus

$$S = \frac{K_5}{D^2 \sin\theta} \int_0^{h_2} h_1 \sin\left(\frac{2\pi h_1}{\lambda} \sin\theta\right) dh_1 \qquad (3)$$

Integrating, we get

$$S = \frac{K_5}{D^2 \sin^2\theta} \left[\frac{\sin\left(\frac{2\pi h_2}{\lambda} \sin\theta\right)}{\sin\theta} - \frac{2\pi h_2}{\lambda} \cos\left(\frac{2\pi h_2}{\lambda} \sin\theta\right) \right] \qquad (4)$$

The application of Equation (4) to the conditions of Fig. 26 results in D Sin θ becoming a constant, since D was increased by the same factor by which sin θ was diminished The expression used to plot curve B is

$$S = K_6 \left[\frac{\sin\left(\frac{2\pi h_2}{\lambda} \sin\theta\right)}{\sin\theta} - \frac{2\pi h_2}{\lambda} \cos\left(\frac{2\pi h_2}{\lambda} \sin\theta\right) \right] \qquad (5)$$

[9] The currents in the conductors of the face are assumed to be in phase, since the phase actually changes 105° between the topmost and the bottommost conductors This assumption meets the Rayleigh quarter-wave criterion for the formation of an image in optics

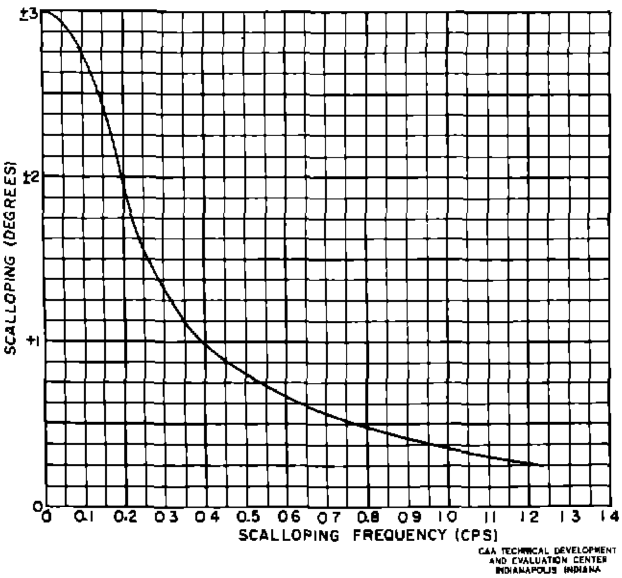


Fig 23 Maximum Acceptable Scalloping for a Given Scalloping Frequency

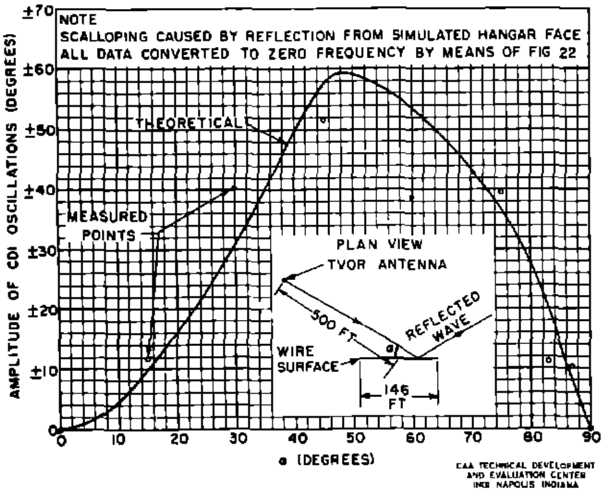


Fig 24 Measured and Calculated Scalloping Amplitude Versus Angle of Incidence

Fig 27 is a plot of the widths of the patterns shown in Fig. 25. These data clearly indicate that the pattern widths decrease with an increase in distance between the simulated hangar face and the TVOR antenna for an angle of incidence of 45°

Several tests were made at 500, 900, and 1,600 feet between the simulated hangar face and the TVOR antenna The reflecting surface was alternately placed in the vertical plane and inclined at 60° to the earth. The lower part of the surface was moved toward the TVOR antenna while the top remained fixed to achieve the inclined position The amplitude of the scalloping was measured at each distance and with the surface set at the two positions These results indicate that the ratio

$$\frac{\text{scalloping at } 60°}{\text{scalloping at } 90°} \times 100 = 11 \text{ per cent (average)}$$

The situation is illustrated in Fig. 28, wherein P is the point of optical reflection from the surface and vector 1D indicates the direction of the reflected wave The equations included in Fig. 28 permit a solution for the components of x, y, and z of the reflected wave Results

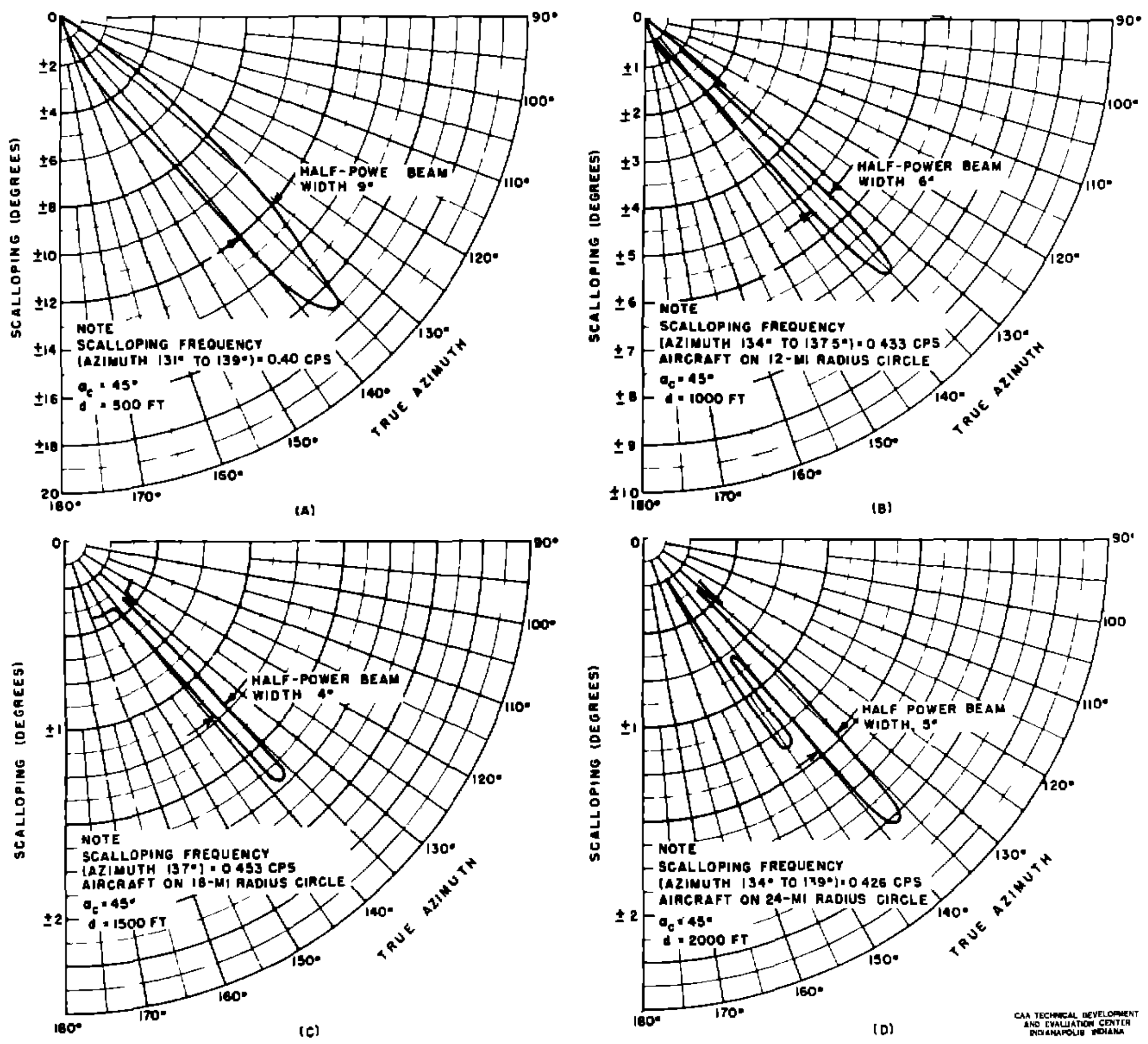


Fig. 25 Polar Plots of Course Scalloping

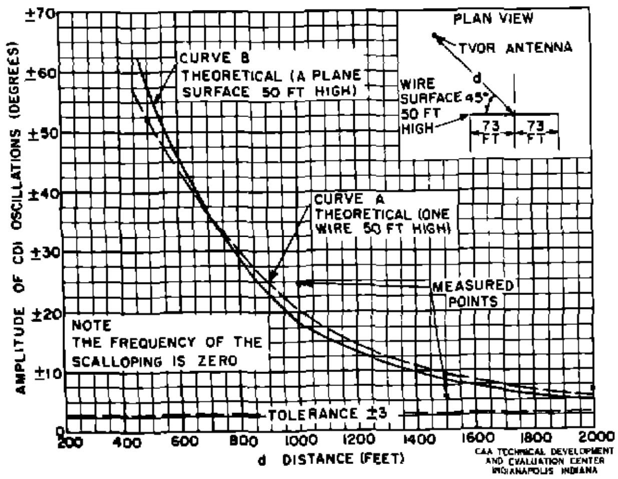


Fig. 26 Variation of the Amplitude of Scalloping With Distance

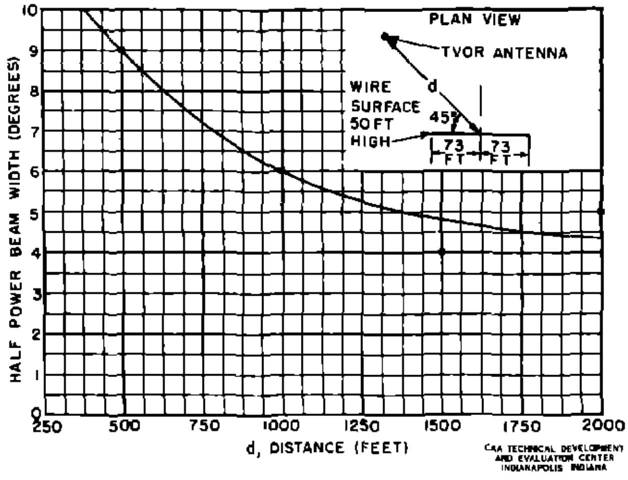
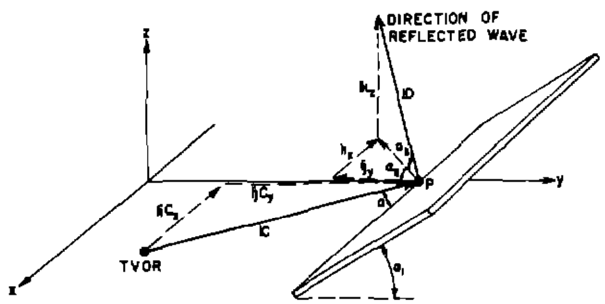


Fig 27 Measured Course-Scalloping Pattern Width as a Function of Distance



$\mathbf{C} = \mathbf{i}C_x + \mathbf{j}C_y$

$\mathbf{D} = \mathbf{i}x + \mathbf{j}y + \mathbf{k}z$

i j AND k ARE UNIT VECTORS IN THE x y AND z COORDINATE DIRECTIONS RESPECTIVELY

$x = C_x$ $\quad a_2 = \tan^{-1}\left|\frac{x}{y}\right|$

$y = C_y \cos 2a_1$

$z = C_y \sin 2a_1$ $\quad a_3 = \tan^{-1}\left(\frac{z}{\sqrt{x^2+y^2}}\right)$

THE CONDITIONS TESTED

DEGREES									DEGREES	
a_1	a	C_x	C_y	C	x	y	z	D	a_2	a_3
60	45	-0 707	0 707	1	-0 707	-0 354	0 613	1	63 5	37 8
90	45	-0 707	0 707	1	-0 707	-0 707	0	1	45	0

NOTE
THE DIRECTION OF THE OPTICALLY REFLECTED WAVE FROM POINT P ON THE SIMULATED HANGAR FACE IS DISPLAYED FOR AN ANGLE OF SLOPE a_1

CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS, INDIANA

Fig. 28 Determination of the Direction of a Wave Reflected From a Plane Surface

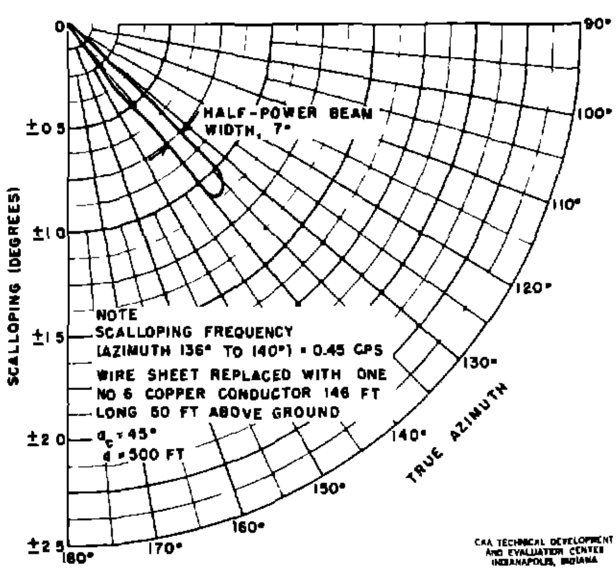


Fig. 29 Polar Plot of Scalloping Pattern

for the conditions tested, a_1 = 60° and = 90°, are tabulated. The values of a_2 and a_3 given in the table indicate that the region of scalloping due to the inclined surface will be at an azimuth 18 5° greater than with the surface vertical and at a large vertical angle, 37.8°. An aircraft would, therefore, receive a reflection from an inclined surface only by flying through the cone where the scalloping frequency may be so great that no scalloping would be observed on the CDI This was verified in flights made through this region.

Two tests were conducted with a horizontal No. 6 copper conductor in place of the simulated hangar face. The copper conductor was 146 feet long and 50 feet above the ground The angle to the center of the wire a_c was 45° for both tests The first test was with a distance of 2,000 feet between the wire and the TVOR antenna No scalloping was observed on a flight of 24 miles in radius The TVOR was moved in to 500 feet from the wire with the resulting scalloping pattern shown in Fig 29.

TESTS OF OBSTRUCTIONS NEAR THE ANTENNA

A proposal to construct and to evaluate a TVOR with the antenna very near the ground called for an immediate investigation of the minimum distance that the transmitter house could be located from the antenna without causing excessive course distortion. In order to keep the loss of power in the feed lines at a minimum and in order to obstruct less of the airport area, it is desirable to locate the transmitter house close to the antenna, however, any object in the region of the antenna may act as a reflector and may produce errors in the courses, the amplitudes of which will be an inverse function of the distance from the antenna to the object.

A four-loop, VOR antenna[10] was mounted on a counterpoise 9 feet in diameter and about 10 inches above the ground. During these tests, the antenna was located 50 feet north of the transmitter house. Various obstructions were moved around the array while the fluctuations of the CDI were recorded at 1,700 feet north. The most informative investigations were conducted

[10] Anderson, Keary, and Wright, op. cit

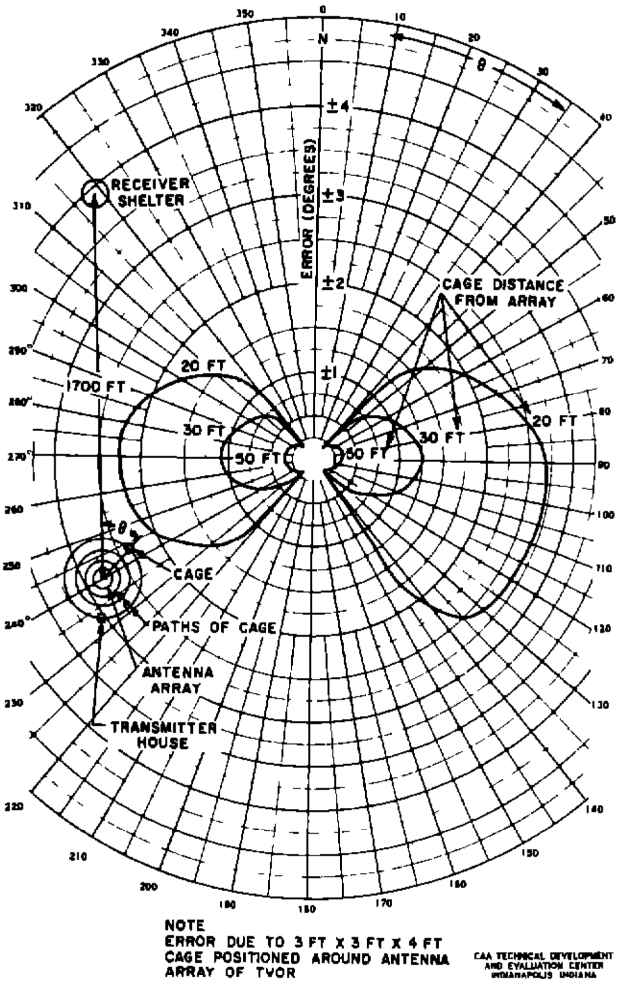


Fig. 30 Degrees of Error Due to Cage (a) Positioned Around Antenna Array of Low-Powered VOR

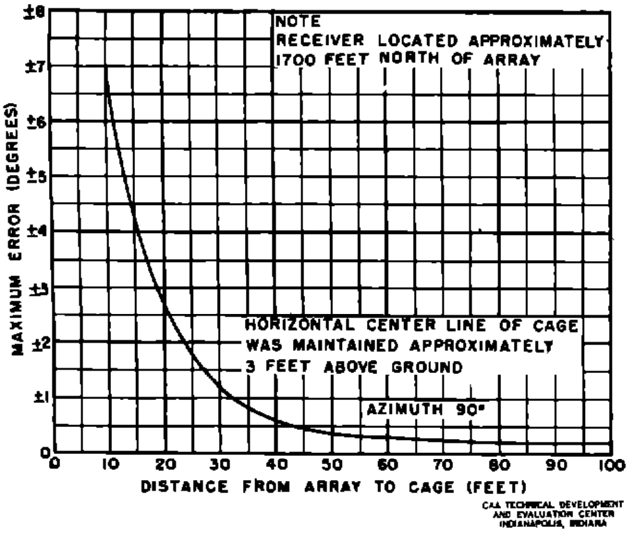


Fig 31 Curve Showing Maximum Error in the Pattern of the Low-Powered VOR Due to Cage (a) Positioned at Various Distances From the Array

with three wire-mesh cages (a) a rectangular cage measuring 3 feet long, 3 feet wide, and 4 feet high and made by wrapping a wooden frame with 1/2-inch-mesh, galvanized, hardware cloth, (b) a similar cage measuring 6 feet by 6 feet by 7 feet, (c) another similar cage measuring 6 feet by 6 feet by 4 feet, and (d) a Ford panel truck These objects could be easily moved around the antenna at a nearly constant rate, and they represented a progression in size from a small object of less than one-half wavelength to an object of more than two wavelengths

To determine the effect of the small cage (a), it was carried over a circular path around the array at various distances from the antenna and the course deviation was recorded The results of these tests are shown in Fig 30 For distances greater than 50 feet, the deviation was so small that it was not reliable and the results were not plotted These tests showed that the greatest course error occurred when the cage was east of the antenna at 90° azimuth A curve showing the error versus the distance from the antenna on the 90° course is shown in Fig 31

Cage (b) was moved around the antenna at a constant radius of approximately 55 feet The course deviation was recorded as before The error data obtained in this test are plotted in Fig 32 This pattern showed that the maximum error was to be found with the cage at about 45° azimuth from the antenna Because of the terrain difficulties, this test was made from 0° to 180° azimuth only, but other tests show that the pattern is nearly symmetrical with slightly lower errors occurring in the 180°-to-360° sector

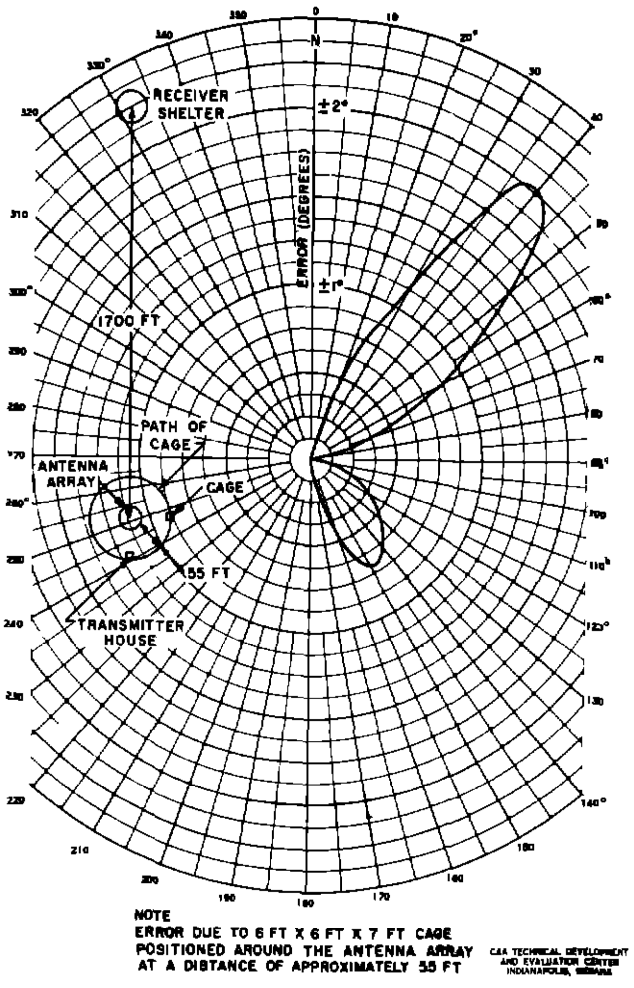


Fig 32 Error Due to Cage (b) Positioned Around the Antenna Array at a Distance of Approximately 55 Feet

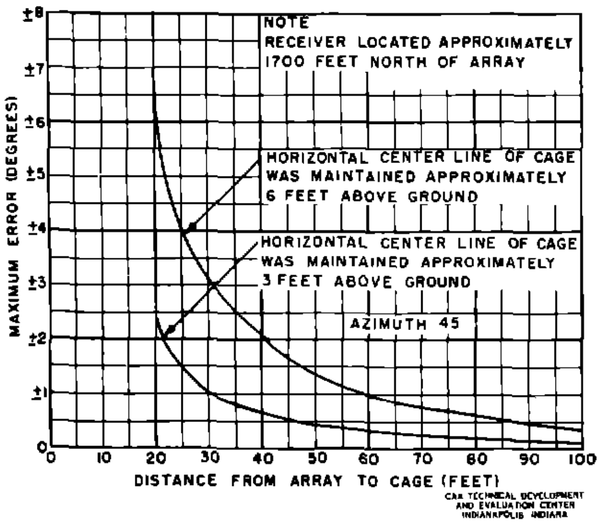


Fig 33 Curve Showing Maximum Error in the Pattern of the Low-Powered VOR Due to Cage (c) Positioned at Various Distances From the Array

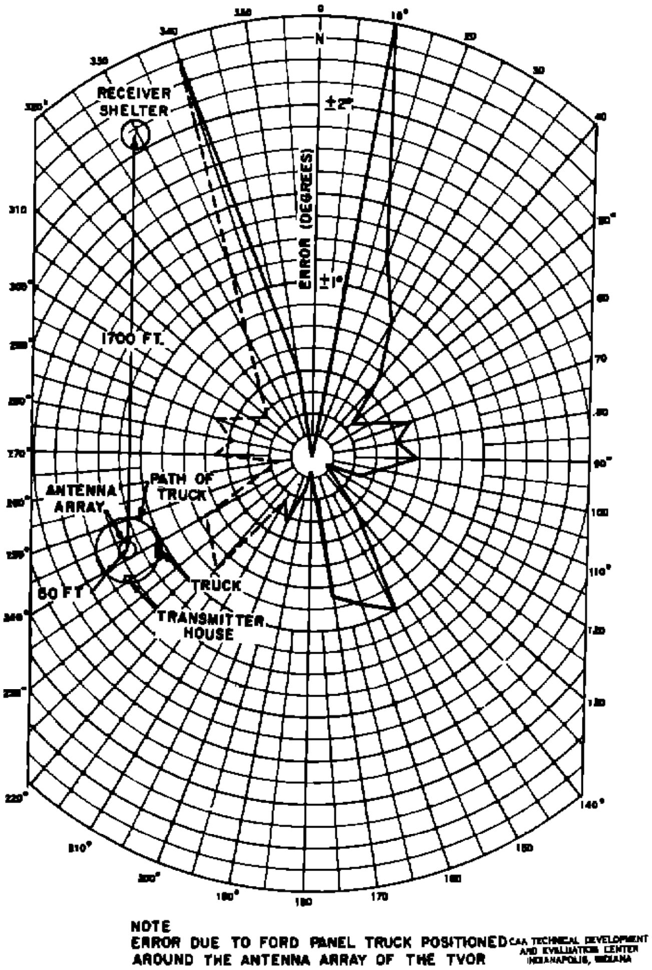


Fig. 34 Error Due to Ford Panel Truck Positioned Around the Antenna Array of the Low-Powered VOR

With this information about the azimuth of maximum error, the region from 0° to 90° was further explored by moving the cage around at various distances from the array in this quadrant. In order to determine the effect of the height above ground of the obstruction, cage (c), similar to cage (b) but measuring 6 feet by 6 feet by 4 feet, was used. The 0° - to -90° quadrant was explored at two different cage heights for various distances from the antenna. Fig. 33 shows the error data.

Similar tests were performed with the use of a large Ford panel truck instead of a cage. Several runs were made around the array at a radius of approximately 50 feet. The results of these runs are plotted in Fig. 34.

The effect of a dipole in the vicinity of the antenna was also checked. The dipole was held in a normal attitude to the radius and approximately eight feet above ground, and it was carried around at various distances from the antenna. The error was more than ± 4.5° for distances up to 25 feet. The 25-foot circle indicated an error of ± 4 5° with peaks occurring at the 45°-azimuth points and indicated a very low error at the four cardinal compass points.

The effect of rotating a cage was checked by placing it on the radius which gave the greatest error and then rotating it about its vertical axis. The small cage (a) was located on an 80° azimuth 20 feet from the antenna. Rotation showed about ± 0.3° variation in error. This procedure was repeated for the large cage (b) at 45° azimuth and 40 feet from the array. The variation in error as cage (b) was rotated was less than ± 0.2° Next, one side of the cage was removed and the afore-mentioned rotation was repeated. The cage was 30 feet from the antenna. The variation in error was approximately ± 1.1°.

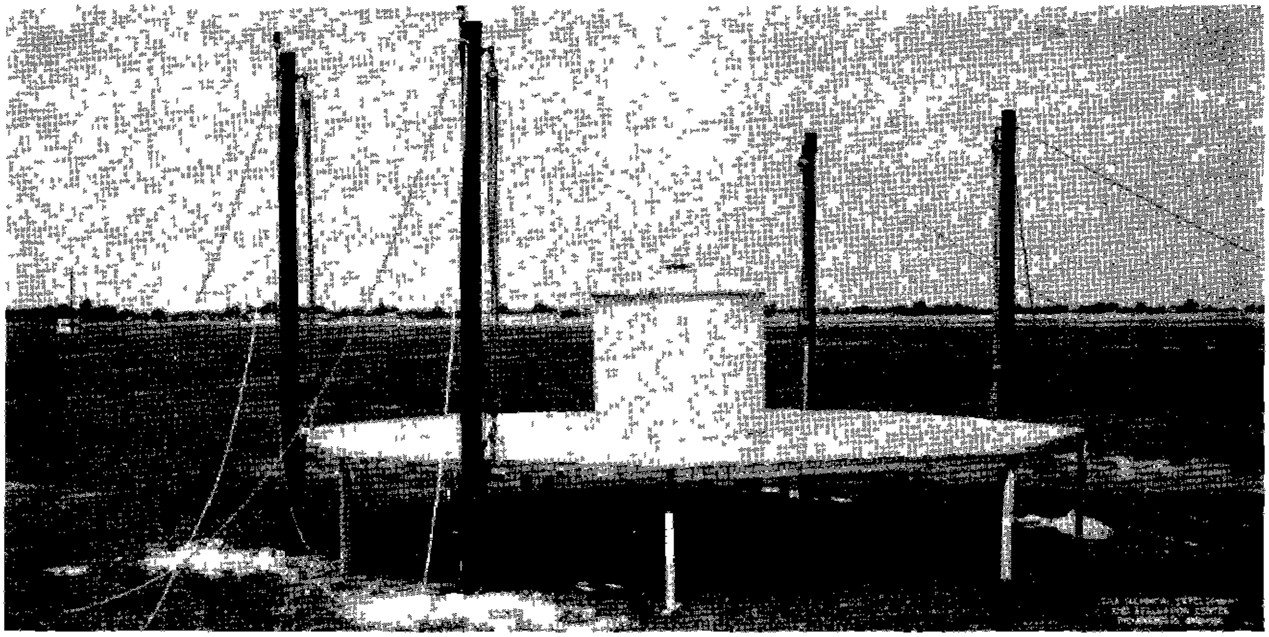


Fig 35 Installation for Adjustable Counterpoise

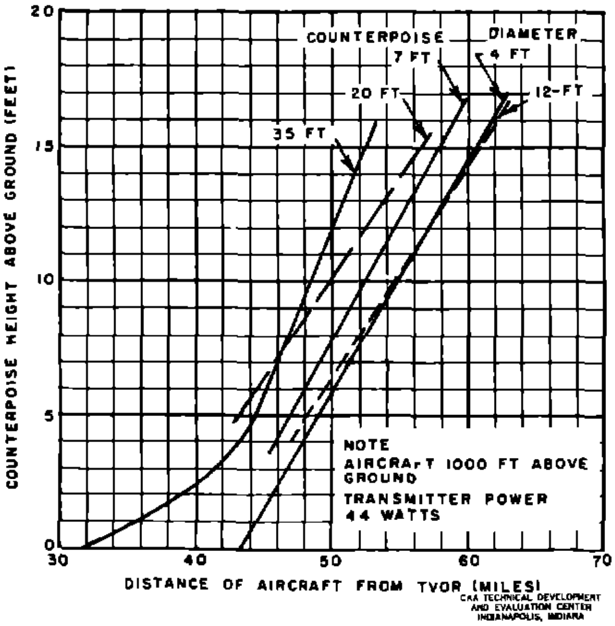


Fig 36 TVOR Distance-Range Variation With Counterpoise Height and Diameter

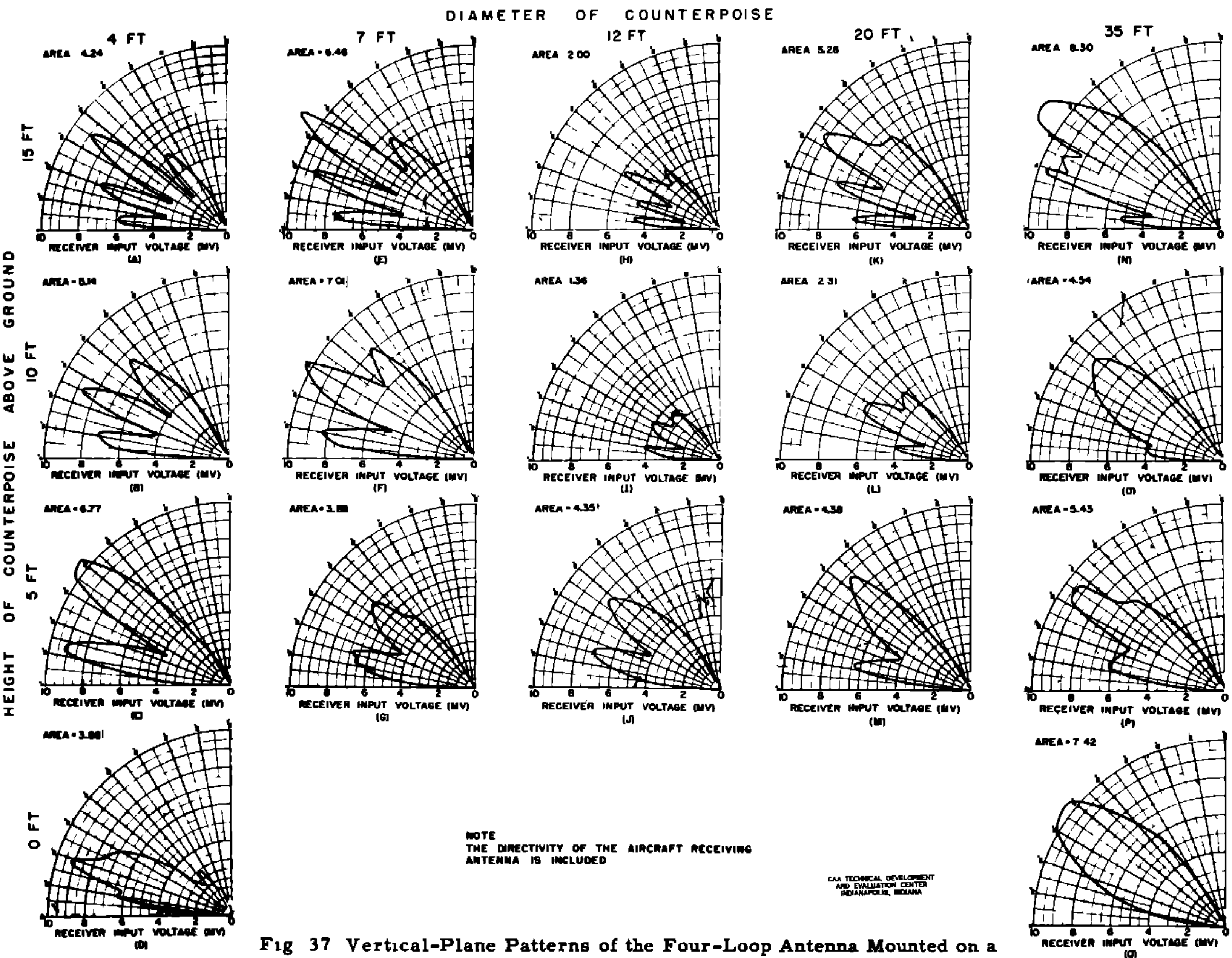


Fig 37 Vertical-Plane Patterns of the Four-Loop Antenna Mounted on a Counterpoise of Differing Heights and Diameters

Other tests were made with a single horizontal wire One end of the wire was anchored at a point 50 feet due east of the antenna and about 6 feet above ground. Its free end was held so that the wire was taut and horizontal. It was then rotated about this anchored point The length of the first wire was approximately 112 feet. This gave a maximum error of ± 1 5° when the wire was at an angle of 45° and aimed approximately northeast. As the wire was shortened to 50 feet, the error dropped to ± 1.2°. The error for a length of 28 feet was 1.1°, and for 10 feet it was 0.7°.

In addition to the previous tests, several flights were made, in one, cage (b) was raised 8 feet above ground, so that its top was 15 feet above the ground, and was placed directly south of and 44 feet from the antenna. This flight showed large-amplitude, low-frequency scalloping of approximately ± 6°. Several flights were made with only the transmitter house as the obstruction. When the house was 30 feet from the antenna, the error was barely noticeable on the recording, and at 50 feet, it was not noticeable at all.

COUNTERPOISE TESTS

During the development of the TVOR, a project was initiated to determine the characteristics of an omnirange using a counterpoise which had dimensions that could be varied. Discontinuous data resulted, although the measurements had been made from time to time on omnirange stations with the use of counterpoises of the following heights and diameters 30 feet high, 35 feet in diameter, 15 feet high, 35 feet in diameter, 10 feet high, 35 feet in diameter, 0 feet high, 35 feet in diameter, 15 feet high, 4 feet in diameter, 10 feet high, 12 feet in diameter, and 10 feet high, 9 feet in diameter Various sites were involved, thereby adding another variable to the already complex problem. It was decided that a round, solid, sheet-metal counterpoise should be supported on an adjustable wooden structure that would facilitate raising and lowering and on which the counterpoise size could be varied by cutting off successive outer rings.

Fig. 35 is a photograph of the equipment adjusted for a counterpoise 35 feet in diameter and 5 feet high. The four-loop antenna was sheltered in the central enclosure. The transmitting equipment was housed in a shelter on the ground and 50 feet from the antenna.

In the planning of this project, it was expected that the supporting wooden structure and its associated hardware (the maximum dimensions of which were held to 1/8 wavelength or less) would have a very minor effect on the radiated fields. However, measurements showed that this was not the case for vertically polarized components of radiation. Large polarization errors changing radically with the azimuth were found to result from the four vertical supporting poles shown in Fig. 35. All measurements of horizontally polarized fields are considered to be valid, however, because the field radiated by the supporting structure was found to be very small compared to the horizontally polarized field emanating from the antenna. Accordingly, the polarization-error data are excluded from this part of the report.

Flight tests were conducted for each condition of counterpoise height and diameter. The counterpoise diameter was varied in steps of 35, 20, 12, 7, and 4 feet. The counterpoise was place at the 5-, 10-, and 15-foot heights for each diameter of the counterpoise and at ground-level height for the 35-foot and 4-foot diameters only The flights made for each combination of counterpoise size and position consisted of (a) a distance-range flight at 1,000 feet altitude

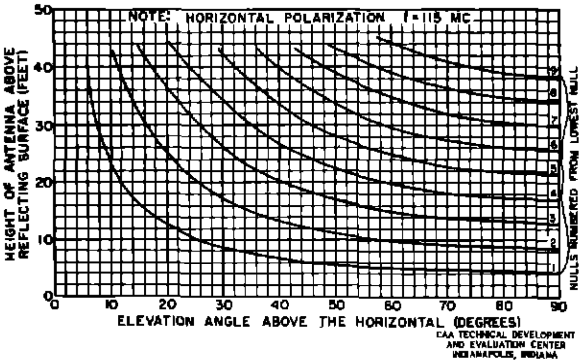


Fig. 38 Null Locations of an Antenna
Located Above Ground Level

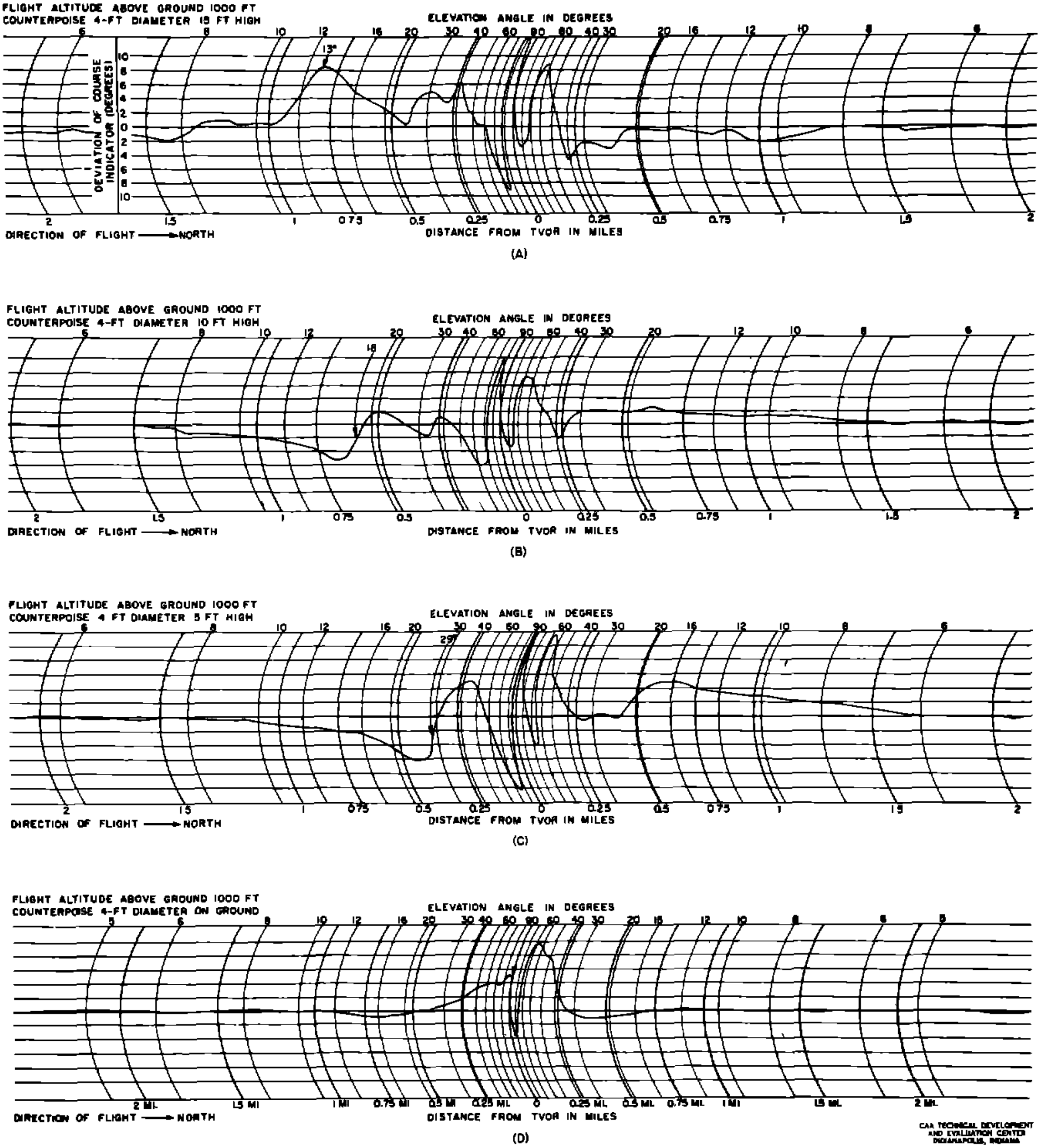


Fig. 39 CDI Movements of the Four-Loop Antenna Mounted on a Counterpoise of Varying Heights and Diameters

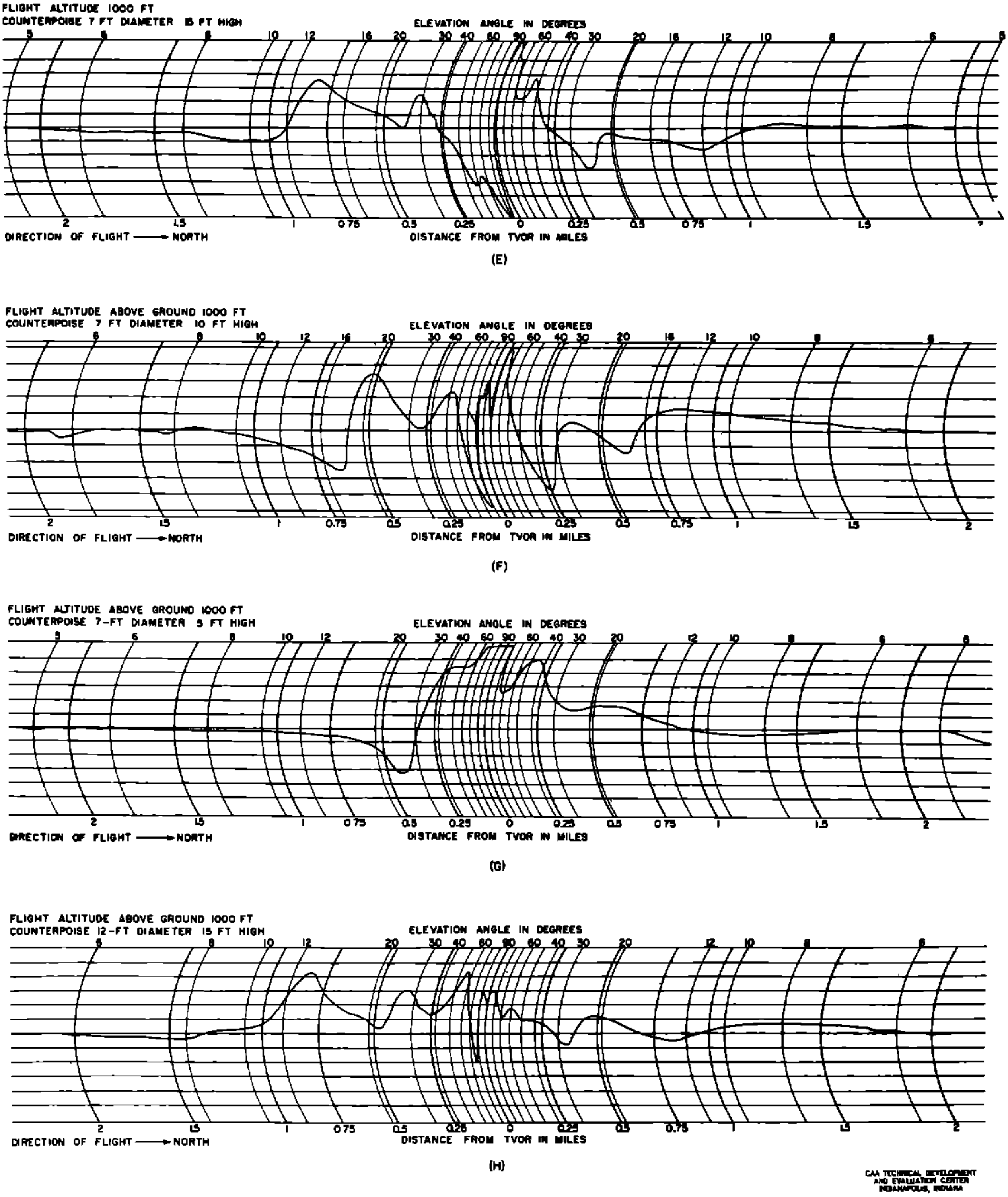
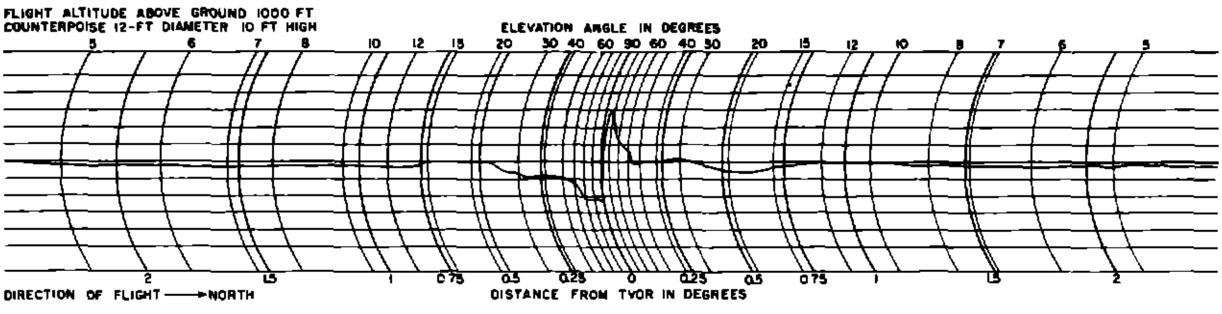
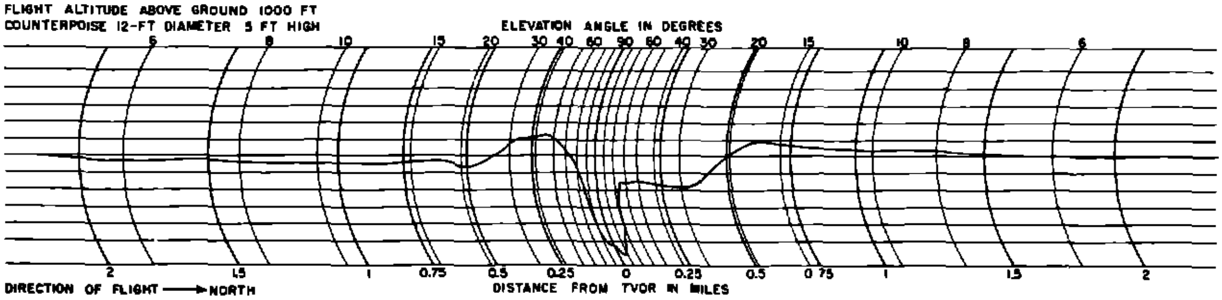


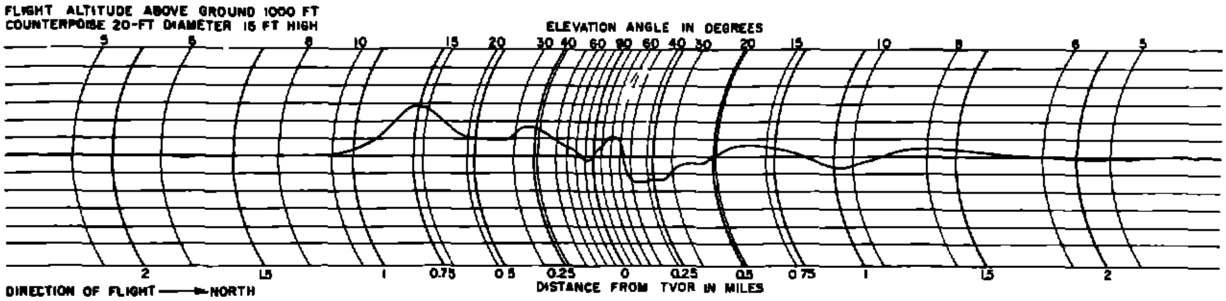
Fig. 39 (Continued) C D I Movements of the Four-Loop Antenna Mounted on a Counterpoise of Varying Heights and Diameters



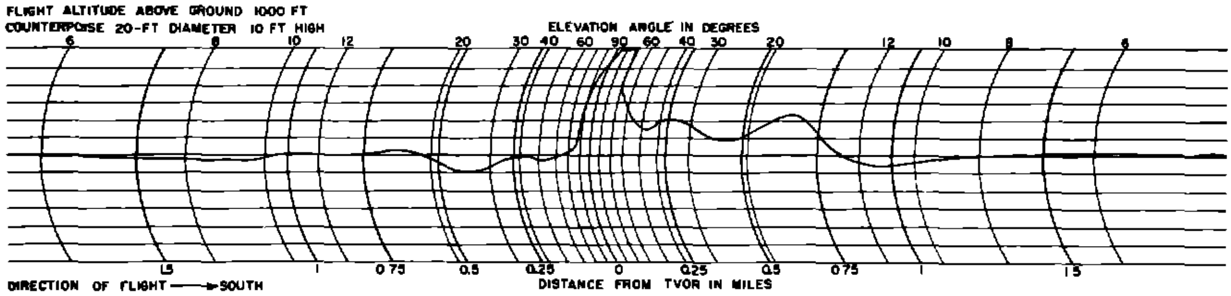
(I)



(J)



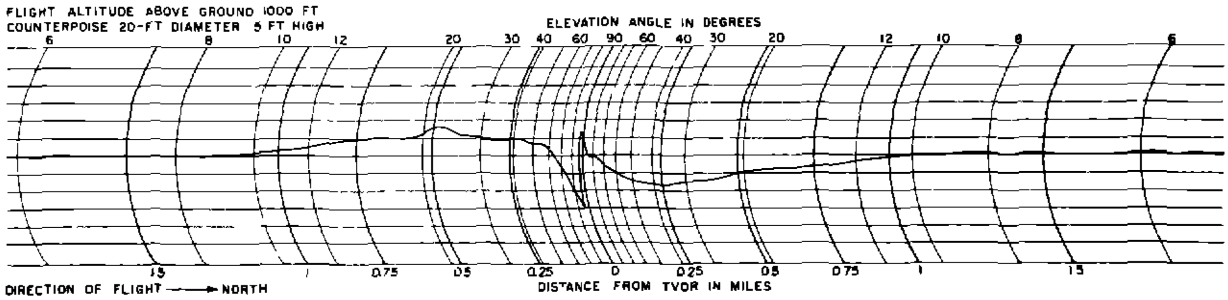
(K)



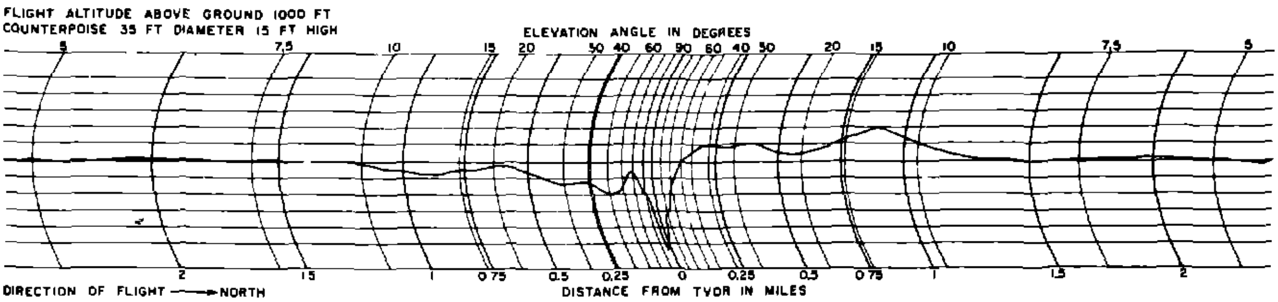
(L)

CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS, INDIANA

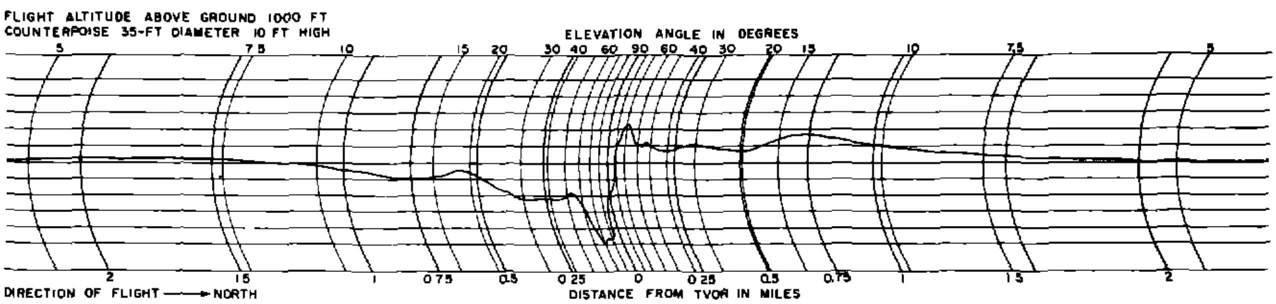
Fig. 39 (Continued) CDI Movements of the Four-Loop Antenna Mounted on a Counterpoise of Varying Heights and Diameters



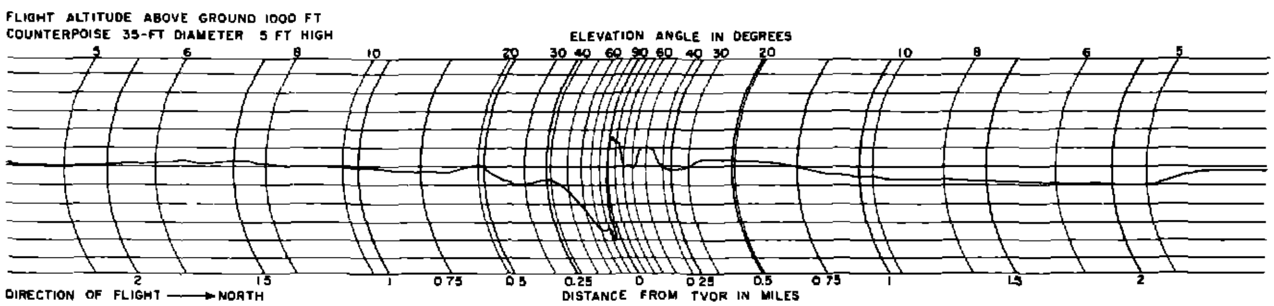
(M)



(N)



(O)



(P)

CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS INDIANA

Fig 39 (Continued) CDI Movements of the Four-Loop Antenna Mounted on a Counterpoise of Varying Heights and Diameters

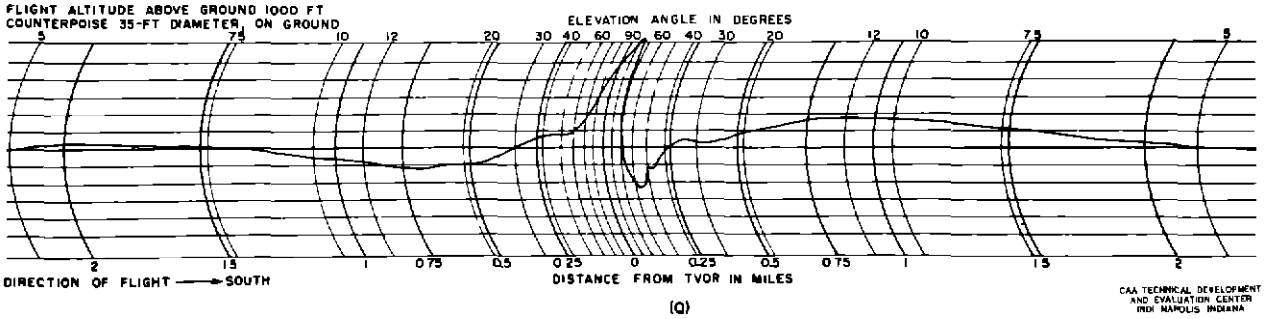


Fig 39 (continued) CDI Movements of the Four-Loop Antenna Mounted on a Counterpoise of Varying Heights and Diameters

above ground, (b) a flight with theodolite guidance over the station at 5,000 feet above ground to measure the cone characteristics, and (c) the first part of the distance-range flight, with theodolite guidance, out to an elevation angle of approximately 2° to derive the vertical-plane field patterns

Fig 36 shows the results of all the distance-range flights The distance range of a VOR facility is defined as that distance from the VOR, in statute miles, at which the course sensitivity, in degrees, becomes double the course sensitivity measured at approximately ten miles from the station The curves show that the distance range increases directly with the height and inversely with the diameter of the counterpoise with one exception, the 12-foot diameter One would expect a decrease in distance range with an increase in counterpoise diameter because with horizontal polarization the counterpoise (if infinite in extent) produces a wave which cancels the direct wave at low elevation angles Increasing the size of the counterpoise approaches the infinite counterpoise

The vertical-plane patterns plotted in Fig 37 are indicative of electric-field intensity variation with the elevation angle for a constant distance from the TVOR antenna When Fig 37B is compared with the calculated Fig 38, it is seen that the predicted null locations 17 5°, 38°, and 67 5° compare reasonably well with the null locations of the measured pattern It should be noted that, when Fig 38 is applied, four feet should be added to the counterpoise height to obtain the antenna height above ground When Fig 37 is followed from B to F, I, L, and O, it is apparent that the reflecting surface has gradually been changed from the ground to the counterpoise Upon reference to Fig 37O and upon the assumption that the antenna height above the reflecting surface is equal to its height above the counterpoise (four feet), Fig 38 predicts only one null at 90° The measured pattern shows a shallow null at 13° as well as the one at 90° This suggests that the counterpoise is still too small for low elevation angles A more complete study of the patterns of Fig 37 clearly indicates that the larger the counterpoise is, the more effectively the nulls are suppressed

Fig 39 indicates that the larger the counterpoise is, the better the cone is That cone distortions are associated with the nulls of the vertical-plane patterns is evident from Fig 39A, B, C, and D, for example, where the large deviation at an elevation angle of approximately 13° on Fig 39A may be identified on B, C, and D as moving progressively into a 90° elevation angle The arrows point to the calculated locations (taken from Fig 38) of the first null

The vertical-plane patterns of Fig 37 were used to obtain the voltages, shown in Fig 40, by taking the values of the receiver-input voltage at an elevation angle of 2 5° The readings were corrected by bringing the areas of the patterns to a common value so that they would be on an equal power and equal field-meter sensitivity basis Fig 40 shows the same trends as Fig 36, that is, Fig 40 indicates that the voltage at the input to the receiver is directly proportional to the counterpoise height and inversely proportional to the counterpoise diameter except in the case of the counterpoise which is 12 feet in diameter Both figures indicate that the 12-foot-diameter counterpoise will produce a distance range equal to or greater than that of any other diameter tested The reason for this unexpected result is unknown The correctness of the data for the counterpoise which is 12 feet in diameter may well be questioned The figures were taken on two consecutive days and in the same way as the other data Duct effect or propagation anomaly does not appear to be responsible, since it is unlikely that it would exist over the period of time necessary to obtain all data for counterpoises 12 feet in diameter and would not occur for the other diameters

GPO 807489 — 2

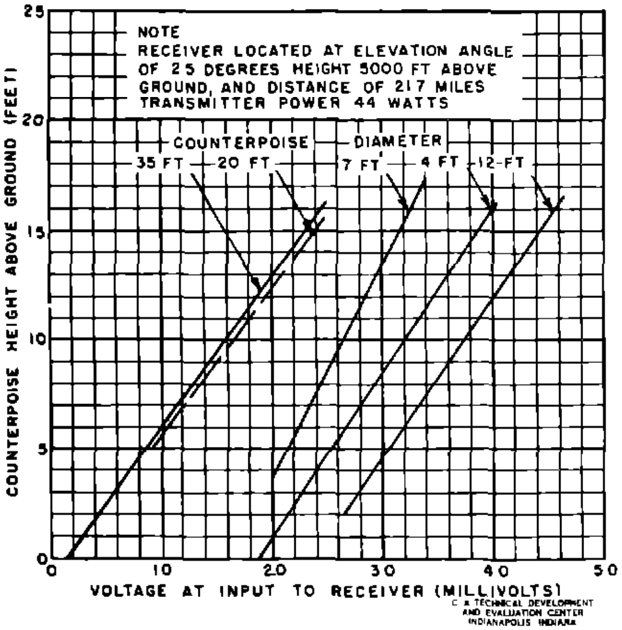


Fig. 40 Voltage Delivered to the Receiver by the Antenna for Various Counterpoise Heights and Diameters

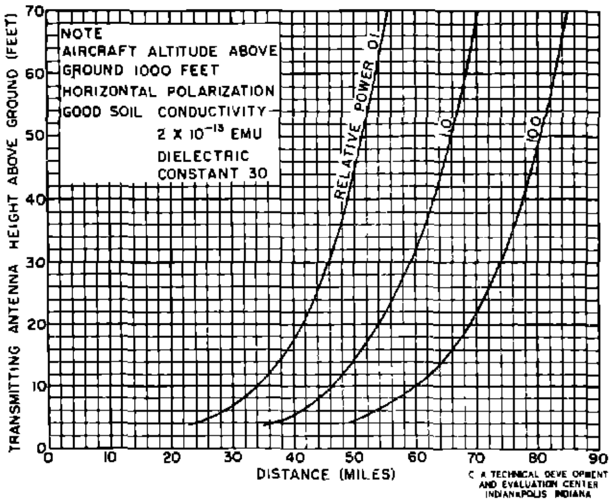


Fig 41 Calculated Distance Range as a Function of Transmitter Power and Transmitting-Antenna Height

The choice of the size and height for a TVOR counterpoise must therefore be a compromise between the conditions producing the greatest distance range and those producing the best cone characteristics A 12-foot diameter and a 10-foot height have been adopted for TVOR facilities. This arrangement is desirable also because it facilitates making the counterpoise the roof of the transmitter shelter. Heat from the transmitter shelter readily flows into the antenna shelter, thus reducing moisture problems. The CAA standard VOR stations, with their counterpoises 10 feet high and 35 feet in diameter, sacrifice range for improved cone characteristics The use of a 200-watt instead of a 50-watt transmitter makes up for the loss in distance range incurred by the use of a 35-foot-diameter counterpoise.

Several theoretically derived curves are included which display the relationships between power, transmitting-antenna height, and distance range. Fig 41 shows the relationship between

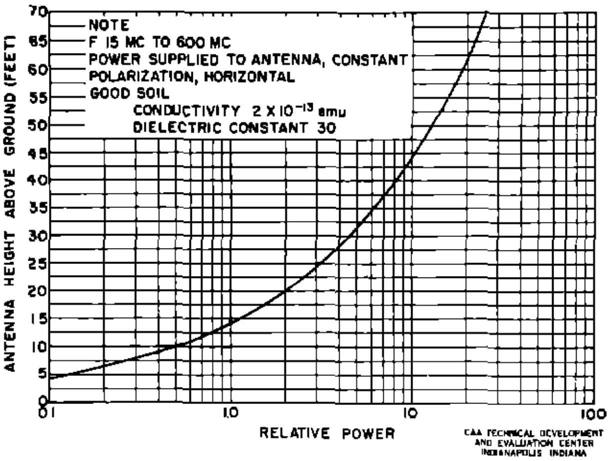


Fig. 42 Calculated Power Radiated by the TVOR at Low Elevation Angles Versus Antenna Height

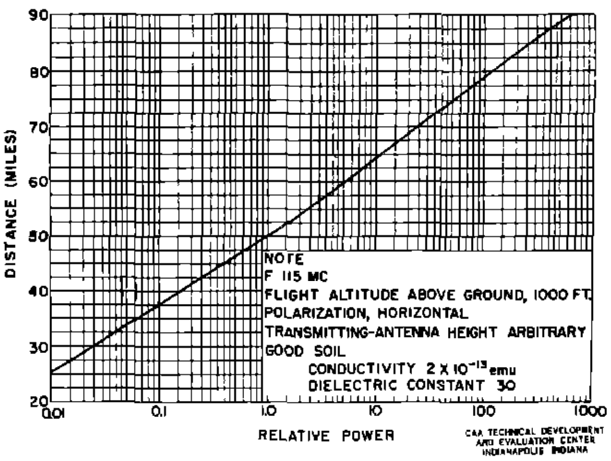


Fig 43 A Calculated Curve of the Power Required for a Specified Distance Range Vs. Distance From the TVOR

transmitting-antenna height and distance range with power as the parameter and may be compared with the measured data of Fig 36 Fig 42 indicates the power gain realized at small elevation angles because of an increase in transmitting-antenna height. If the power of a TVOR is changed, a resulting change in distance range will occur. Fig. 43 displays this situation. As an example, Fig 36 indicates that a counterpoise 10 feet high, 35 feet in diameter, and using a 50-watt transmitter will provide a distance range of 48.5 miles In Fig 43, 48.5 miles corresponds to a relative power of 0.76 A 200-watt transmitter will provide $0.76 \times \frac{200}{50} = 3.04$, and according to Fig 43, a relative power of 3 04 corresponds to 56.5 miles. The measured distance range for the VOR which uses a 200-watt transmitter is 56 miles.

CONCLUSIONS

On the basis of the flight tests conducted on TVOR installations at six airports in the United States and on the basis of the many special tests conducted at this Center, it is concluded that a TVOR located on an airport and adjacent to runway intersections can serve a very useful purpose by providing

1. Approach routes on designated radials to serve the various runways for almost straight-in approaches under existing procedures
2. Possible additional departure routes, depending on such factors as obstructions, amount of traffic, and terrain
3. Additional holding patterns in the immediate vicinity of the airport.
4. An extremely accurate fix The employment of the four-loop array in the TVOR allows the TO-FROM indicator actually to pinpoint the station on any on-course track
5. Courses to and from airports under all weather conditions, which fact will permit the establishment of precise routes for VFR operations and thus will reduce the IFR-VFR accident potential near airports
6. Radial information to pilots engaged in radar approaches This may reduce communications required for plan-position-indicator (PPI) approaches and will provide a check on radar navigation.

The TVOR is not to be regarded as a precision approach aid such as an instrument landing system (ILS), however, it offers more accuracy and more reliability under atmospheric static conditions and offers more ease of navigation and of orientation than any low-frequency or medium-frequency aid currently in use. It will provide guidance for aircraft descending under IFR conditions to minima (to be established), so that the aircraft will be in a position to land on a runway when the pilot establishes visual contact with the airport

The data obtained with regard to reflections from objects clearly indicate that precautions must be observed in siting the TVOR Small objects such as an automobile or a horizontal dipole close to the antenna can cause substantial bearing errors Distant objects such as buildings, overhead power lines, and other objects are capable of causing large course scalloping Scallopin of low enough frequency will result in bearing errors

It is recognized that a few airports may not be suitable as installation sites for the TVOR because of the surrounding terrain, the airport layout, and other contributing factors In these cases the TVOR can be installed adjacent to the airport at a location that will serve best under existing or proposed approach procedures

GPO 807489 — 1