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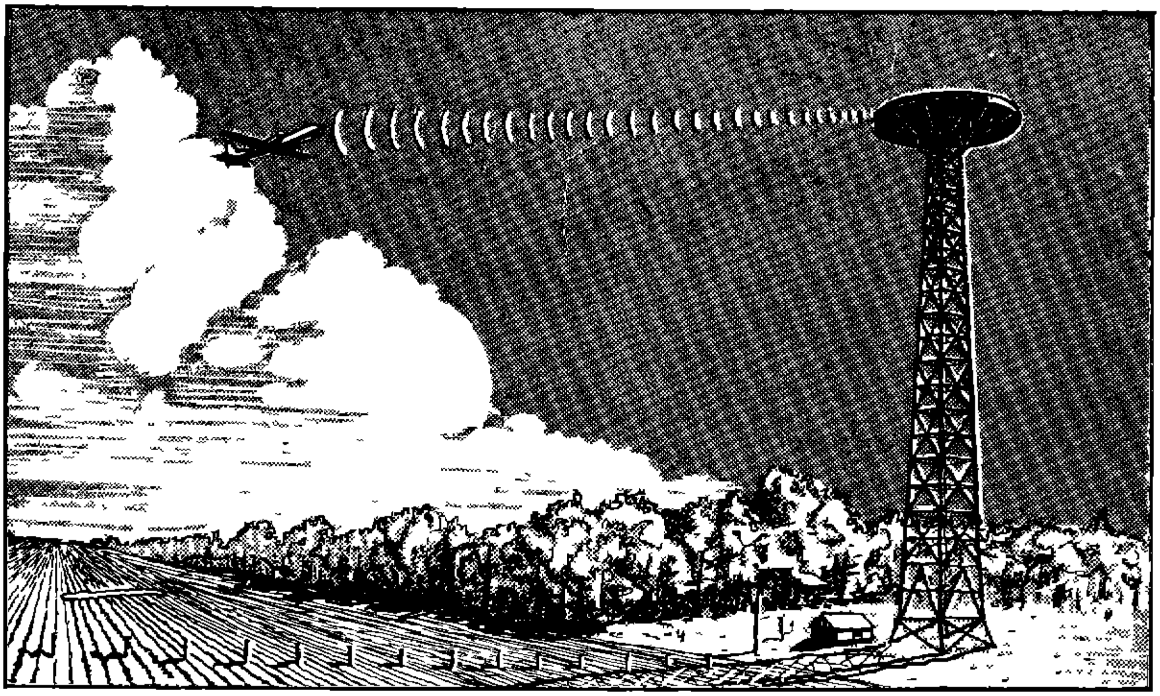

A REPORT ON

CHARACTERISTICS OF A VOR ON A 200-FOOT TOWER

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FINAL REPORT

CHARACTERISTICS OF A VOR ON A 200-FOOT TOWER

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This report is based on a technical evaluation of equipment and procedures available to the Bureau of Research and Development It has been reviewed by the Agency and is approved for distribution

A. C Packard
Acting Director
Bureau of Research and Development
Federal Aviation Agency

April 1960

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CHARACTERISTICS OF A VOR ON A 200-FOOT TOWER

SUMMARY

A mobile VOR station located in a cleared area 200 feet square at one corner of a heavily wooded site was flight tested. A maximum course scalloping of plus or minus 11 5° was recorded at a radius of 20 miles and an altitude of 1,000 feet Later, a VOR antenna was erected on a 200-foot tower with a 60-foot-diameter counterpoise Similar flight tests indicated a scalloping maximum of plus or minus 0 5°. A 20-mile-radius orbital flight in the first null (1 2°) produced scalloping of plus or minus 6° maximum. The distance range, for a receiver input signal of 5 microvolts, varied from 63 miles at 300 feet altitude to 175 miles at 9,000 feet altitude.

It is shown that with an antenna 200 feet above ground, while there still are objectionable course bends in the nulls of the vertical plane radiation pattern, the detrimental effect of the site on VOR performance was reduced at low elevation angles, and the low-altitude coverage was extended This type of installation should be useful in heavily wooded terrain where a suitable site cannot be obtained for the installation of a more conventional station.

INTRODUCTION

During the establishment of the VHF omnirange system (VOR), two major problems have been (1) the provision of sufficient low-altitude coverage due to the inherent line-of-sight propagation, and (2) the extensive site preparation required, including removal or replacement of wire fences, and removal of trees and other obstructions

The Air Coordinating Committee on April 20, 1955, recommended to the Air Navigation Development Board that a project be initiated to improve the low-altitude coverage and minimize site preparation of VHF omnirange stations This project was assigned to the CAA Technical Development Center, Indianapolis, Ind

This report includes results of tests conducted with a mobile VOR station having an antenna 14 feet high, compared with the results obtained when the antenna was erected on a tower 200 feet high with a counterpoise 60 feet in diameter. Both VOR's were tested at the same heavily wooded site which had negligible preparation.

SITE AND EQUIPMENT

The site was a large wood with trees 60 to 75 feet tall, occupying an area 0.4 by 0 75 mile A topographic map of the site is shown in Fig. 1.

A mobile VOR station, having a transmitter power of 50 watts, and an Alford slotted-cylinder antenna, mounted on the truck with a counterpoise 14 feet high and 12 feet in diameter, was used in the preliminary tests A view of the mobile VOR in the center of the 200-foot-square cleared area is shown in Fig. 2

For the high-tower tests, a 200-foot tower was modified to support a counterpoise 60 feet in diameter The counterpoise was covered with Robertson Q-flooring. A standard four-loop VOR antenna[1] and Fiberglas dome were installed at the center of the counterpoise. Two views of the tower and woods are shown in Figs 3A and 3B

Flight observations were made in a DC-3 aircraft equipped with Collins Type 51R-3 navigation receivers and Esterline-Angus graphic recorders to record the operation of the course deviation indicator (CDI). A 51R-1 receiver was converted into a linear field strength meter and used to obtain data for plotting vertical-plane field patterns

TESTS

An area 200 feet square was cleared in the southeast corner of the woods, and the mobile VOR was located at the center of the clearing for preliminary flight tests in order to obtain data for the site with negligible preparation. A maximum scalloping of plus or minus 11.5° was recorded on a 20-mile orbital flight at 1,000 feet altitude. This is shown in Fig. 4. The least scalloping was observed in a direction directly through the woods on the 340° radial. This improvement in scalloping may have been due to the fact that the trees were symmetrically disposed on either side of the course, which cancelled the reflections containing both "left" and "right" information. This theory was borne out in later tests, after erection of the tower The largest scalloping amplitude was measured on the north course because most of the reflecting trees were west of the course which reradiated westerly signals Figure 5 shows recordings obtained on radial flights in which course bends occur with amplitudes of 5 1/2° on the 90° radial and 5 0° on the 270° radial. The long-period bends are characteristic of reflecting objects close to the VOR station.

Following these tests, a tower 200 feet high with a counterpoise 60 feet in diameter was erected. A preassembled four-loop antenna mounted on a standard array plate was installed on the tower. Operation was initiated using a 50-watt transmitter. An east-to-west radial flight showed a great improvement in close-in performance when compared with the mobile VOR. This recording is shown in Fig. 5 also The 204-foot height of the transmitting antenna and the shadowing effect of the counterpoise combined to increase the ratio of direct to reflected signal at the aircraft and reduce the amplitude and period of the course bends and scalloping as the cone was

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

approached. A 20-mile orbital flight at an altitude of 1,000 feet indicated a large reduction in scalloping, that is, a maximum of plus or minus 1.0° The data from this flight are plotted in Fig 4.

Two 20-mile calibration circles were flown after the transmitter power was increased to 200 watts These data are plotted in Fig 6 The first circle was at 1,000 feet above ground in the lower lobe of the vertical plane radiation pattern, and the system error was plus or minus 1 05°. A scalloping of plus or minus 0 5° was the maximum recorded. The second circle was at 2,200 feet above ground in the calculated first null at 1.2° elevation angle. A maximum scalloping of plus or minus 6° was recorded in an easterly direction, where the aircraft actually was in the null, while considerably lower errors were encountered on the west side of the station where the null was not at the calculated position due to terrain irregularities The system error was plus or minus 0 9°.

During the course of flight tests, it was noted that the scalloping in the nulls did not always repeat in amplitude or shape on successive flights. Since the second null was the worst, a more thorough investigation was conducted near the 90° radial at a distance of approximately 40 miles and 9,000 feet above ground. Five radials were flown in each direction about 2° apart while using both hatch- and tail-mounted aircraft antennas The recorded scalloping varied from minus 19 4° to plus or minus 2.5° Figure 7 is a plot of the data from this test

The distance range of the 200-foot VOR was considerably greater than that of a VOR using a standard 10-foot-high counterpoise, as may be seen in Fig 8

A detailed investigation of scalloping was conducted on eight radials with particular emphasis on the field strength in the nulls and the resultant course scalloping. The automatic volume control action was sufficient to prevent a CDI disturbance due to a drop in signal strength alone, and there was only general correlation between the depth of the null and the scalloping recorded due to the differences in terrain and tree locations on the radials tested Figure 9 shows the scalloping on the radials in relation to the station and immediate woods It can be seen from this figure that the best VOR course, 270°, was obtained because the ground was sufficiently rough to prevent the formation of deep nulls in the vertical plane pattern The next best course was the 315° radial directly through the woods, where the extent of the trees causing the reflections was "balanced" about the course being flown The roughest course was the 90° radial where the trees to the north of the VOR caused r-f energy containing quadrature azimuth information to reflect into the deep nulls of the vertical plane pattern

Detailed graphs of these radials showing data taken at 1,000 and 5,000 feet above ground are presented in Fig 10. The theoretical locations of the nulls are shown on the graphs The correlation with actual nulls was quite good on those radials where the ground was level for 1 mile from the station. For example, Fig 10D shows the points of maximum scalloping at slightly lower angles than the theoretical The ground slopes downward at 135° azimuth, and the effect is that of a taller tower in that direction.

Vertical plane patterns on five radials are shown in Fig. 11 in both polar and rectangular coordinates These data were obtained using a tail-V aircraft antenna on an outbound heading in order to minimize possible proximity effects of the aircraft Variations in the depths of nulls on the same radial occur because of variations in roughness and tree growth at the point at which the r-f energy causing the interference strikes the ground.

Figure 12 shows a comparison of field strength and scalloping in the nulls on five selected radials There is a fair correlation between null depth and scalloping in the null, although there are several examples where negligible scalloping occurs in the deeper null.

THEORETICAL CONSIDERATIONS

A theoretical study is necessary to understand the characteristics of the VOR antenna atop the 200-foot tower. Although a counterpoise 12 feet in diameter was used at a height of 10 feet, and a counterpoise 60 feet in diameter was used at a height of 200 feet, the mathematics assumes no counterpoise. This assumption simplifies the analysis and appears to be justified for low elevation angles A perfect earth is assumed

Figure 13 shows a diagram of the situation studied, wherein the VOR antenna is h_o above a perfect flat earth, the reflecting object is h_1 above ground, and D is the distance between antenna and reflector The reflecting object for simplicity is assumed to be effectively located at one point. The waves travel to the aircraft from the two sources at elevation angle θ The amplitude of the VOR course scalloping, S, may be expressed by[2]

$$S = \frac{K_3 D_2 f(a) \, \mathrm{Sin}\left(\frac{2\pi}{\lambda}\frac{h_o h_1}{D}\right) \, \mathrm{Sin}\left(\frac{2\pi h_1}{\lambda}\,\mathrm{Sin}\,\theta\right)}{D_1 D \, \mathrm{Sin}\left(\frac{2\pi h_o}{\lambda}\right) \mathrm{Sin}\,\theta} \qquad (1)$$

where

S = amplitude of VOR course scalloping

D_1 = distance from the reflector to the aircraft

[2] S R Anderson and H F Keary, "VHF Omnirange Wave Reflections from Wires," Technical Development Report No 126, May 1952, Equation (8), p 8.

D_2 = distance from VOR antenna to aircraft

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

$f(\alpha)$ = a function of the reflecting object and the azimuth angle.

In the present application, $f(\alpha)$ is constant since the azimuth angle and reflecting object are held unchanged S is the course scalloping for a given height h_o of the VOR antenna above ground The course scalloping associated with a different VOR antenna height, h_o', above ground may be designated by S'. Thus

$$S' = \frac{K_3 D_2 f(\alpha) \, \mathrm{Sin}\left(\frac{2\pi}{\lambda} \frac{h_o' h_1}{D}\right) \mathrm{Sin}\left(\frac{2\pi h_1}{\lambda} \, \mathrm{Sin}\, \theta\right)}{D_1 D \, \mathrm{Sin}\left(\frac{2\pi h_o'}{\lambda} \, \mathrm{Sin}\, \theta\right)} \qquad (2)$$

Combining Equations (1) and (2)

$$\frac{S'}{S} = \frac{\mathrm{Sin}\left(\frac{2\pi}{\lambda} \frac{h_o' h_1}{D}\right) \mathrm{Sin}\left(\frac{2\pi h_o}{\lambda} \, \mathrm{Sin}\, \theta\right)}{\mathrm{Sin}\left(\frac{2\pi h_o'}{\lambda} \, \mathrm{Sin}\, \theta\right) \mathrm{Sin}\left(\frac{2\pi}{\lambda} \frac{h_o h_1}{D}\right)} \qquad (3)$$

The conditions of the high-tower tests may be applied to Equation (3) by letting $S' = S_{204}$ = amplitude of VOR course scalloping with the VOR antenna 204 feet above ground. Also, $S = S_{14}$ = amplitude of VOR course scalloping with the VOR antenna 14 feet above ground

h_o' = 204 feet

h_o = 14 feet

= 8.56 feet

Thus

$$\frac{S_{204}}{S_{14}} = \frac{\mathrm{Sin}\left(8{,}580^\circ \frac{h_1}{D}\right) \, \mathrm{Sin}\,(589^\circ \, \mathrm{Sin}\, \theta)}{\mathrm{Sin}\left(589^\circ \frac{h_1}{D}\right) \mathrm{Sin}(8{,}580^\circ \, \mathrm{Sin}\, \theta)} \qquad (4)$$

Figure 13 is a plot of Equation (4) for two values of the parameter $\frac{h_1}{D}$ It is evident from Fig 13 that the course scalloping decreases upon raising the VOR antenna from 14 feet above ground to 204 feet at elevation angles of 0° to 1.05° and 1 45° to 2.05° for $\frac{h_1}{D} = 0\ 025$ Much flying takes place in the airspace below 1° where a substantial improvement in scalloping is realized for $\frac{h_1}{D} = 0\ 025$

Figure 14 is another plot of Equation (4) where the parameter θ equals 0 613° This shows that when $\frac{h_1}{D} < 0\ 01$, an improvement in relative course scalloping results

The significance of Figs 13 and 14 may be obtained by reference to the actual high-tower VOR site The site consists primarily of trees 60 to 75 feet high. It can be shown that the upper portion of reflecting objects contributes most to the VOR course scalloping For this analysis, let h_1 = 50 feet From Fig 14, it can be seen that the scalloping remains constant as the VOR antenna is raised from 14 feet to 204 feet for trees 5,000 feet from the VOR ($\frac{h_1}{D} = 0\ 01$) For trees from 227 feet to 2,941 feet, the course scalloping is reduced approximately two thirds. For trees at greater distances than 5,000 feet, the course scalloping increases to a maximum of 1 6 times that for a 14-foot-high VOR It is important to point out that experience has shown that trees beyond approximately 3,000 feet from the VOR cause negligible scalloping.

Applying the 50-foot tree reflector to Fig. 13, the $\left(\frac{h_1}{D} \leq 0\ 002\right)$ curve may be though of as a curve for $D \gtrsim 25{,}000$ feet, a distance too great to cause perceptible effects on the VOR course scalloping The $\left(\frac{h_1}{D} = 0\ 025\right)$ curve applies for D = 2,000 feet when the reflecting object is 50 feet high VOR course scalloping is experienced from reflectors at this distance. The infinite values of VOR course scalloping, which occur theoretically at 1.2°, 2.4°, 3.6°, and so forth, are explained by the term $\sin(8{,}580° \sin \theta) = 0$ of Equation (4). Equation (4) in this way takes into account the nulls in the vertical plane field pattern of the 204-foot VOR antenna.

CONCLUSIONS

The tests of a VOR on the 200-foot tower have shown that·

1 The largest course scalloping appears in the nulls of the vertical plane field pattern.

2 The counterpoise is very effective in providing straight courses at elevation angles between 7° and 65°, thus permitting guidance when flying over the VOR.

3. This type of installation could be used in rough, heavily wooded terrain where a suitable site cannot be obtained for a more conventional VOR. However, this facility would not meet flight inspection requirements in the nulls between 1° and 7°.

4. While there still are objectionable course bends in the lower nulls of the vertical plane pattern, the effects of a detrimental site have been reduced at low elevation angles, and the low-altitude coverage has been extended very substantially. For example, the distance range has been increased 70 per cent at an altitude of 500 feet.

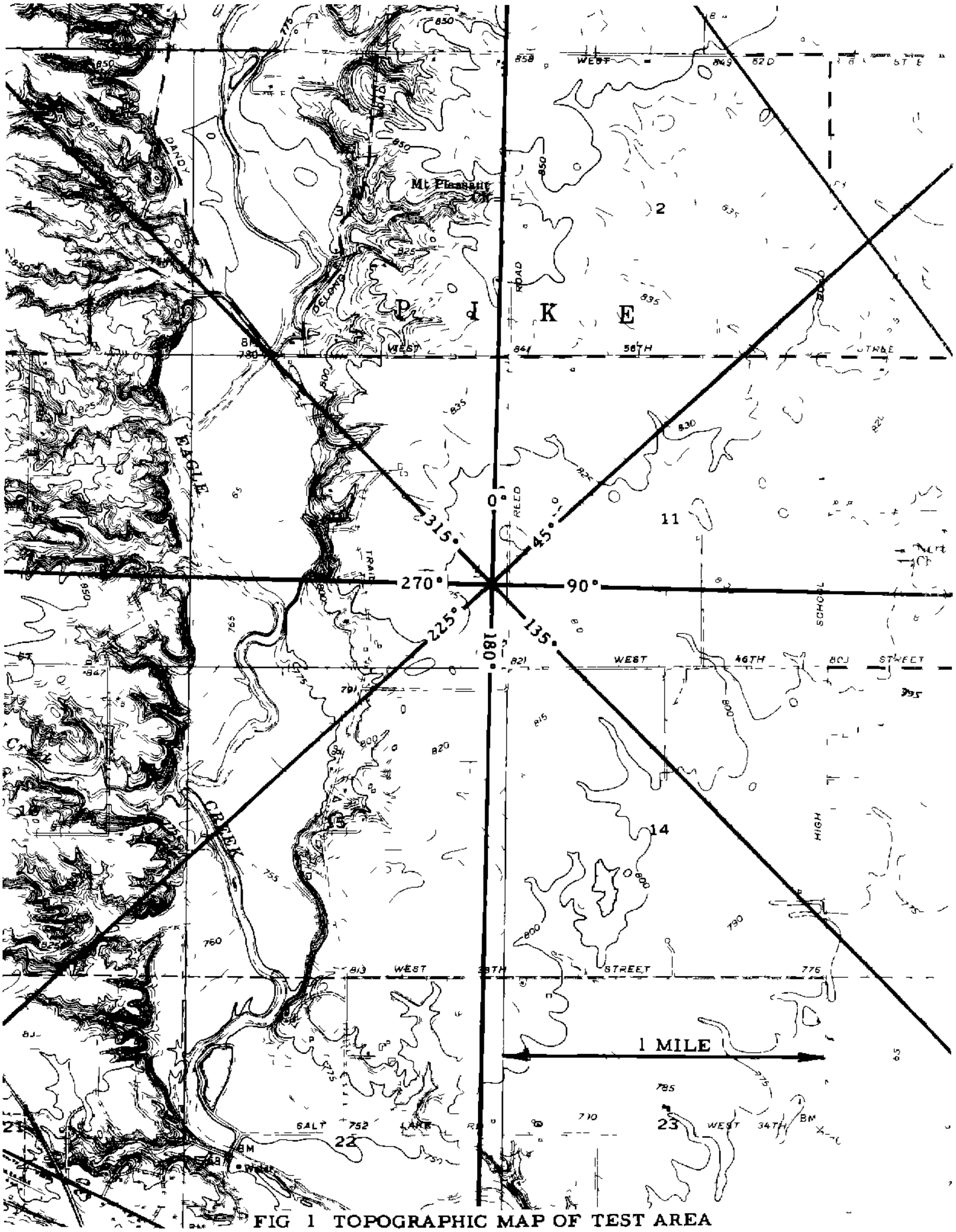


FIG 1 TOPOGRAPHIC MAP OF TEST AREA

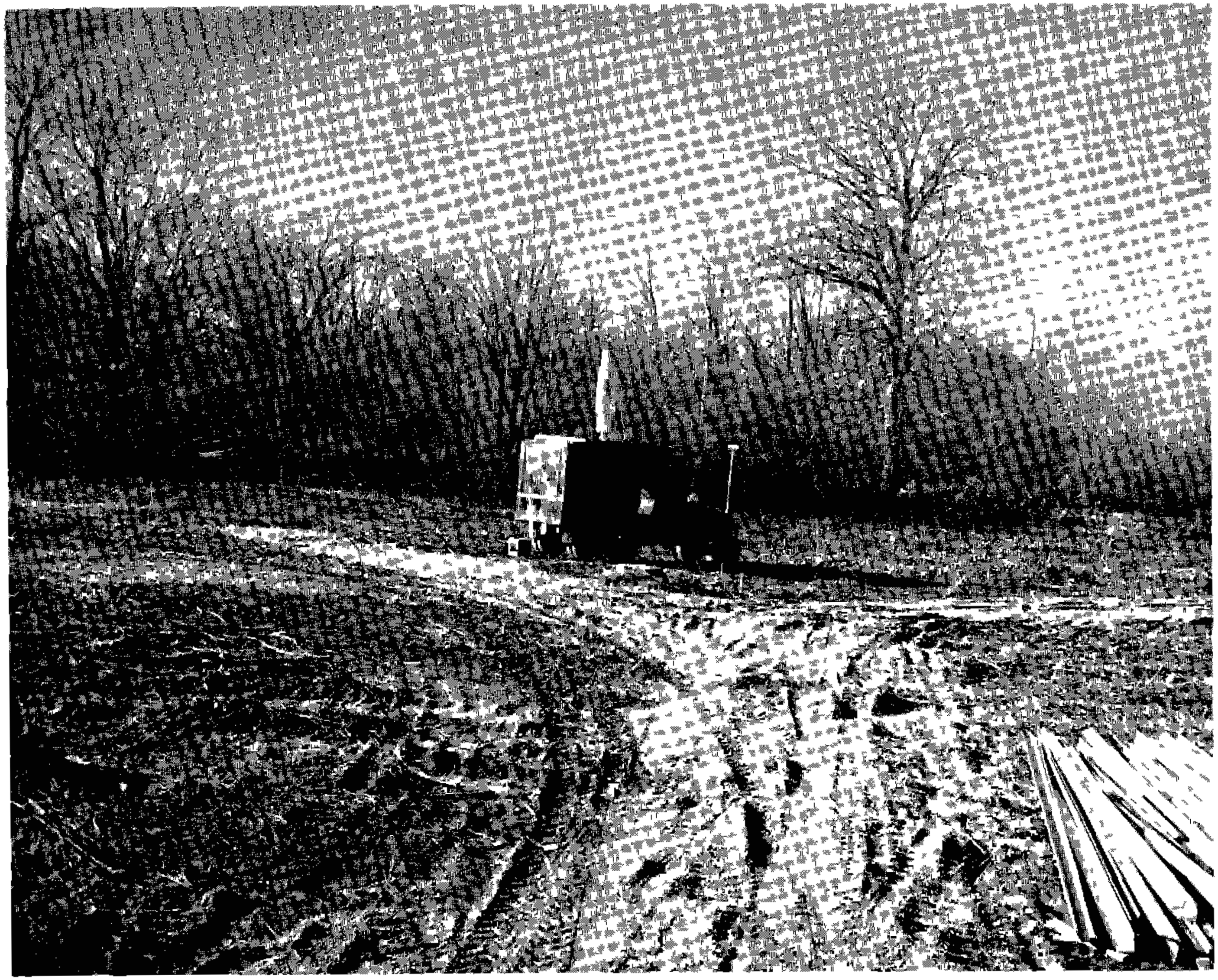


FIG. 2 MOBILE VOR IN CENTER OF CLEARED AREA

FIG 3A VIEW OF TOWER AND WOODS LOOKING NORTHWEST

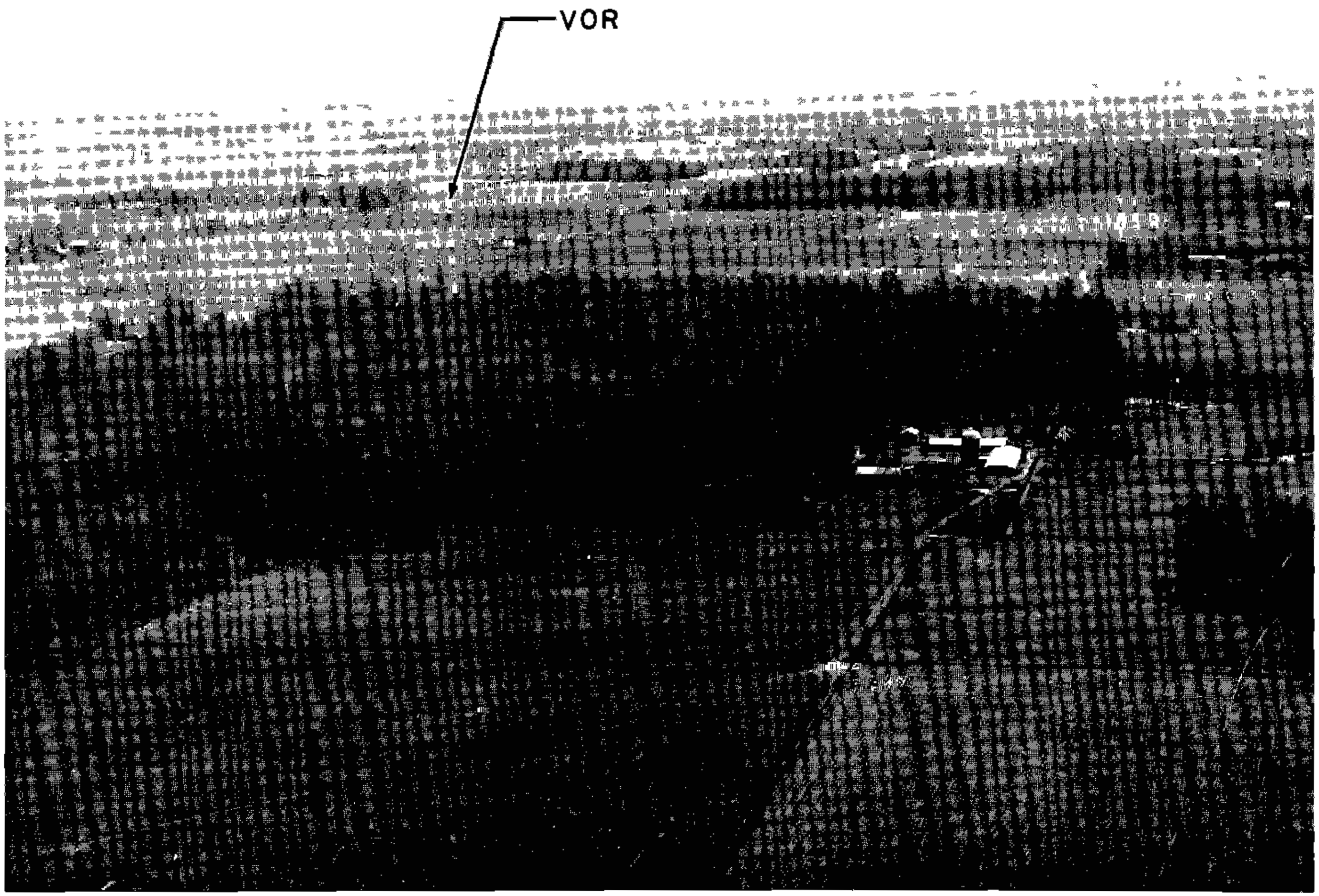


FIG 3B VIEW OF TOWER AND WOODS LOOKING SOUTHEAST

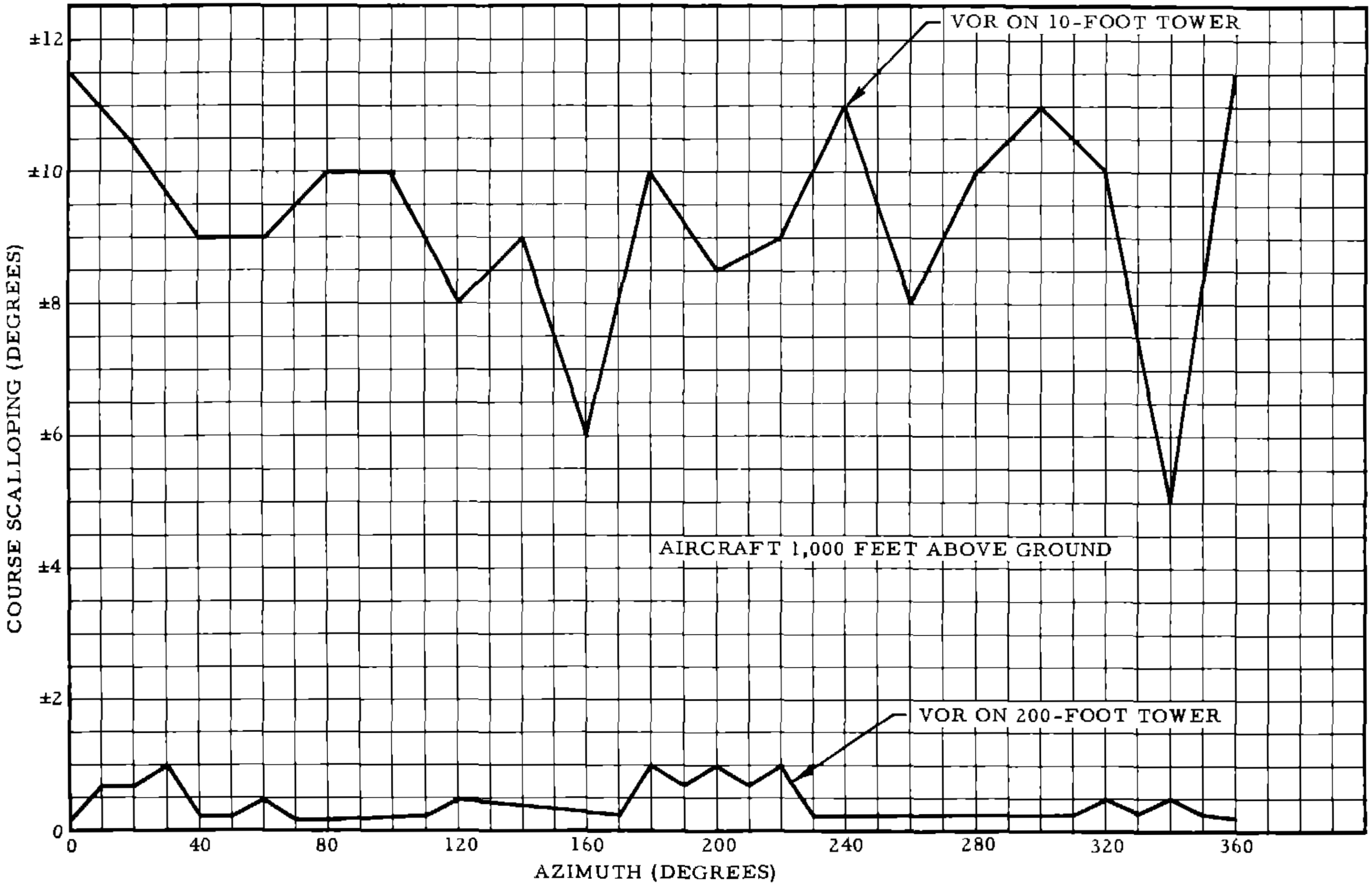


FIG 4 COURSE SCALLOPING ON A 20-MILE ORBIT FLIGHT WITH VOR ON 10- AND 200-FOOT TOWERS

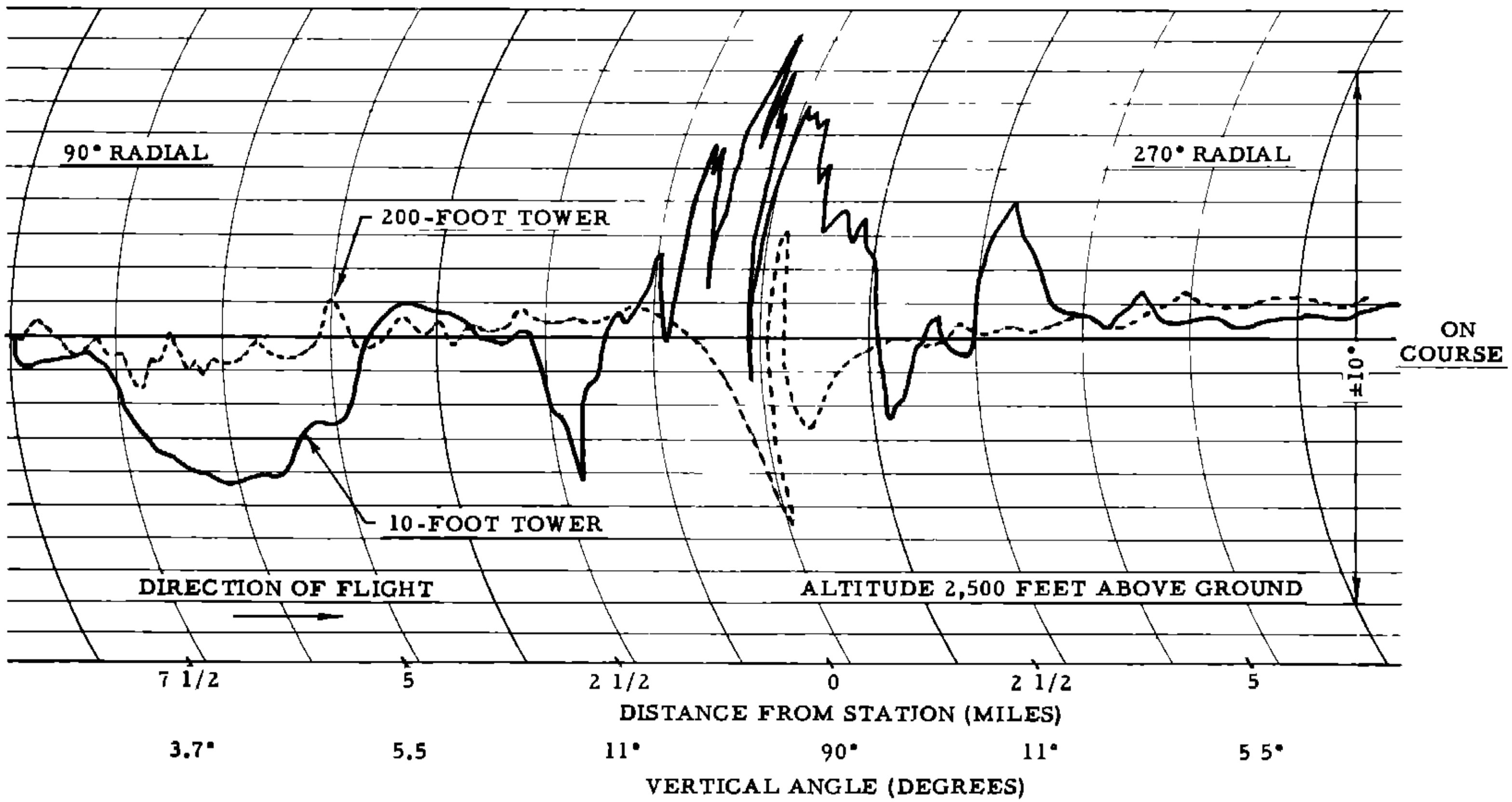


FIG 5 RECORDINGS OF CDI CURRENT ON EAST TO WEST RADIAL FLIGHTS

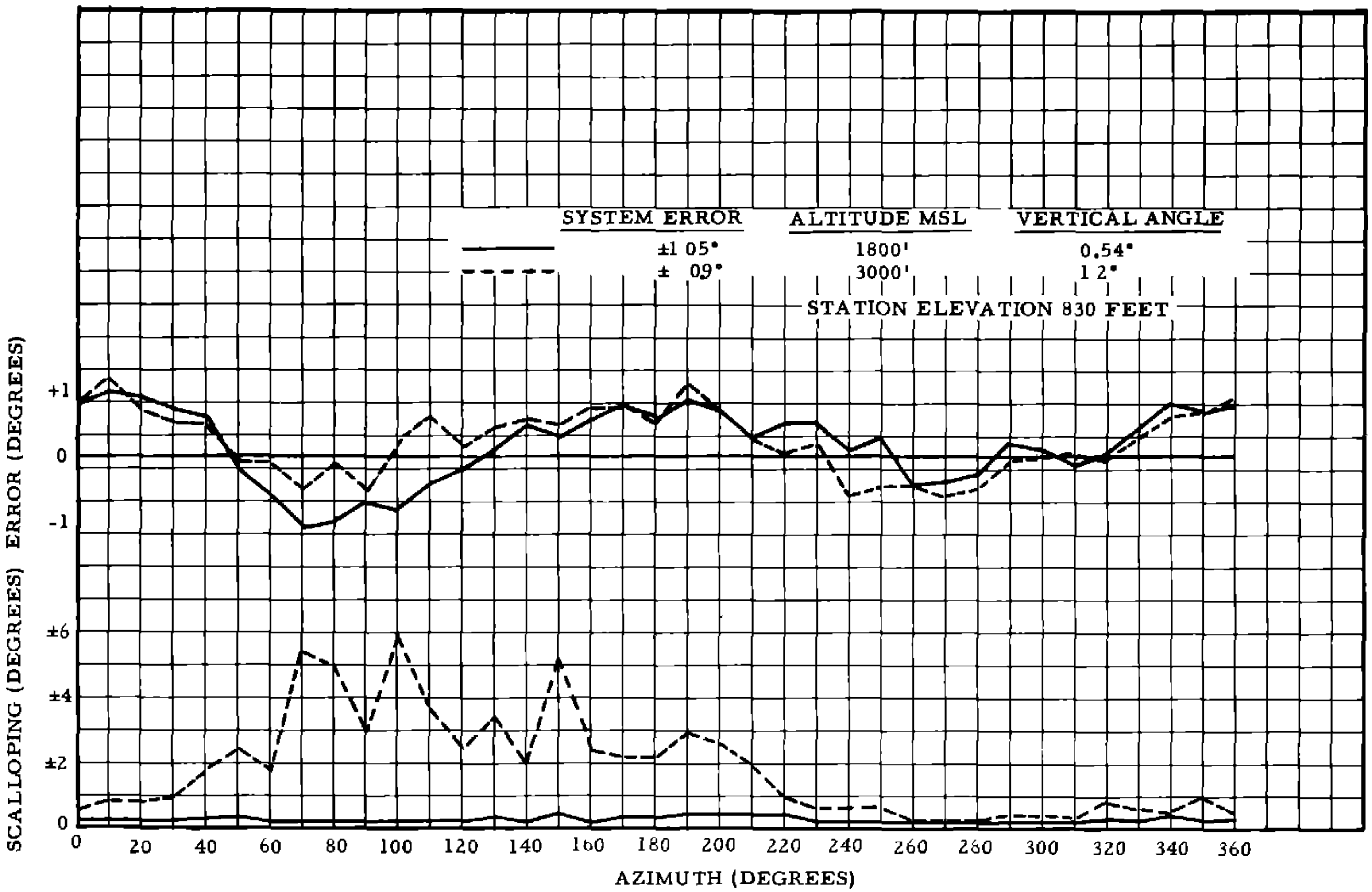


FIG 6 CALIBRATION AND SCALLOPING

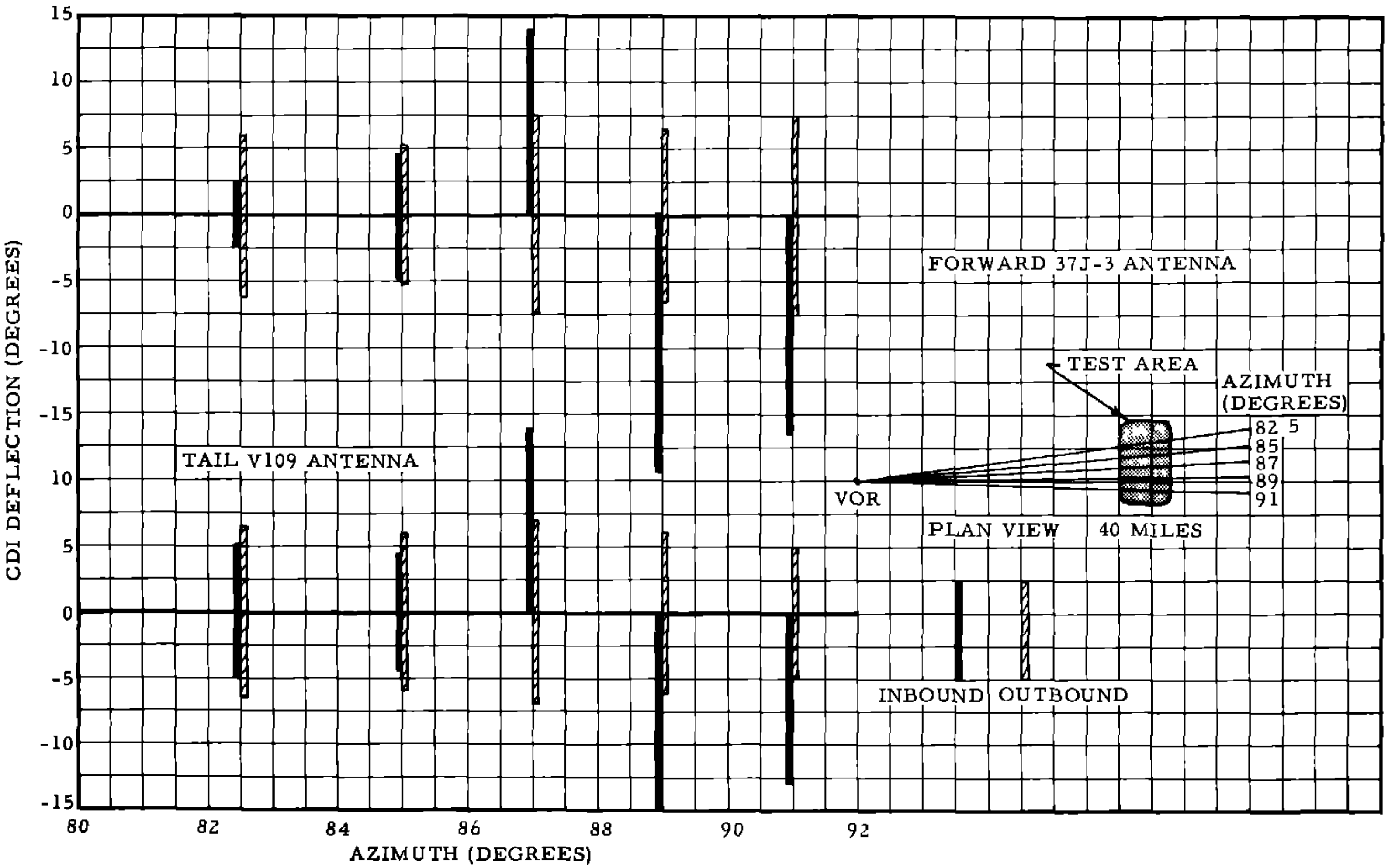


FIG 7 SCALLOPING IN 2 5° NULL

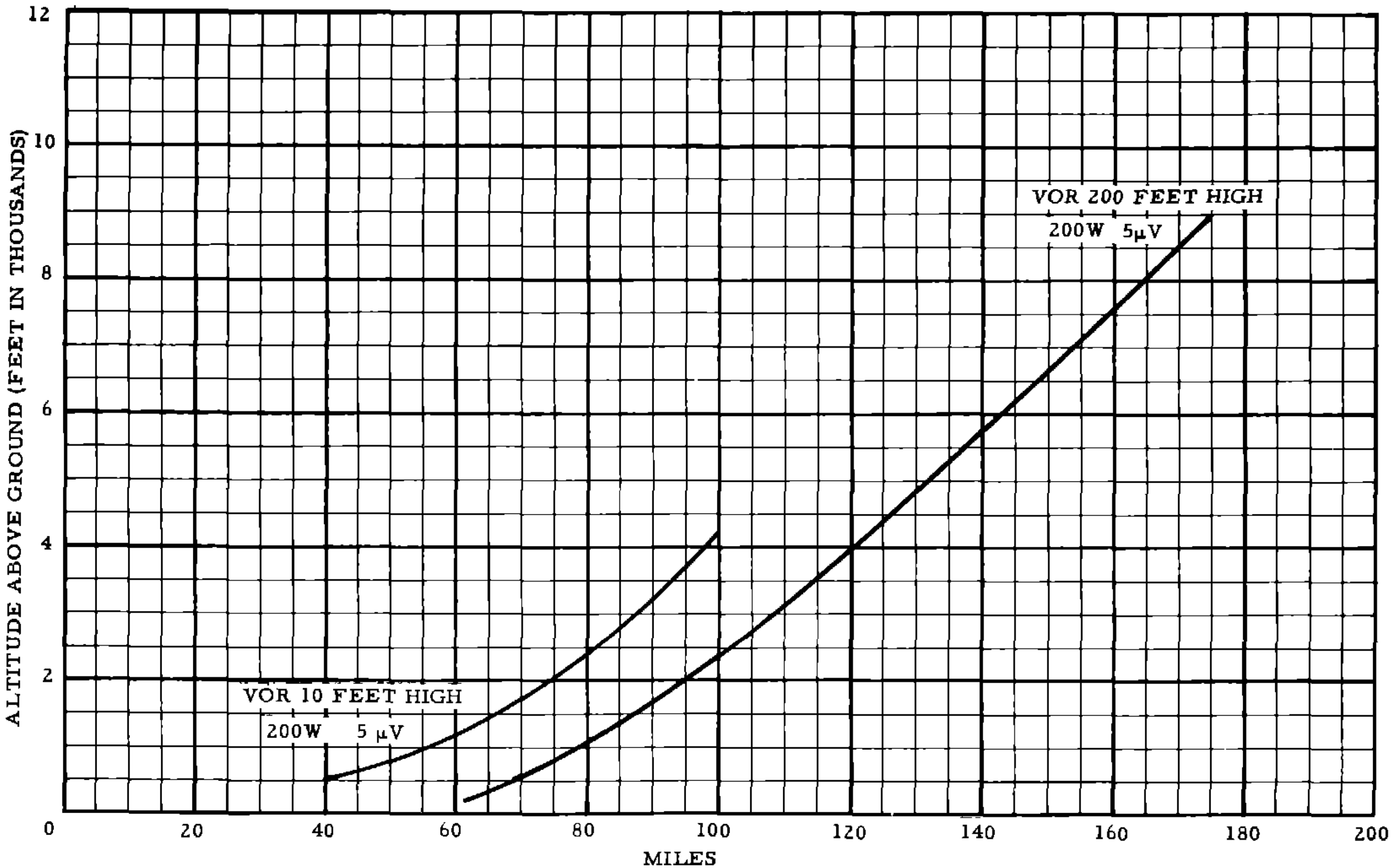


FIG 8 VOR DISTANCE RANGE WITH VOR ANTENNA ON 10- AND 200-FOOT TOWERS

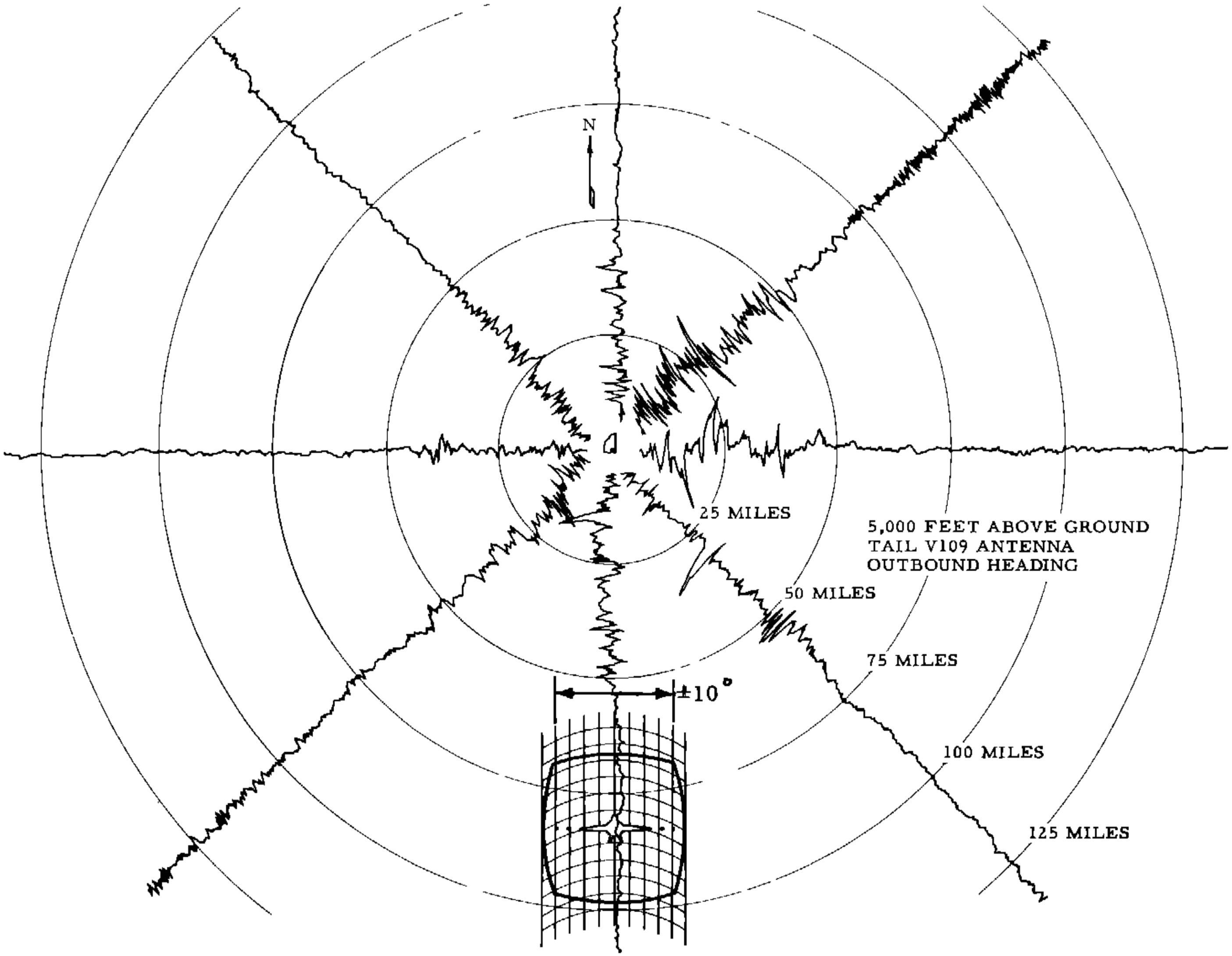


FIG 9 PLAN VIEW OF SCALLOPING ON 8 RADIALS

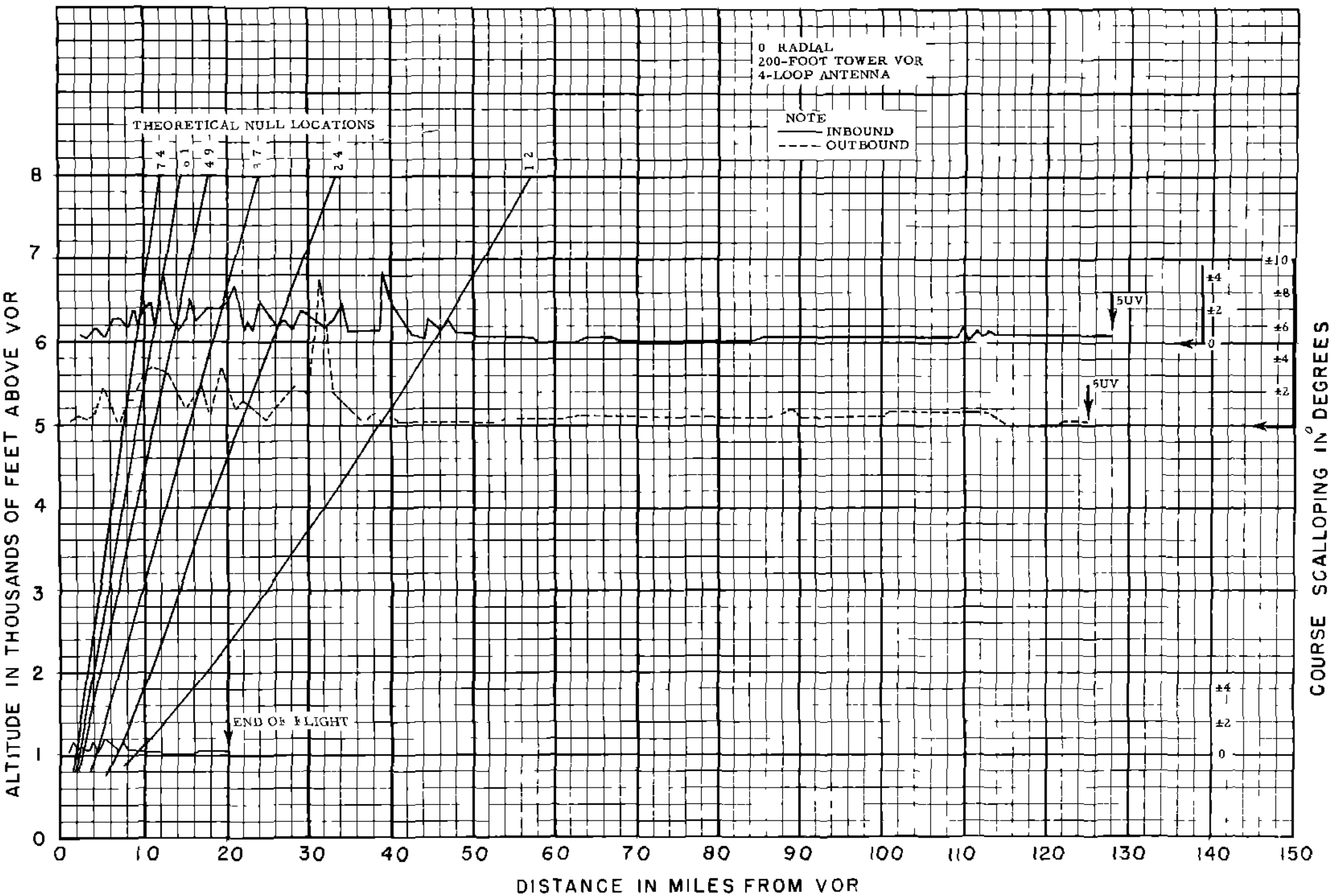


FIG 10 A COURSE SCALLOPING ON RADIAL FLIGHTS

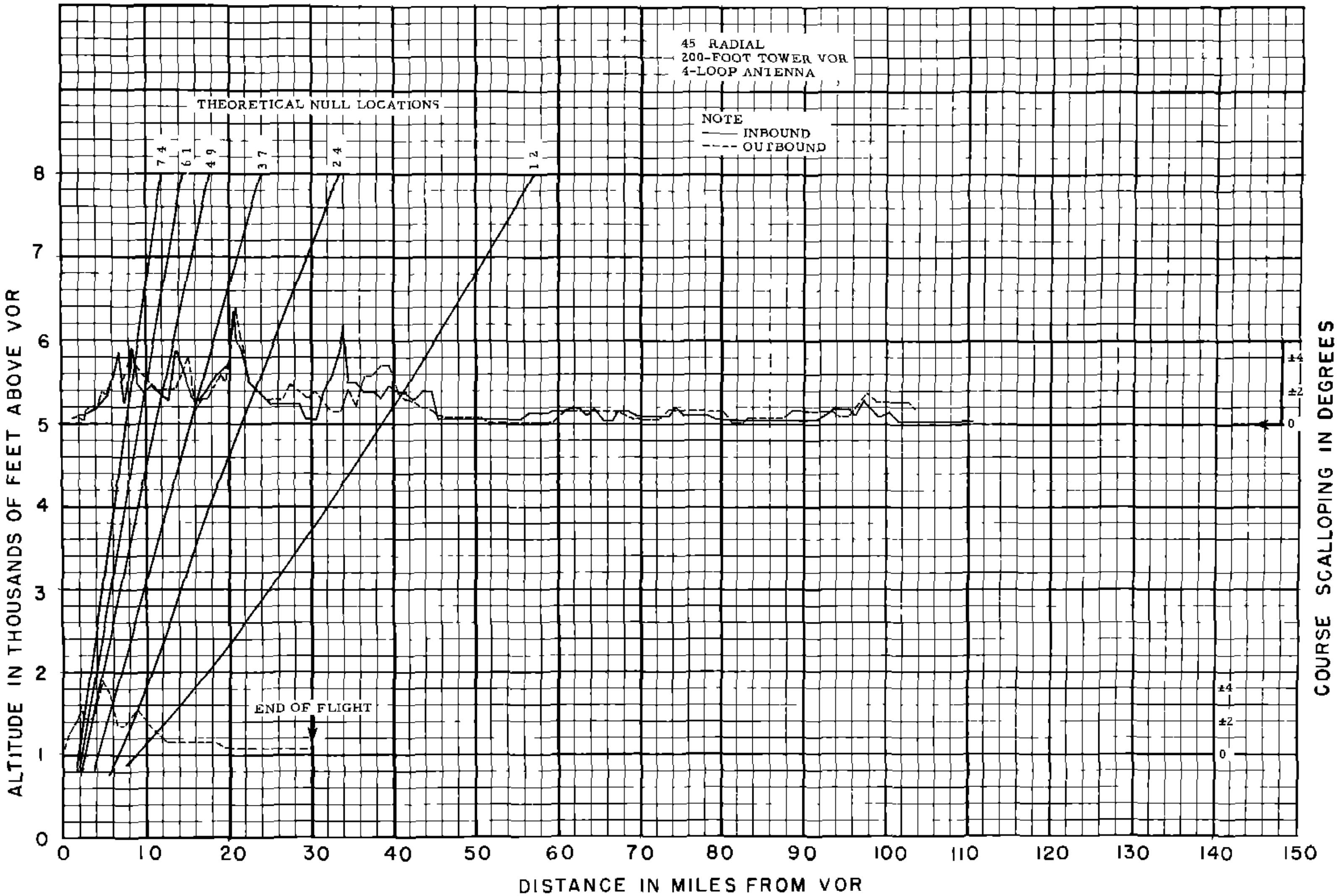


FIG 10 B COURSE SCALLOPING ON RADIAL FLIGHTS

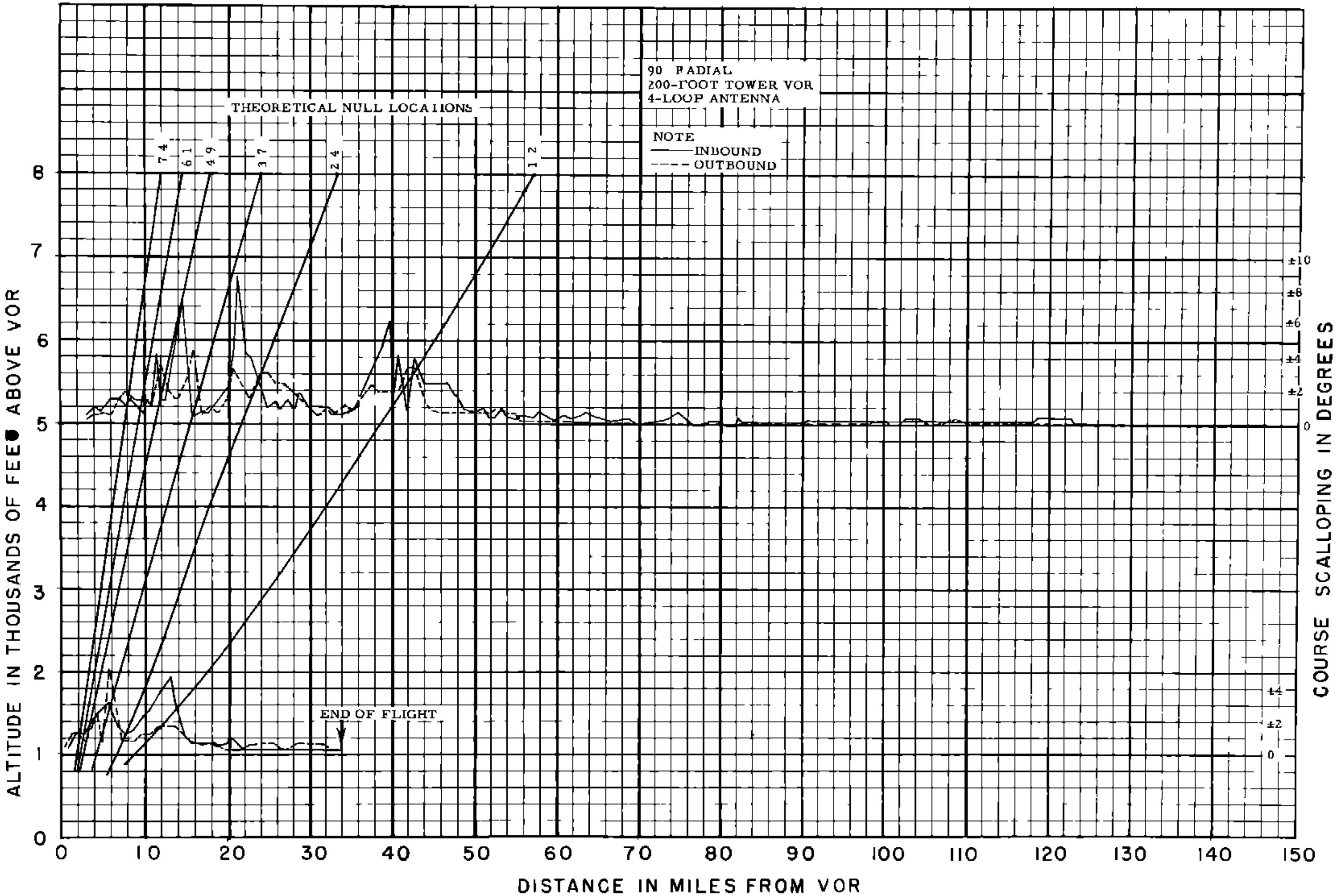


FIG 10 C COURSE SCALLOPING ON RADIAL FLIGHTS

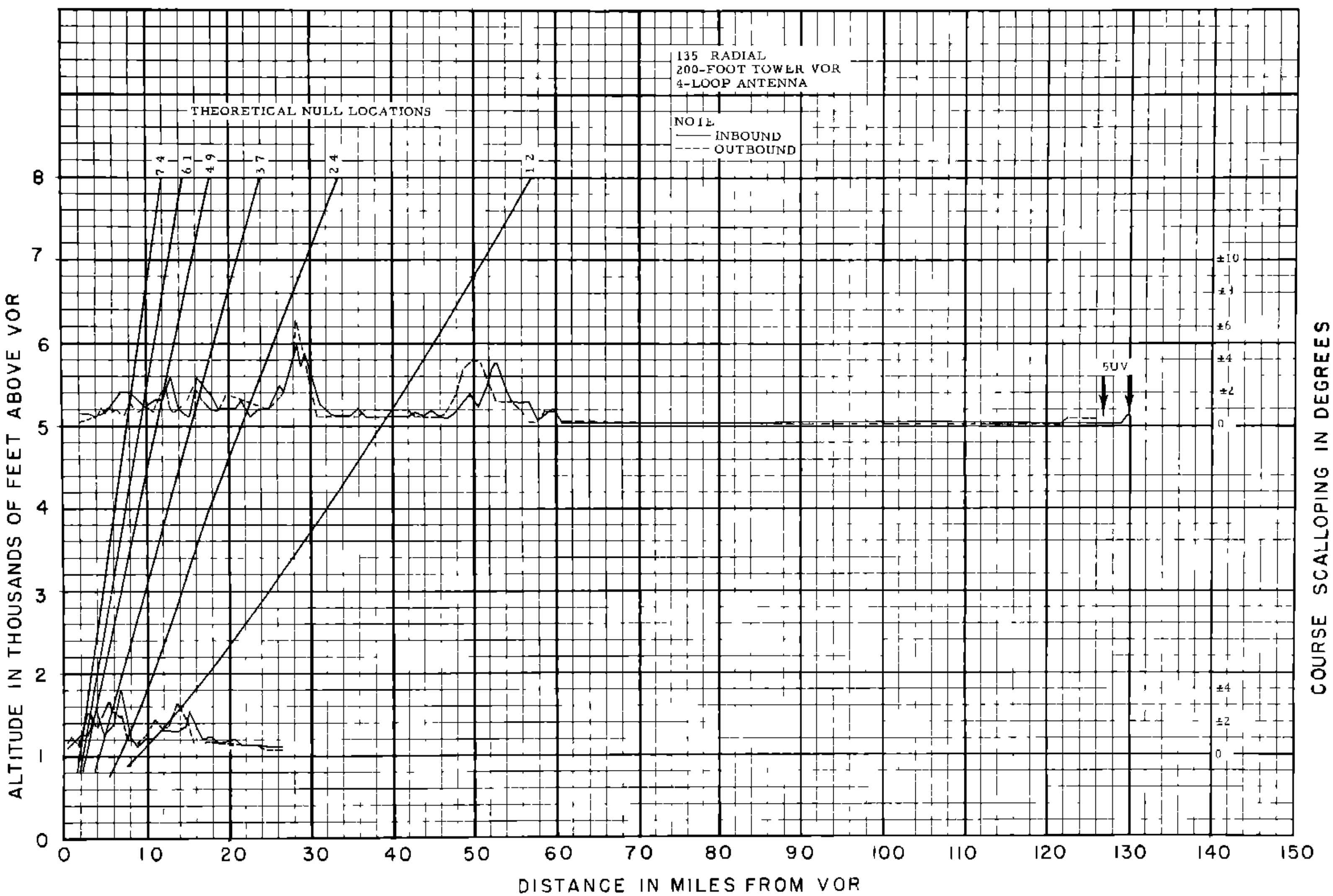


FIG 10 D COURSE SCALLOPING ON RADIAL FLIGHTS

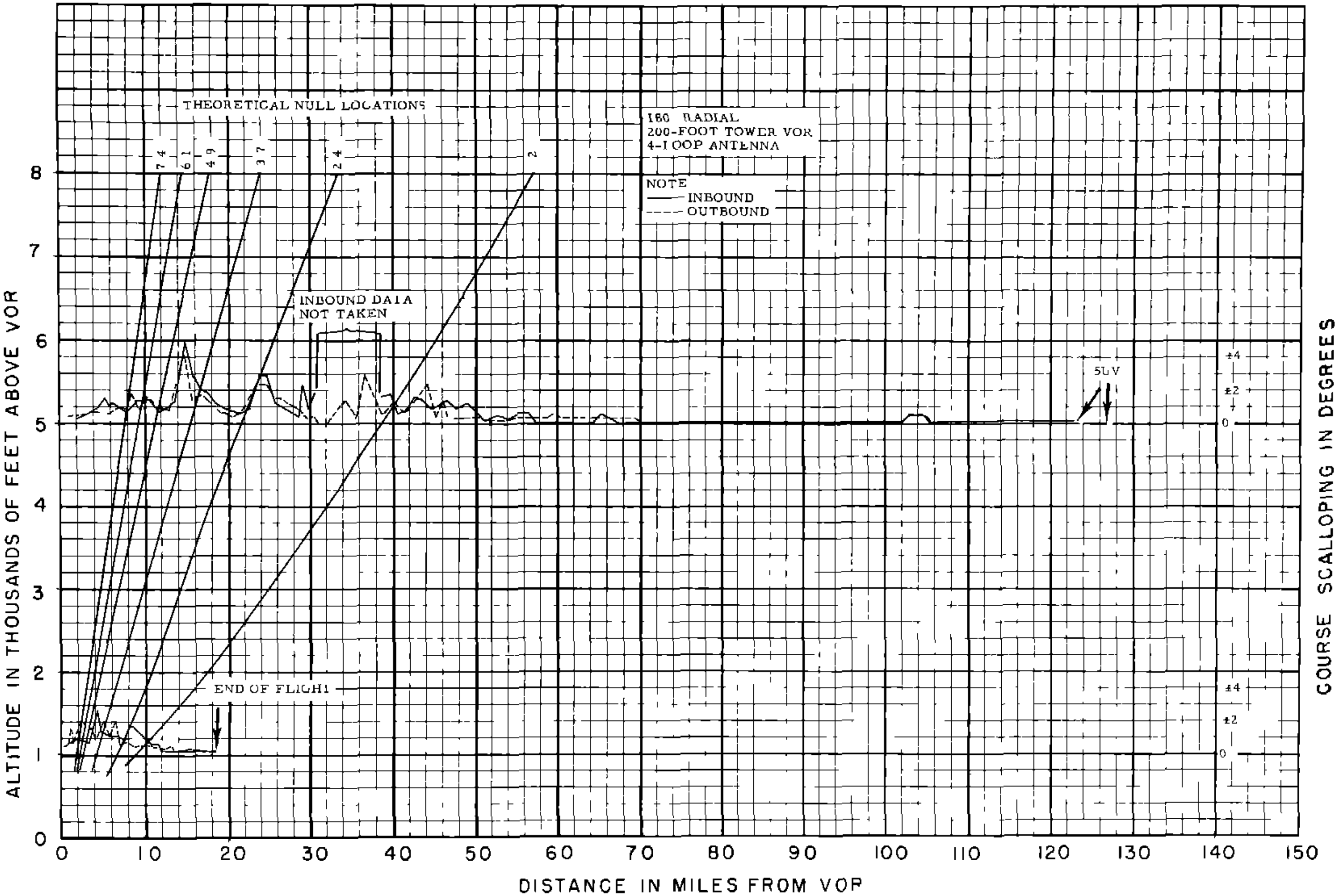


FIG 10 E COURSE SCALLOPING ON RADIAL FLIGHTS

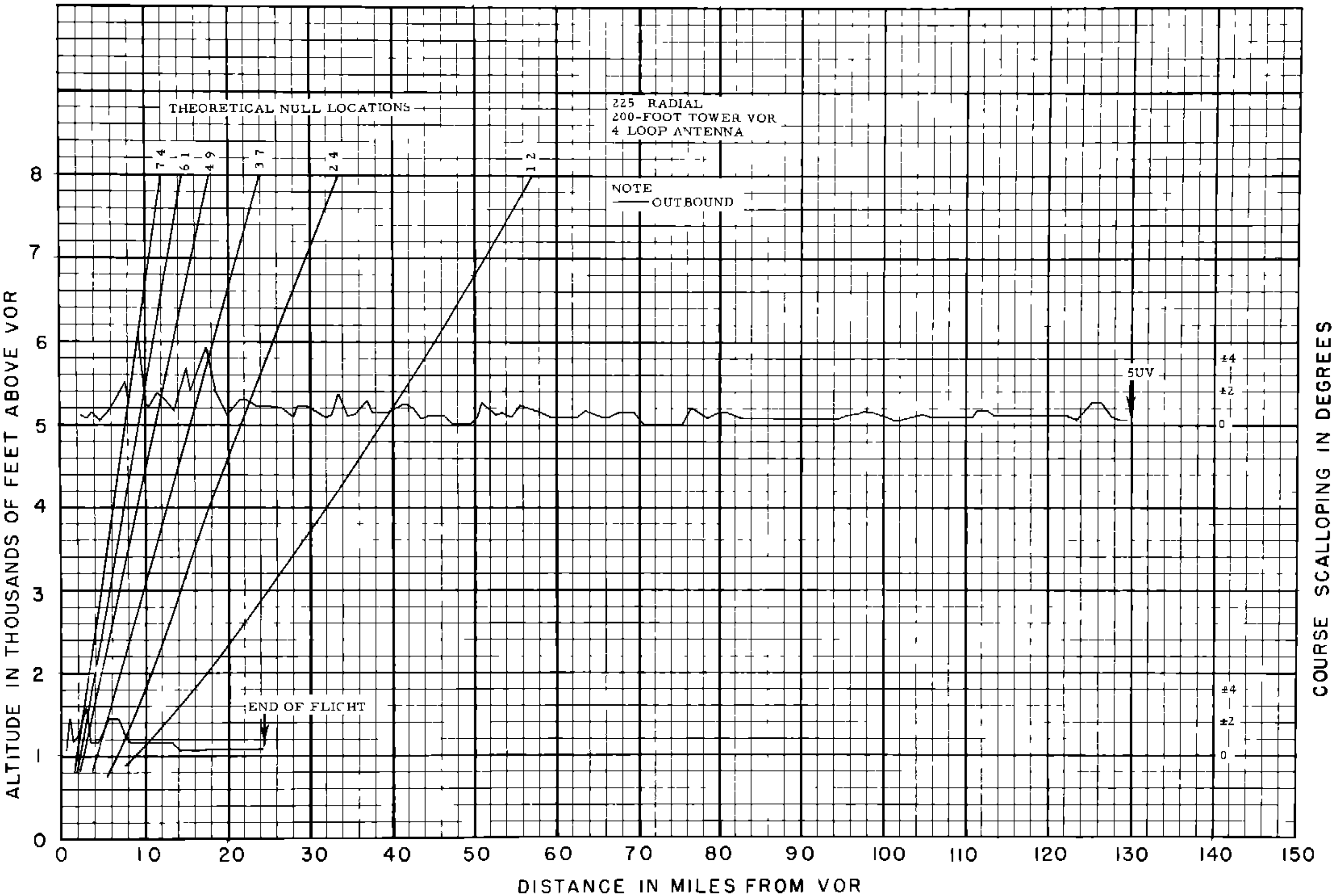


FIG 10 F COURSE SCALLOPING ON RADIAL FLIGHTS

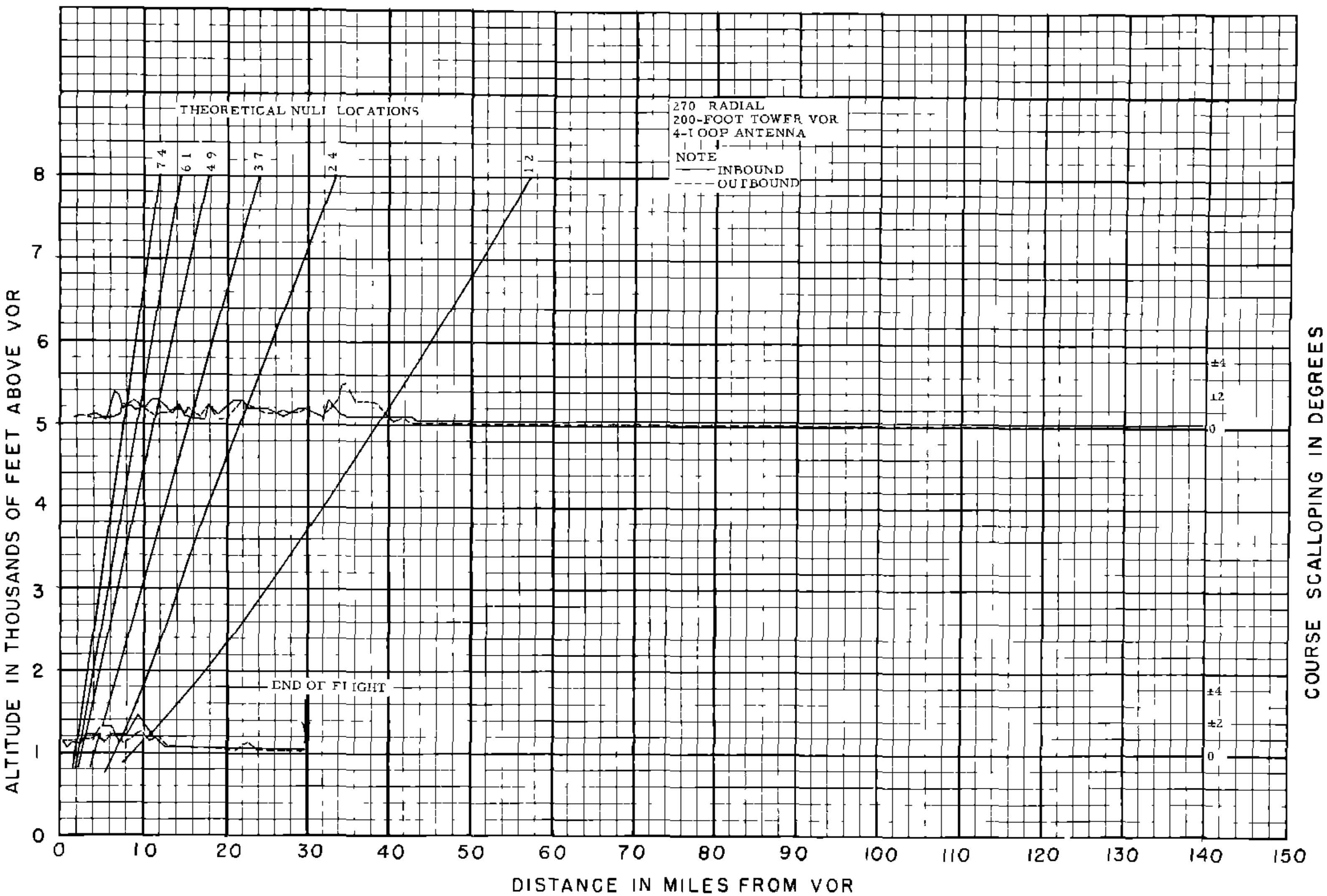


FIG 10 G COURSE SCALLOPING ON RADIAL FLIGHTS

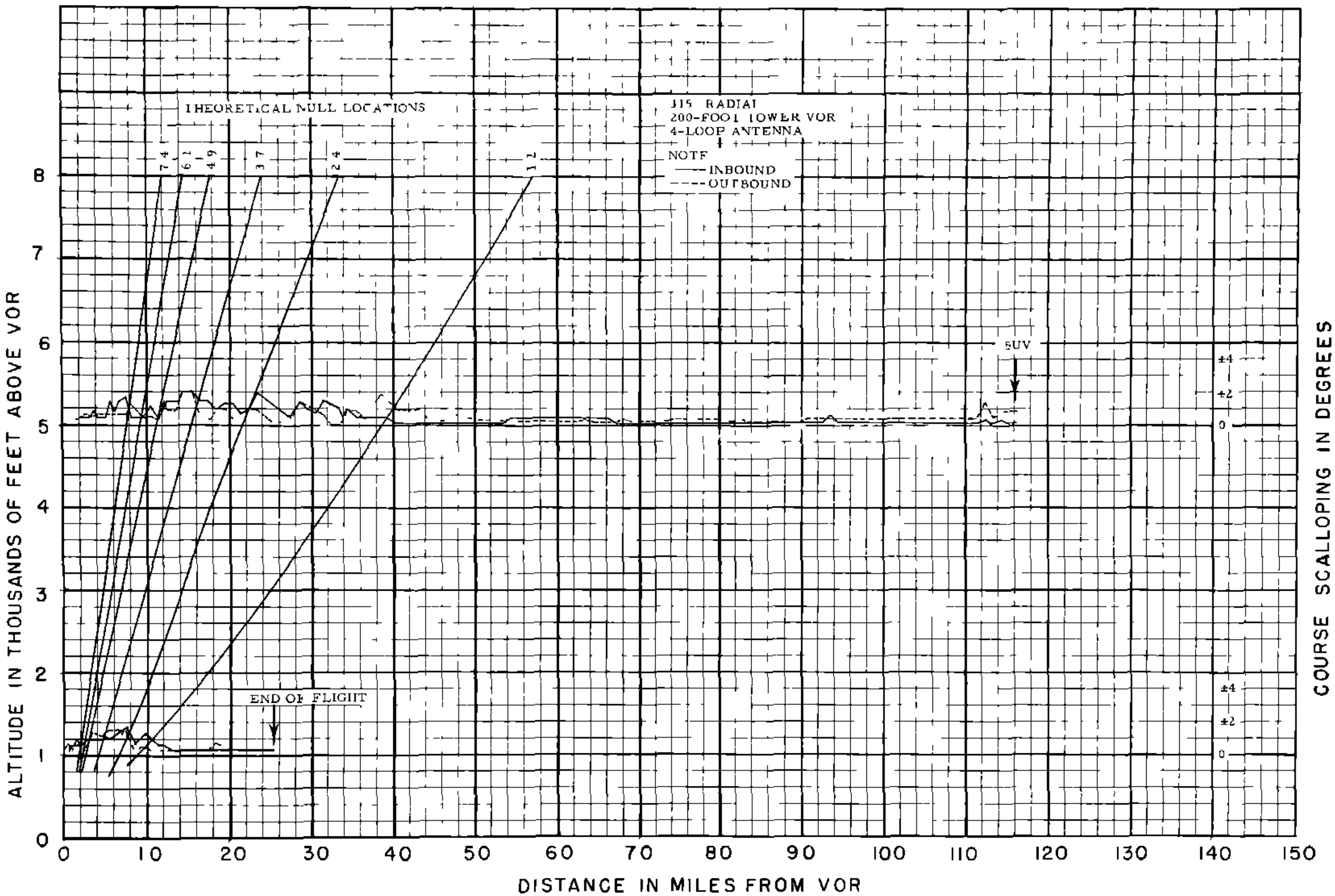


FIG 10H COURSE SCALLOPING ON RADIAL FLIGHTS

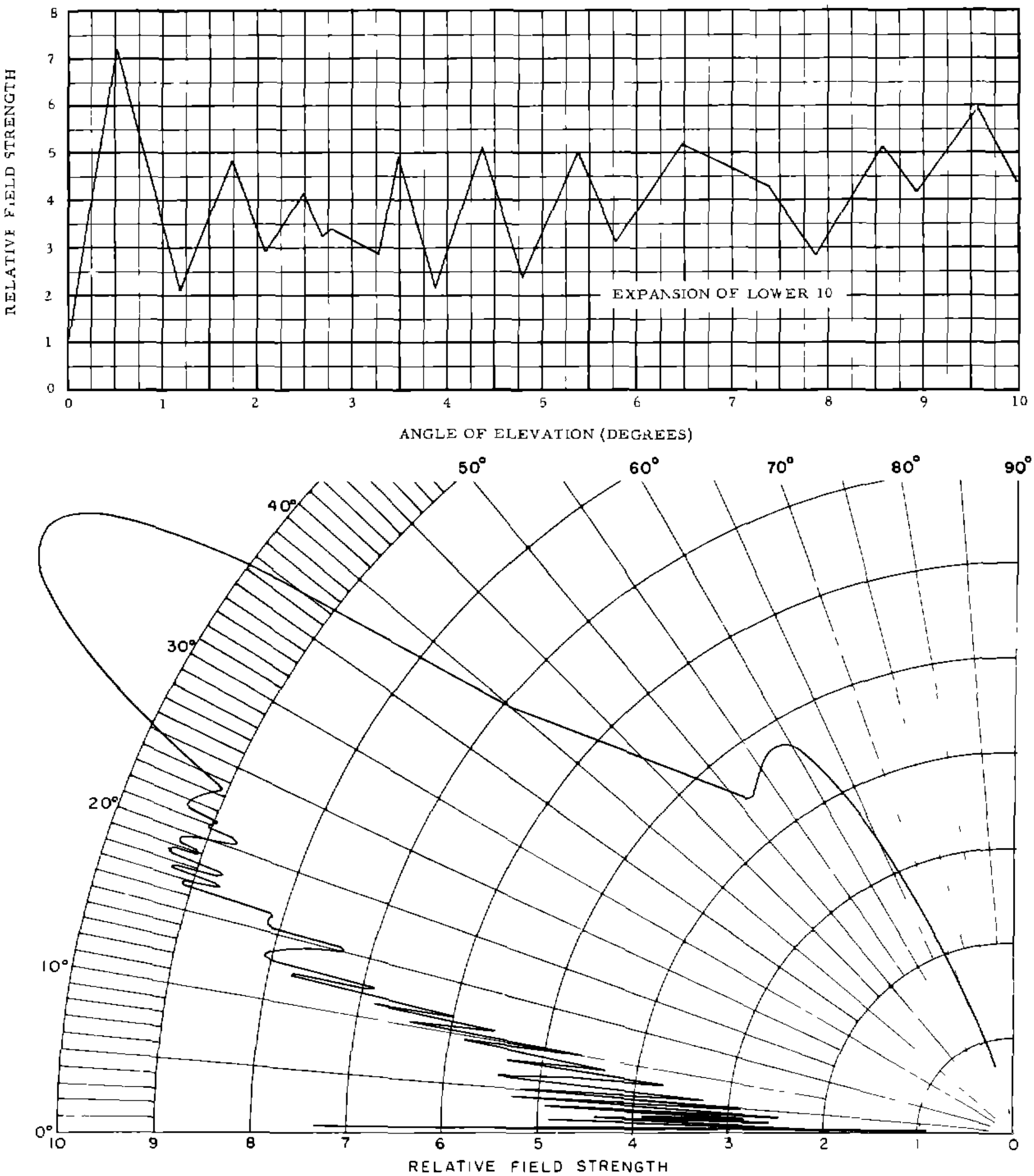
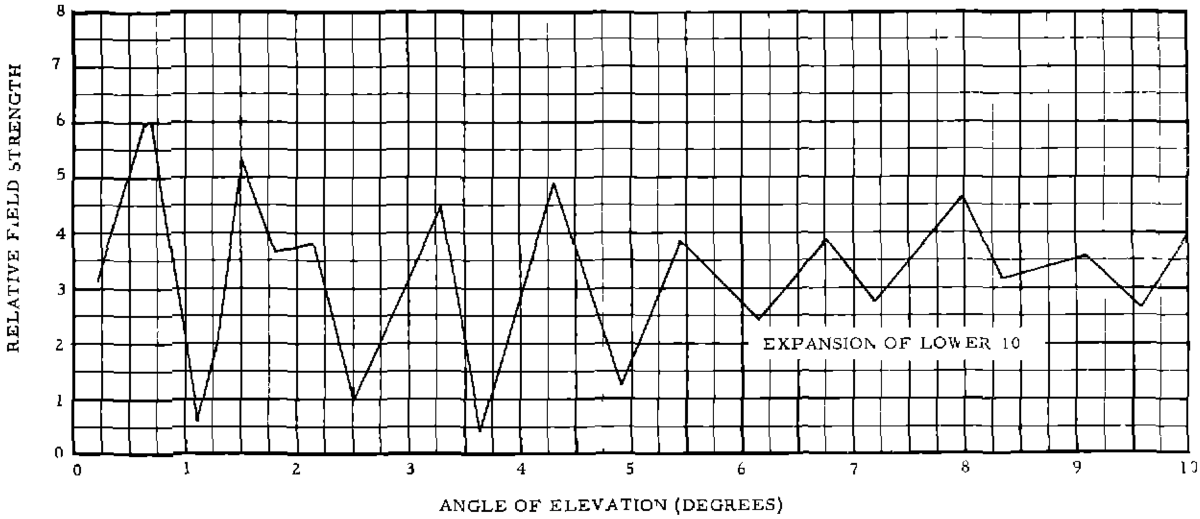


FIG 11A VERTICAL PLANE FIELD STRENGTH PATTERNS OF 0 RADIAL



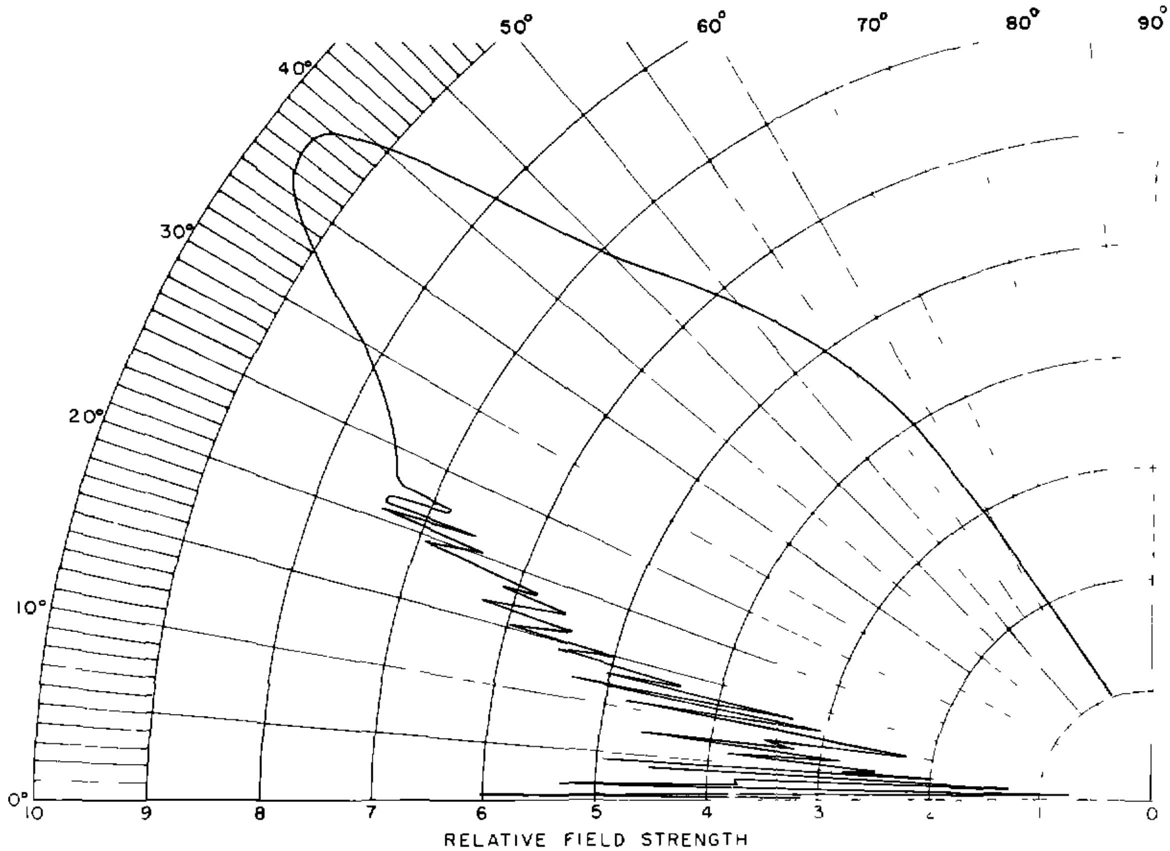


FIG 11B VERTICAL PLANE FIELD STRENGTH PATTERNS OF 90 RADIAL

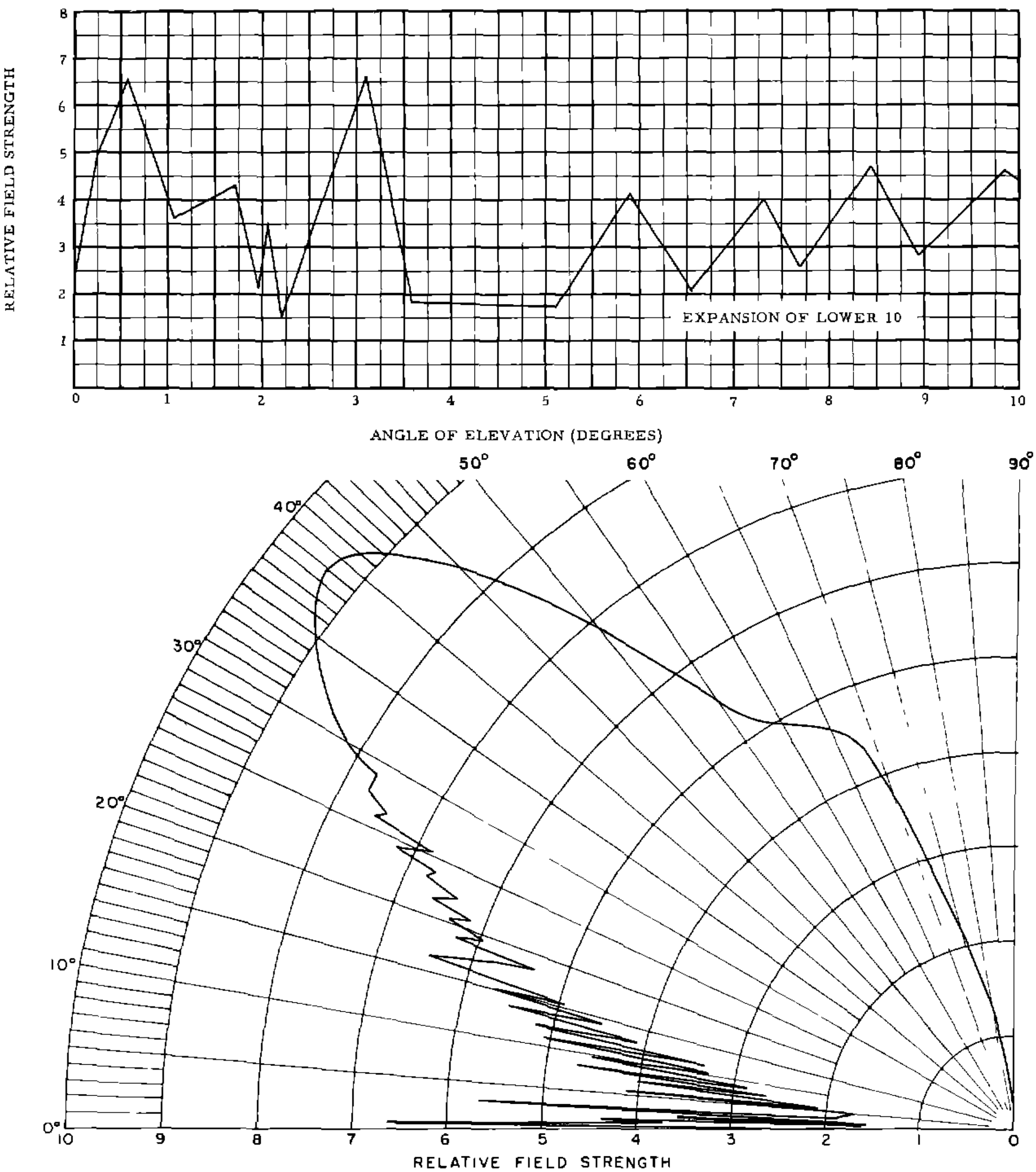
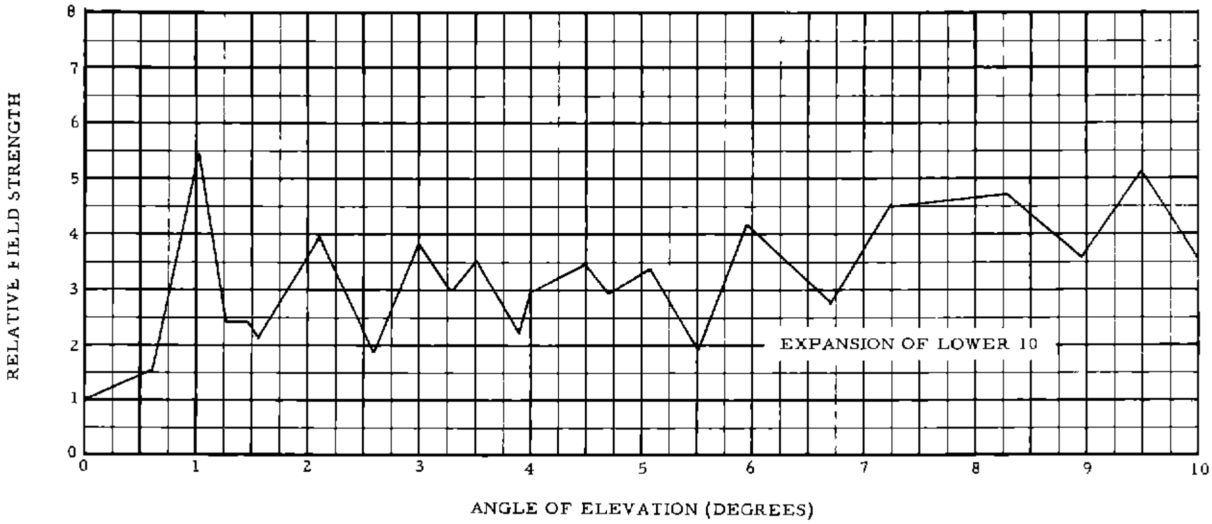


FIG 11C VERTICAL PLANE FIELD STRENGTH PATTERNS OF 180 RADIAL



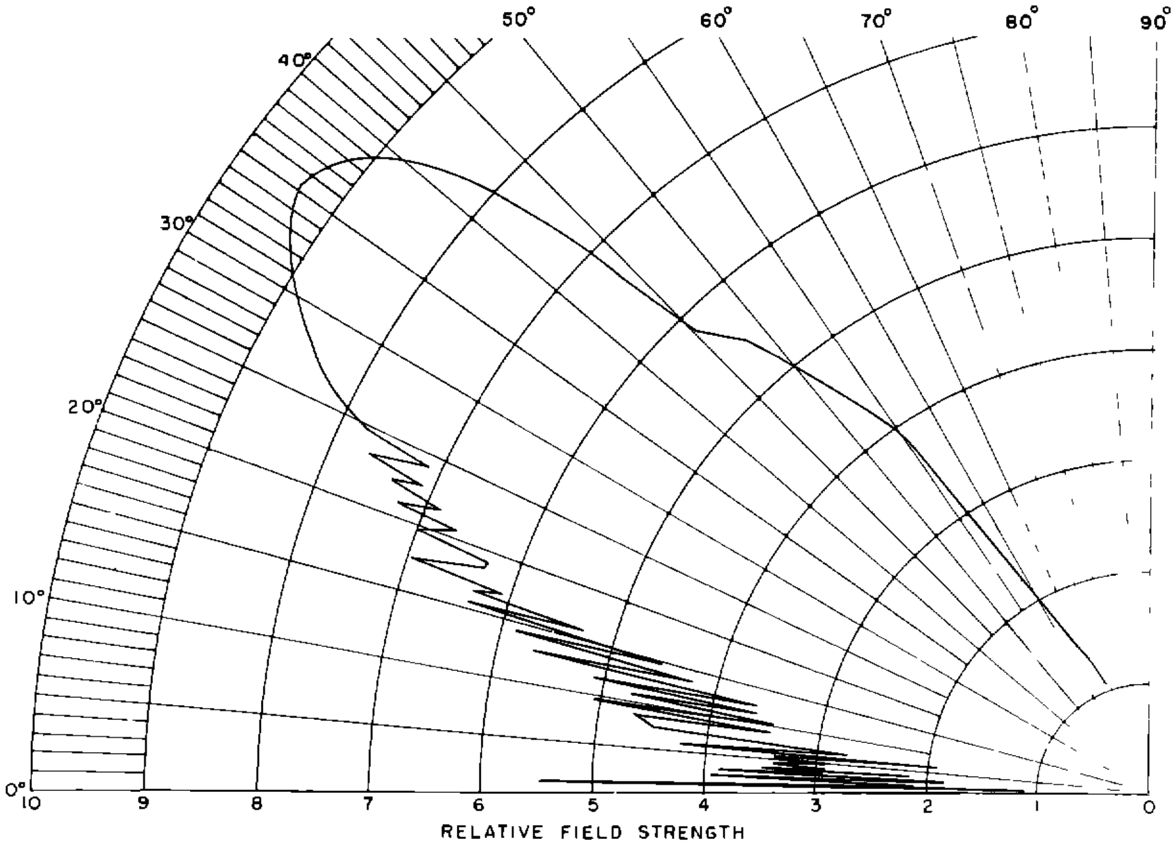


FIG 11D VERTICAL PLANE FIELD STRENGTH PATTERNS OF 270° RADIAL

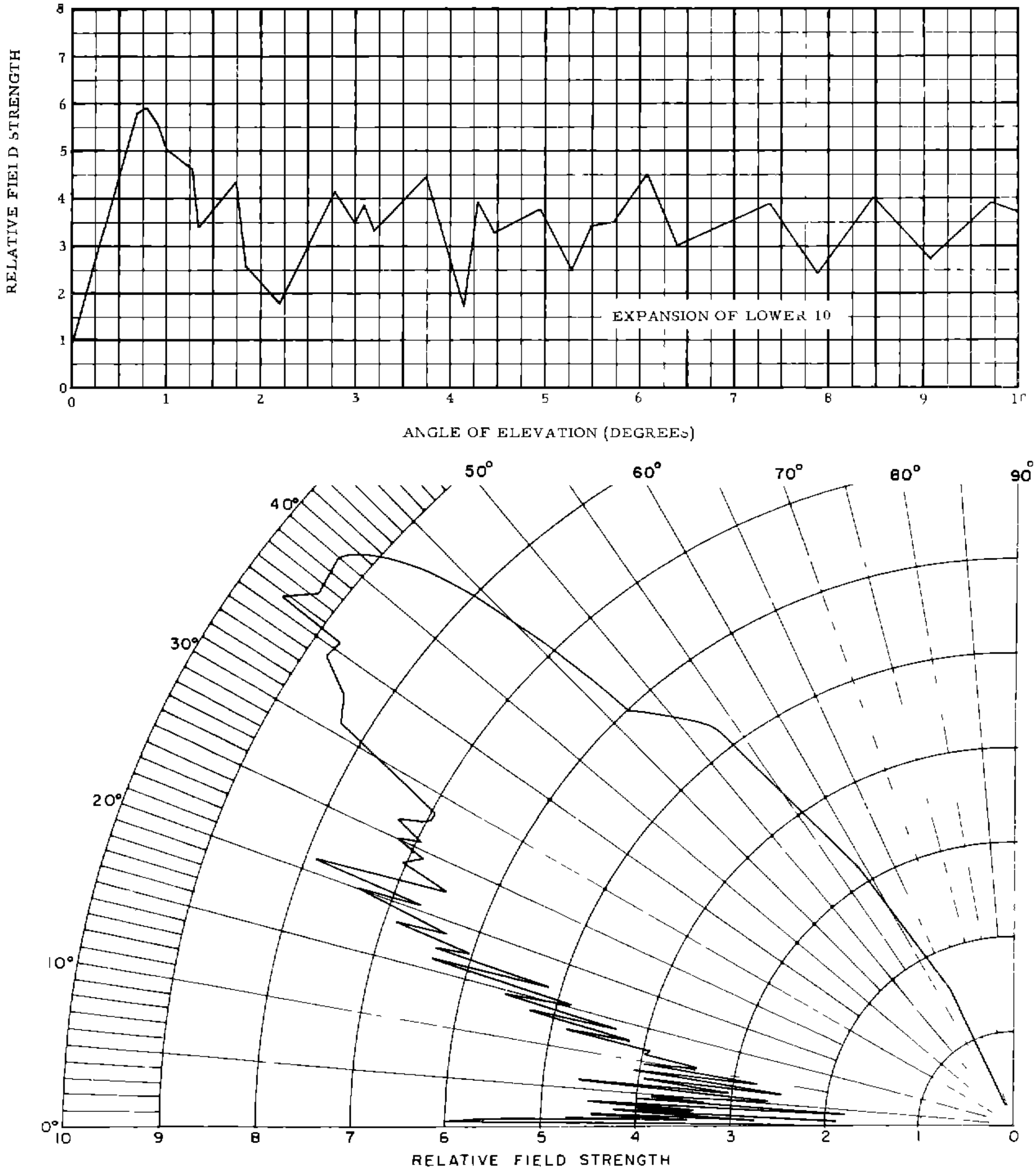


FIG 11E VERTICAL PLANE FIELD STRENGTH PATTERNS OF 315 RADIAL

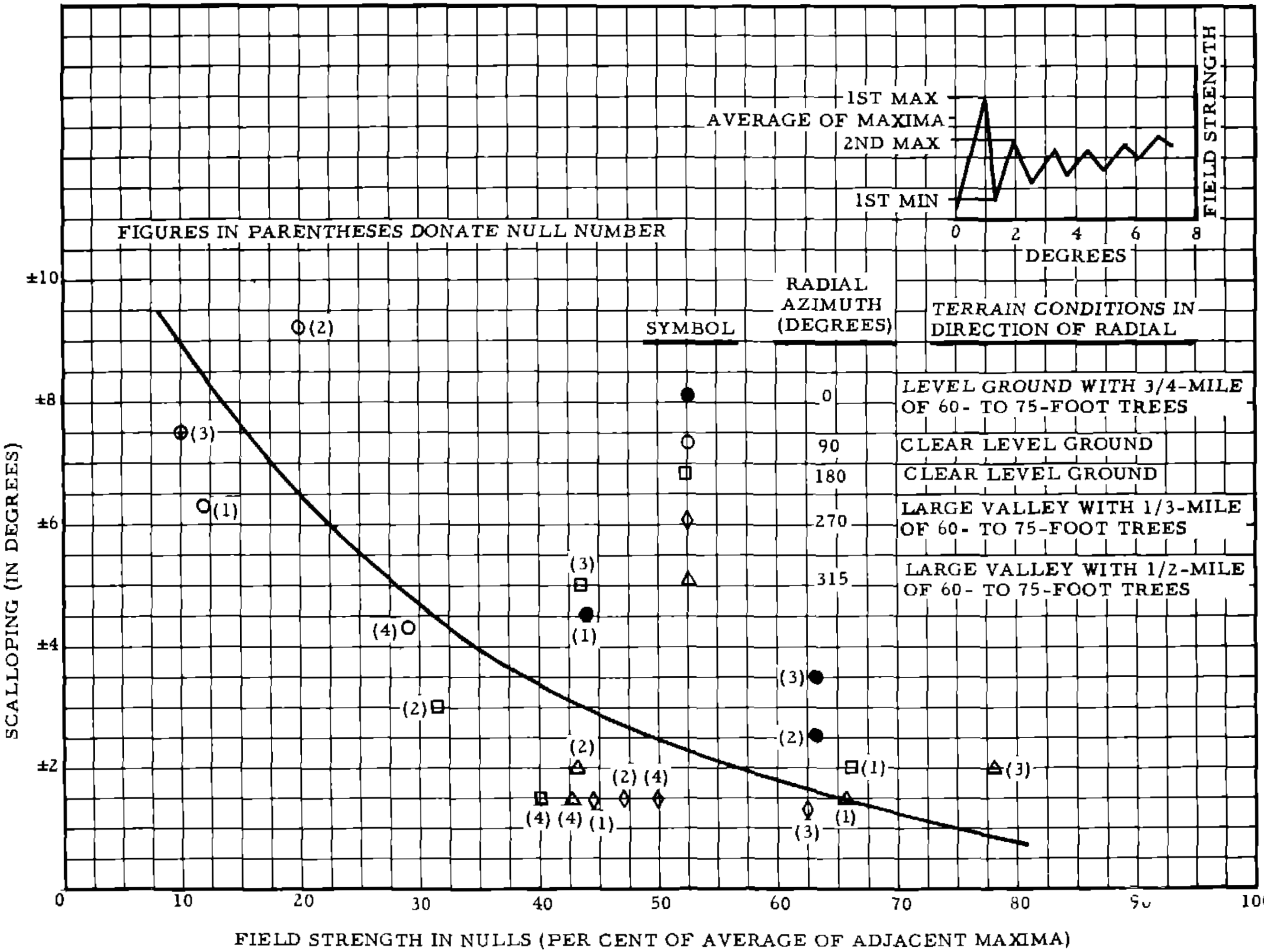


FIG. 12 SCALLOPING AS A FUNCTION OF FIELD STRENGTH IN NULLS

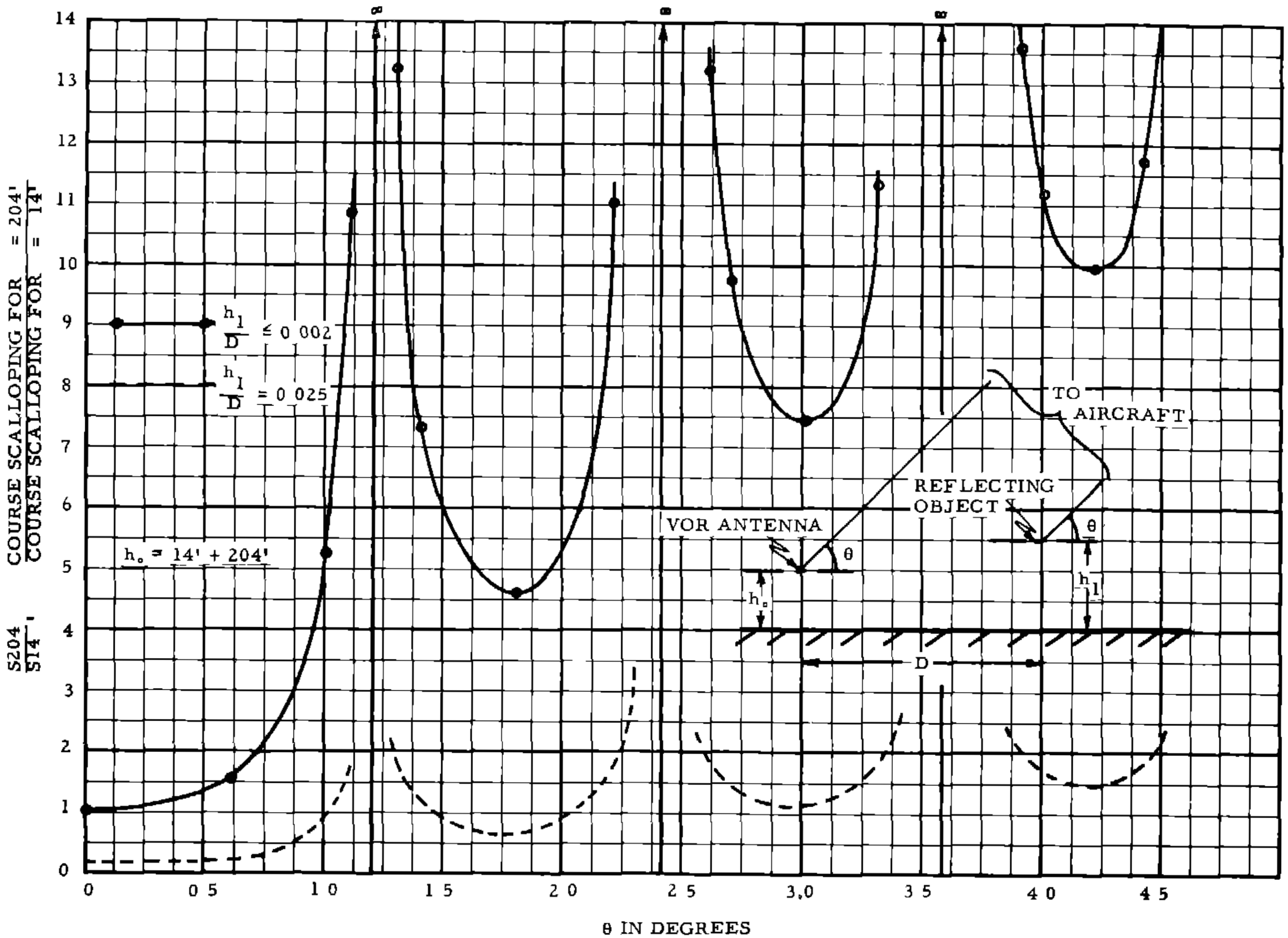


FIG. 13 THEORETICAL COURSE SCALLOPING VERSUS VERTICAL ANGLE

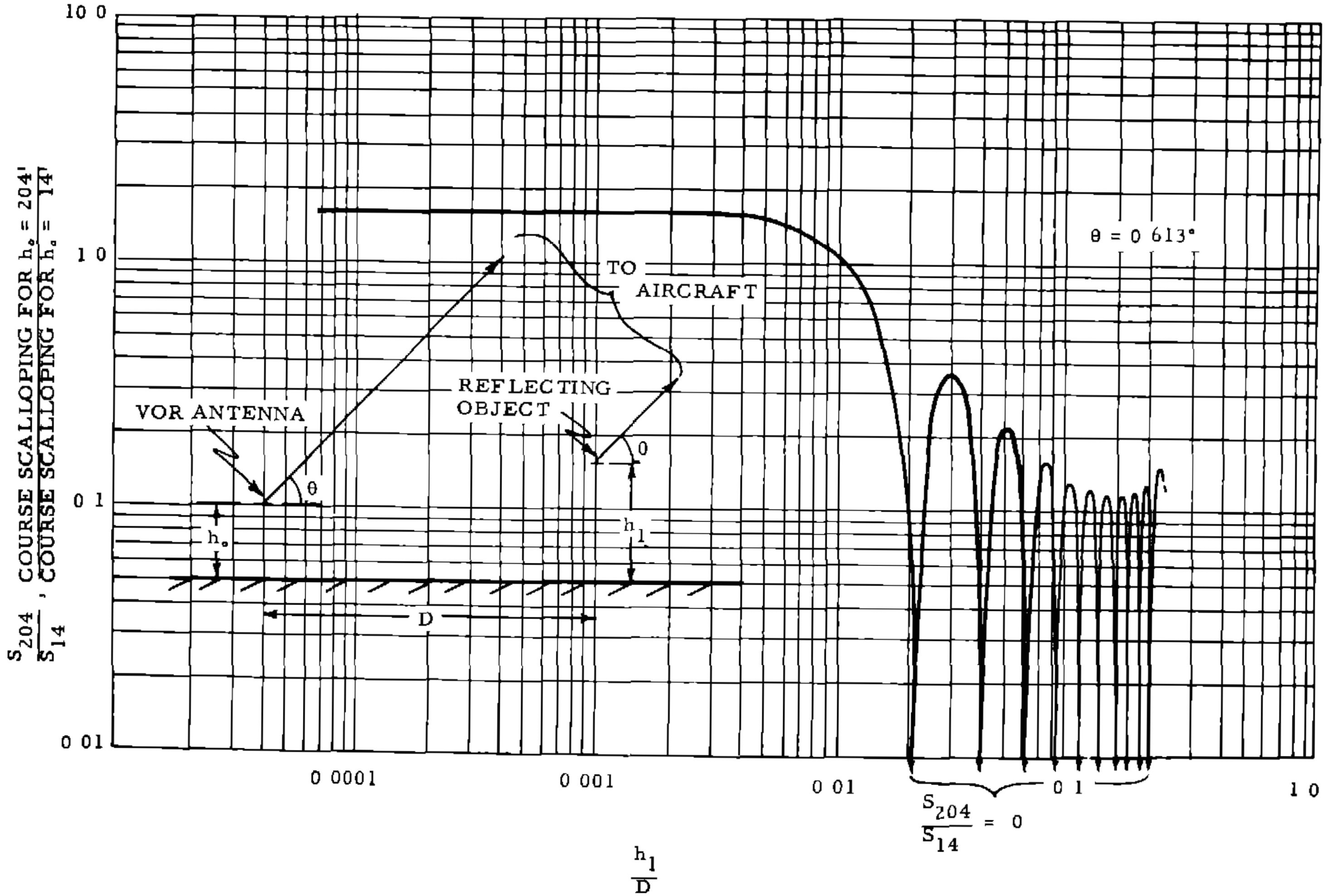


FIG. 14 THEORETICAL COURSE SCALLOPING VERSUS REFLECTOR LOCATION