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WADC TECHNICAL REPORT 52-135

AIR-TO-AIR TROPOSPHERIC PROPAGATION OVER WATER

GARNER B. FANNING
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AIRCRAFT RADIATION LABORATORY

JUNE 1952

WRIGHT AIR DEVELOPMENT CENTER

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ABSTRACT

Air-to-air tropospheric one-way radio wave propagation tests over smooth fresh water are described and the resulting data analyzed. Signal strength for frequencies of 250, 1000, and 3300 mc was recorded simultaneously in a receiving aircraft as a function of separation distance from a transmitting aircraft at 1000 feet altitude. Analyses include primarily those phenomena due to earth reflections, and, to a less extent, the effects of lower atmosphere refraction. The recorded interference lobe structure envelope compares favorably with the theoretical except for a maximum range foreshortening probably due to a substandard refractive condition. The indicated lobe rates and reflection coefficients closely compare with the theoretical with some scatter primarily due to rapid unavoidable excursions of aircraft altitude. Theoretical frequency dependent diffraction slopes calculated for signal strength beyond the horizon are closely duplicated in the data. No severe fades were observed that could not be attributed to earth reflection phenomena.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

for R. J. Beaver

LAWRENCE H. LEWIS
Colonel, USAF
Chief, Aircraft Radiation Laboratory
Directorate of Laboratories

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I. INTRODUCTION

It is well established knowledge that all propagation of radio waves within the troposphere is affected markedly by the presence of the earth and its atmosphere. At frequencies of about 40 mc and higher, signal level as a function of range is deviated chiefly from theoretical propagation in free space by atmospheric refraction or bending, and by earth reflection phenomena. To determine propagation characteristics under these conditions, many factors are involved, such as, the geometry of the situation, the refractive index of the medium (air) supporting the propagation, the frequency and polarization of the electromagnetic radiation involved, and the electrical characteristics of the reflecting earth. The geometry includes the location of the receiver and transmitter with respect to the earth and the physical contours of the earth's reflecting area. Electrical characteristics of the earth that enter in are the dielectric constant and conductivity.

Several experiments of this nature have been conducted in the past. (1, 2) Such experiments, with at least one notable exception (2), have usually been conducted for short ranges or have maintained either the receiver or transmitter, or both, fixed on the earth. Considerable additional knowledge can be accrued by utilizing an air-to-air propagation link and recording in a receiving aircraft the signal level as a function of range from a transmitting aircraft. In the experiments reported here, the two aircraft opened range on reciprocal headings at 1000 ft above a body of smooth fresh water, while three separate and distinct propagation frequencies were operated simultaneously. The frequencies employed were 250 mc, 1000 mc, and 3300 mc.

Referring to Fig. 1, earth reflected signals affect the total signal level at the receiving antenna by vectorially combining with the direct path signal to produce an alternate partial cancellation and reinforcement of the signal level at the receiver. The shape, period, and magnitude of this regular fluctuation of signal, termed lobe structure, are determined theoretically by the operating wavelength, altitude of transmitter and receiver, range between terminals, and the nature of the reflecting surface. Such an experiment as depicted in Fig. 1 can yield much information for ready comparison with theoretical, such as, lobe rate for each operating wavelength, lobe envelope, maximum range, and earth reflection coefficients.

II. CONDITIONS OF THE EXPERIMENT

In these experiments, it was intended to minimize the effects of atmospheric refraction and emphasize the phenomena associated with specular earth reflections. Idealized specular reflections can be realized better experimentally for the air-to-air case while flying over a large area of smooth homogeneous surface such as an inland lake. Such a body of water was selected for the present flight tests. In the interest of flying safety and anticipated optimum results, the altitude of both aircraft during the tests was chosen as 1000 feet above the lake surface, such altitude being determined by

radio altimeter. This lake, called Grand Lake, is located in northwestern Ohio and is shown in Fig. 2 on sections of Coast and Geodetic topographic maps. The early portion of the flight paths is also shown. The aircraft separated sharply over the center of the lake at 1000 feet altitude for the start of each of three separate runs, the transmitting aircraft (type C-46) flying eastward, the receiving-recording aircraft (type B-17) going westward. Flying path accuracy and location was determined precisely by the pilots logging exact times over predetermined check points. Such times were used also in the data reduction to determine the distance between aircraft as a function of time, which, in turn, was employed to indicate range on the field strength recordings.

Although an effort was made to maintain the center point between aircraft fixed at the center of the lake, some constant drift did occur. This drift was carefully computed and is shown in Fig. 3 for each of the three separate test runs performed. Since the most important data for purposes of reflection calculations were obtained for aircraft separations of 40 miles or less, the limits of drift indicated can be considered unimportant.

Grand Lake is not ideally large. On the other hand, its limited extent contributed to the mirror-like smoothness of surface enjoyed on the day of these experiments.

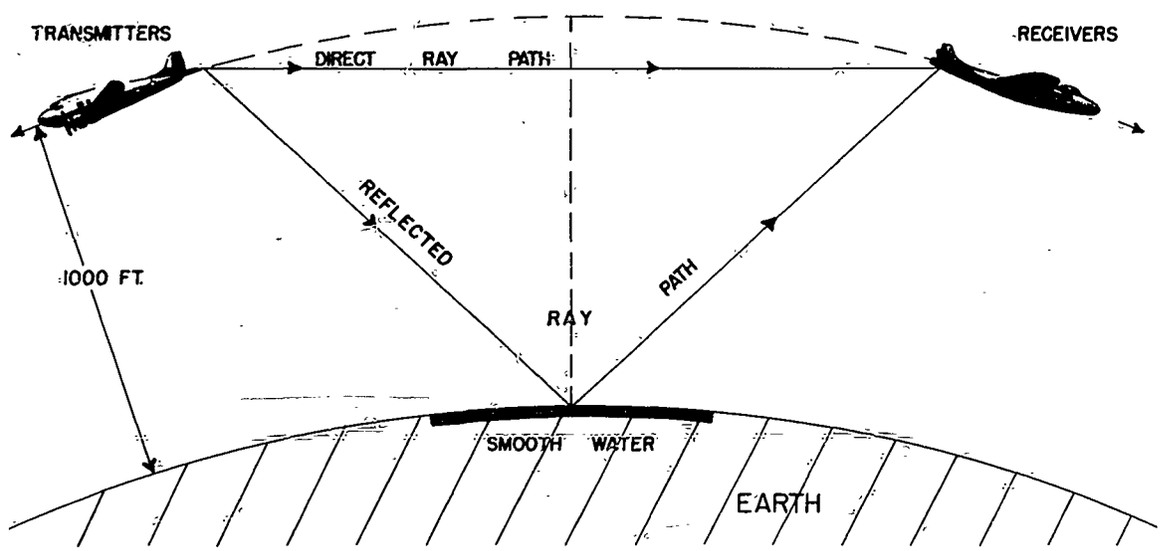


Figure 1. Geometry of the Experiment

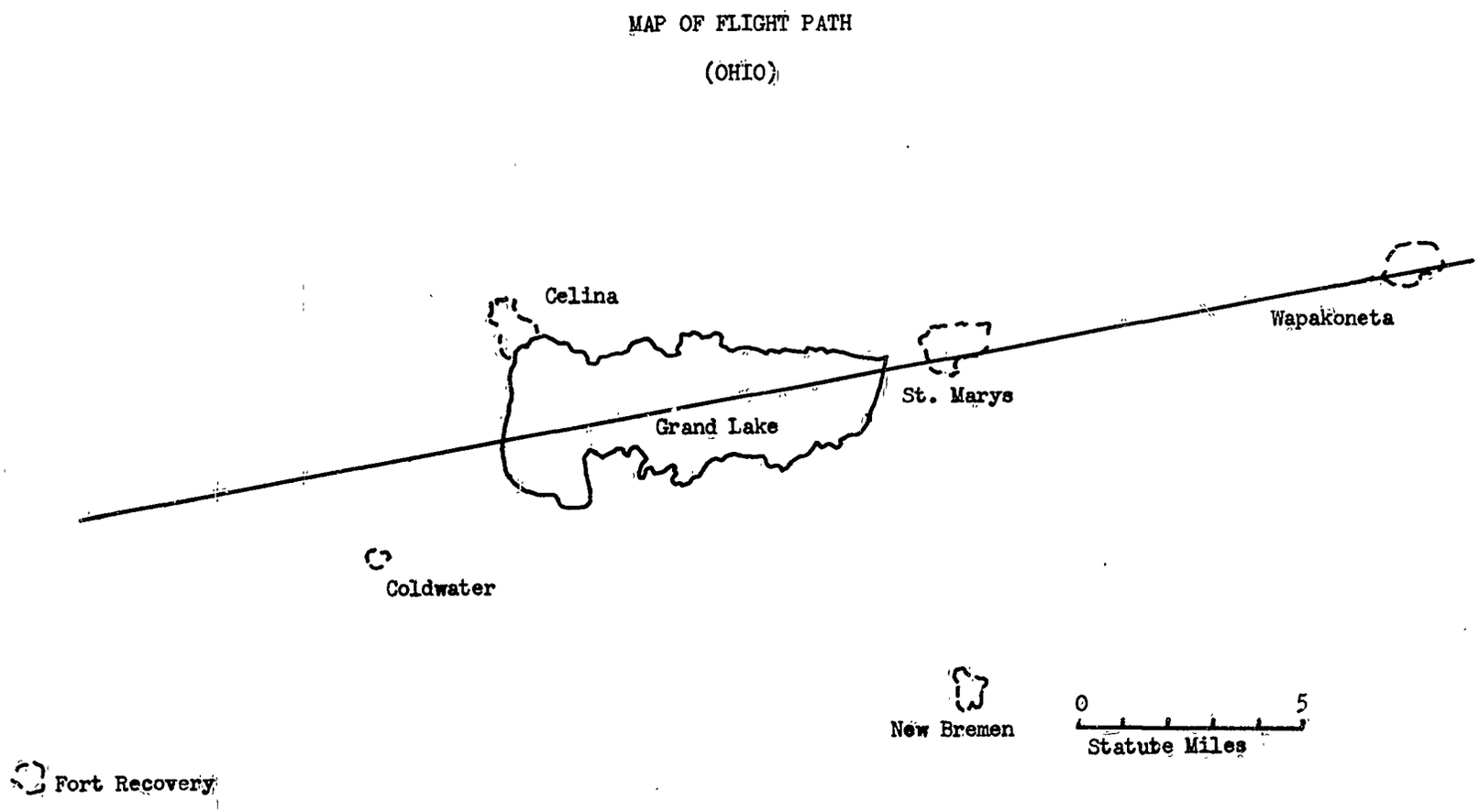


FIGURE 2. Map of Flight Path

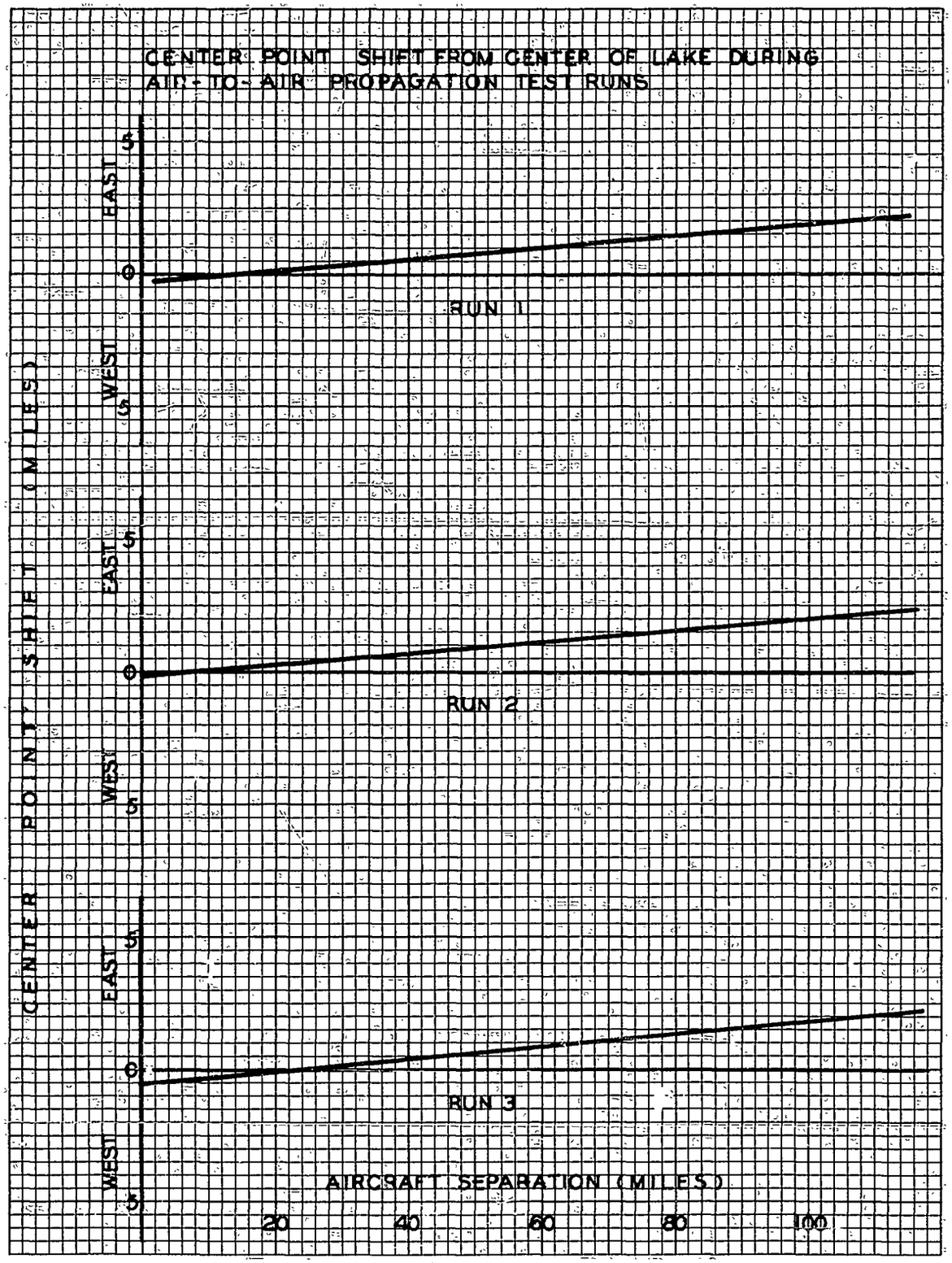


FIGURE 3. Center Point Shift from Center of Lake

Where a large area of the earth is illuminated by the radio-frequency energy, earth reflections occur over quite an extent. Obviously, for a smooth reflecting surface, not all the rays striking the earth can reach the vicinity of the receiving antenna. In fact, on the basis of pure optical theory which may be applied, only one ray can so reflect with angle of incidence equal angle of reflection. For both aircraft at the same altitude this reflecting point is the center point between aircraft. For other reflecting rays that differ by one-half wavelength in exact path travel between aircraft, the points of reflection define an ellipse on the reflecting surface. The area of this elongated ellipse is termed the First Fresnel Zone. It is important because most of the reflected energy arriving at the receiver vicinity is included in this bundle of rays. The region between this ellipse and a second ellipse defined by another half wavelength path difference is termed the Second Fresnel Zone, and so on for successive Fresnel Zones. The second and succeeding zones are decreasingly important in determining the effect at the receiver of the reflections. Fig. 4 illustrates these zones.

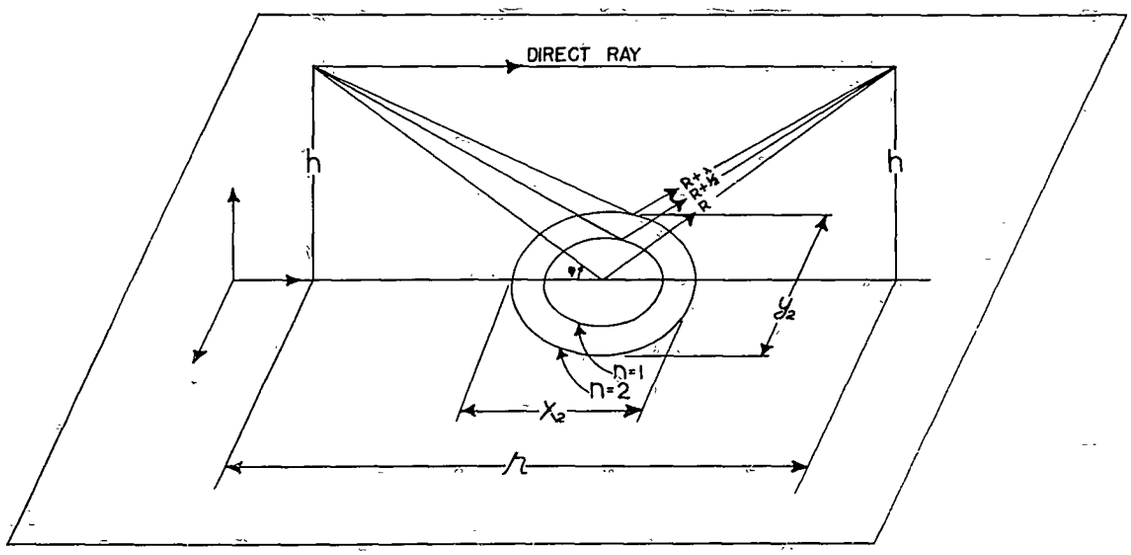


Figure 4. Fresnel Zone Geometry

An excellent discussion of these Fresnel Zones and their importance can be found in the literature (3). With regard to the experiments reported here, it is important to know the extent of these elliptical Fresnel Zones for the conditions imposed. Useful approximations have been derived by Kerr (3) to

yield the length of the major and minor axes of the successive Fresnel Zones. For both aircraft at the same altitude, the approximations can be further reduced to:

$$x = r/\sqrt{1 + \frac{4h^2}{n\lambda r}} \qquad \text{and } y = \sqrt{n\lambda r}$$

where x = length of major axis in miles.
y = length of minor axis in miles.
n = number of Fresnel Zone considered.
r = distance between aircraft in miles.
h = altitude of both aircraft in miles.
λ = operating wavelength in miles.

Upon close examination of these expressions it is apparent that the ellipses are markedly elongated along the line connecting the propagation terminals -- such elongation increasing very rapidly as the range increases to the horizon. For the geometry and operating wavelengths employed, Table I gives the dimensions of the first two Fresnel Zones at various ranges.

TABLE I

r (miles)	freq. (mc)	x_1(miles)	x_2(miles)	y_1(miles)	y_2(miles)
20	250	6.14	8.31	0.122	0.172
20	1000	3.17	4.29	0.062	0.088
20	3300	1.76	2.49	0.034	0.048
30	250	10.95	14.65	0.150	0.211
30	1000	5.83	8.04	0.075	0.106
30	3300	3.22	4.55	0.041	0.058
40	250	16.5	21.6	0.172	0.243
40	1000	8.9	12.2	0.087	0.122
40	3300	4.96	6.99	0.047	0.067

From these data it can be concluded that for aircraft separation ranges up to approximately 40 miles the most important First Fresnel Zone is confined to the surface of the lake. Moreover, calculations related to earth reflections can be valid assuming the major contributing reflections to be from the mirror-smooth fresh water surface.

For some calculations involving ranges greater than 40 miles the actual earth's surface is important. At these ranges the dominant reflecting areas extend beyond the lake boundaries. However, the surrounding terrain is relatively smooth. This is indicated in a terrain profile, Fig. 5, which was derived for that part of the flight path shown on the map in Fig. 2. The small town of St. Marys on the east edge of the lake was estimated to have isolated buildings or structures of approximately 50 feet in height. This estimated region of the profile is shown in cross hatching.

Again, the profile can be important in determining the theoretical maximum range for which the direct and reflected rays can reach the receiving aircraft. All rays or signal received beyond this total horizon range is due to diffraction. This very rapidly decreasing signal with increasing range is indicated by the steep slope near the horizon range. Such slope theoretically is a function of operating wavelength, with steepness increasing with frequency. The possible shortening of the total horizon range by the terrain irregularities indicated is almost negligible. In fact, a 100-foot change in altitude of the center point (the worst case and equivalent to both aircraft changing altitude by 100 feet from 1000 feet) results in a change in total horizon range of approximately 4 miles. For comparison purposes the total horizon range is indicated in Table II, assuming various values for the adjusted earth radius. The 3/3 earth radius applies for geometrical range; 4/3 and 5/4 earth radius apply for accepted standard atmospheres with linearly decreasing index of refraction with altitude.

TABLE II

Altitude of each Aircraft (Feet)	Total Horizon Range (Miles) Actual Earth Radius to be Multiplied by a Factor of:		
	3/3	5/4	4/3
500	54.9	61.2	63.3
600	60.2	67.0	69.3
700	65.0	72.3	74.8
800	69.4	77.4	80.0
900	73.7	82.1	84.9
1000	77.7	86.5	89.5
1100	81.4	90.8	93.9
1200	85.1	94.8	98.1
1300	88.6	98.7	102.1
1400	92.0	102.4	106.0
1500	95.2	106.0	109.6

Another possible result of irregular reflecting surface is that of diffuse scattering of the radio waves rather than uniform and specular reflections. A measure of surface roughness is indicated by K. A. Norton (4) and is dependent on grazing angle, height of the irregularity, and operating frequency. According to Norton a realistic criteria for deciding when the smooth-earth theory may be used with confidence is when

$$h \sin\psi < \lambda/32$$

where, h is the height of the irregularity
ψ is the grazing angle
λ is the operating wavelength.

During the test runs of these experiments the roughness of the earth's surface can be described generally by the above criterion for three separate regions.

(1) Essentially smooth out to ranges short of where the First Fresnel Zone leaves the lake surface.

(2) Essentially smooth at far ranges (and small grazing angles) where $h \sin \psi$ becomes vanishingly small.

(3) Intermediate region between (1) and (2) for which essentially rough conditions are possible, especially for the shorter wavelengths. Under rough conditions the signal level can have either an irregular lobe structure or none at all, but never a regular lobe structure.

Manifestly, the propagation of radio waves is affected to some extent by the refractive index of the medium traversed. In the present experiments this medium is, of course, the bottom 1000 feet of the atmosphere, next to the earth over the flight path. Refractive index, or more important, refractive index gradients, are difficult to obtain over such an extent; such measurements usually involve the accurate measurement of pressure, dry temperature, and partial vapor pressure. More recent devices have been successfully developed independently by G. Birnbaum at the National Bureau of Standards and C. M. Crain, University of Texas, EERL, using microwave cavity techniques. Flying safety prohibited these airborne measurements to be taken at very low altitudes. As the more important phenomena related to earth reflections, particularly at ranges under 40 miles, are not affected seriously by refractive effects, the present experiments involved no extensive meteorological measurements. Although some unexplained deviations in the data from theoretical can be attributed to atmospheric refraction, no serious discussion of this will be attempted.

Some mention of the general weather situation is in order. These tests were performed on 20 March 1951 from about 1130 to 1530 EST. The entire area was blanketed with approximately two inches of snow which had been deposited during the passage of a low pressure cell some 36 hours before. Although the surface air temperature was approximately 0°C, there was no indication of ice on the mirror smooth lake. A weak high pressure cell extended over the test area with visibility excellent and clear sky. Although of no particular importance, the surrounding radiosonde stations within 200 miles indicated a moderate subsidence at 5000 feet MSL.

The propagation measuring equipment used in these tests was used extensively in collecting propagation data on previous high altitude air-to-air flights. Although details of its characteristics have been given in a previous report on these earlier tests (5), general characteristics are offered here for completeness. Three separate propagation links were operated simultaneously; namely, 250 mc and 1000 mc interrupted continuous wave, crystal controlled at 1818.18 cps; and 3300 mc, 2.25 microsecond pulse, 320 pps. All polarizations were vertical. The power output of all three transmitters was monitored continuously

and found to vary less than one-half decibel. The main inverter voltage in both aircraft was also recorded continuously and found to have negligible variation. The receiver-recorder installation was calibrated with appropriate signal generators several times before and after each of the three test runs. All recordings were performed using the Model AW Esterline-Angus, zero to one milliampere, ink recording milliammeter, with a chart speed of three inches per minute. The 0.5-sec time constant of this instrument was actually the limiting factor for the frequency response of the propagation recording system; such response was a maximum of about two cycles per second.

In order to ensure that no observed signal variations were due to antenna patterns while the aircraft yawed or pitched, all antennas were located and measured such that gain variations over a 20° cone directly to the rear of each aircraft were negligible.

As a result of exhaustive tests both on the bench and in the air, it can be concluded that all fluctuations in signal strength observed and recorded represented actual changes in field strength due to propagation phenomena.

III. DATA AND RESULTS

The original recorded data are shown in Fig. 6, 7, and 8. No data are shown for the third run for 3300 mc; the receiver was inadvertently detuned just prior to the run and the rapid excursions of signal level prevented immediate retuning. Increasing mileage between aircraft is indicated from right to left at the bottom of each chart. Signal level decreases from a maximum at the top to receiver noise level near the bottom. As there is some nonlinearity over the dynamic range of the receivers, a calibration for each run is indicated on each chart.

In order to examine further some features of the recorded data it was found convenient to replot for each mile on linear-linear graph paper the signal level in db (decibels) below 0.1 volt (50 ohms) vs separation of aircraft. Such replots are shown in Figs. 9, 10, and 11, where the signal level envelope is plotted over the region of rapid lobe rate. Superimposed on each of these replots are curves representing the theoretical envelope of the interference lobe structure and the theoretical curve for propagation in free space. These theoretical curves were derived from common formulas available in the literature (6). The lake surface was assumed to have a dielectric constant of 80 and a conductivity of 1×10^{-14} emu. It should be noted that for the frequencies involved, the shape of these curves is essentially independent of the operating wavelength.

Several remarks concerning these replots are justified. In all the data, the free space trend is apparent, with good correlation out to ranges well within the interference region. Moreover, the signal level is fairly well confined to the theoretical envelope.

It appears that the total horizon range obtained in these experiments is somewhat less than theoretical. In this respect, it is interesting to examine the location and character of the last interference lobe (first one back from the total horizon range). This lobe is well defined in all the data and can serve as a yardstick for comparison with theoretical. Theoretically, the exact location of the maxima of this lobe is a function of altitude of each aircraft, operating frequency, and the particular linear refractive index lapse rate assumed for the atmosphere. Although the details of these calculations are tedious, they have been greatly simplified by methods and charts recently available. (7). By making use of these expedients and assuming various index profiles, the exact location of these lobe maxima have been derived for each of the three pertinent operating wavelengths and an altitude for both aircraft of 1000 feet. The assumed profiles were derived from assuming an effective earth's radius of 3/3, 5/4, and 4/3 of actual. The use of 3/3 earth radius is tantamount to assuming a constant index vs altitude, whereas, the conventional use of 4/3 results from assuming a linear lapse rate of twelve $(n - 1)\ 10^6$ units per thousand feet. The use of the 5/4 earth radius representation has been employed extensively by Booker (8). Fig. 12 represents the actual plot of the experimental data for all the last lobes with theoretical locations of maxima, assuming various earth radii. From these plots it appears that the actual conditions encountered for these tests were such that the integrated refractive effect over the propagation path approached that to be expected from 3/3 earth radius conditions. More simply, the actual location of the lobe maxima compares favorably with a theoretical that assumes a constant index of refraction profile (zero gradient). This situation, referred to as a substandard condition, is rather uncommon. A more likely explanation would involve perhaps a marked substandard condition for the lower 100 feet or so of air next to the earth with an ordinary lapsing index on up to 1000 feet. Propagation through such a medium can result in an overall effect similar to that indicated in the data.

At this time it is interesting to compare the slope of the decaying signal near the end of the runs for each frequency. As the signal beyond the total horizon range is due predominately to diffraction, this diffraction field can be computed using first mode theory and the well established relationship due to Booker (9):

$$\text{Rate of signal level drop} = 25.8 \text{ db per } \left[\lambda\,(ka)^2\right]^{1/3} \text{ miles}$$

Where: λ is operating wavelength in miles
a is actual earth's radius in miles
k is assumed factor modifying the earth's radius

Table III gives various diffraction slopes derived from this expression.

TABLE III DIFFRACTION SLOPES IN DB. PER MILE

Operating Frequency (mc)	k		
	3/3	5/4	4/3
250	1.14	0.98	0.938
1000	1.81	1.56	1.495
3300	2.68	2.28	2.22

Differences between theoretical and actual slopes are difficult to reconcile and will not be discussed further except to note that pure diffraction conditions were not duplicated in these experiments, and even the theoretical slope shown (that due to first mode) is valid only for ranges well beyond the horizon. It does appear that the slope resulting from assuming a 3/3 earth's radius approximates more closely the experimental data. These theoretical slopes are indicated in the right portion of Figs. 9, 10 and 11.

Turning again to the original data recordings of Figs. 6, 7, and 8, it is fruitful to examine the actual lobe rate for the various frequencies involved. This lobe frequency is dependent in a complicated way on altitude, range and grazing angle, and operating frequency. In more simple terms, the signal level will change from any maximum to an adjacent minimum when the path length difference between direct and reflected rays is half the operating wavelength. The theoretical values of this lobe rate for the three frequencies employed have been calculated and are presented in Figs. 13, 14, and 15, as a continuous solid line. The actual values derived from measurements on the original recordings are shown as single points. These curves indicate quantitatively a characteristic apparent in the recording; namely, a considerable irregularity in lobe rate. For some portions of the recording there appears to be a slight frequency modulation superimposed; in other more severe cases, one or more lobe maxima or minima appear to be washed out altogether. In many portions of the data, the maximum or minimum has been appreciably displaced in range.

The above phenomena of irregular lobe rate has a ready explanation, suggested by Dr. Donald E. Kerr during extensive private consultation on these experiments. As indicated before, a change of path difference between direct and reflected rays by a half wavelength will slide the signal from a maximum to a minimum. This change in path length difference is accutely sensitive to aircraft altitude for the geometry involved. This is especially true for the shorter wavelengths. The exact relationship for both aircraft at 1000 feet is depicted graphically in Fig. 16. Consider, for example, the case of 20 miles separation. If either aircraft changed altitude by only 8 feet, the 3300-mc signal level would change from maximum to minimum. The same effect would be experienced for the 1000-mc and 250-mc signals, respectively, by either aircraft changing altitude by 27 feet and 103 feet. If excursions in altitude of both aircraft occur, this effect can be doubled. If one aircraft "bounced" through a minimum it might do so with such speed that the Esterline-

lobe structure, but remain near the free space level. In this case, the indicated ρ would be zero. This reasoning can be used in an attempt to explain the very wide scatter in ρ evidenced in Figs. 23 and 24. In fact, toward the end of each run in the original data, the definite lobe structure seems to be absent except for 250 mc. The corresponding reflection coefficients for this region would approach zero.

IV. CONCLUSIONS

Results of these experiments and subsequent calculations suggest several important conclusions. The conditions of the experiment were satisfactory for observing phenomena peculiar to air-to-air tropospheric propagation over smooth fresh water. Such phenomena include the effect of earth reflections and, to a lesser degree, the refractive effect of the earth's atmosphere.

From an examination of the data presented herein, the following specific conclusions can be drawn:

(1) From the best fit free space curves indicated in the replotted data, Figs. 9, 10, 11, the general trend of signal strength vs range follows an inverse distance curve.

(2) The actual lobe structure envelopes compare favorably with the theoretical, especially at close range. Notable exceptions are evident in Figs. 9, 10, and 11, where the lower envelope boundary sags below theoretical in all cases. At long ranges the envelope correlation is poor. As the theoretical exceeds in range the actual in all cases, a substandard refractive condition is suggested.

(3) The experimental diffraction slopes approach closely those frequency dependent slopes theoretically calculated assuming first mode diffraction theory. Close examination indicates better correlation of actual with theoretical slopes when a 3/3 earth's radius (substandard atmosphere) is assumed.

(4) The position of the last lobe maxima for all three test runs occurred near that anticipated for a 3/3 earth's radius.

(5) No severe or extended fades in signal level were occasioned that could not be explained on the basis of earth reflections.

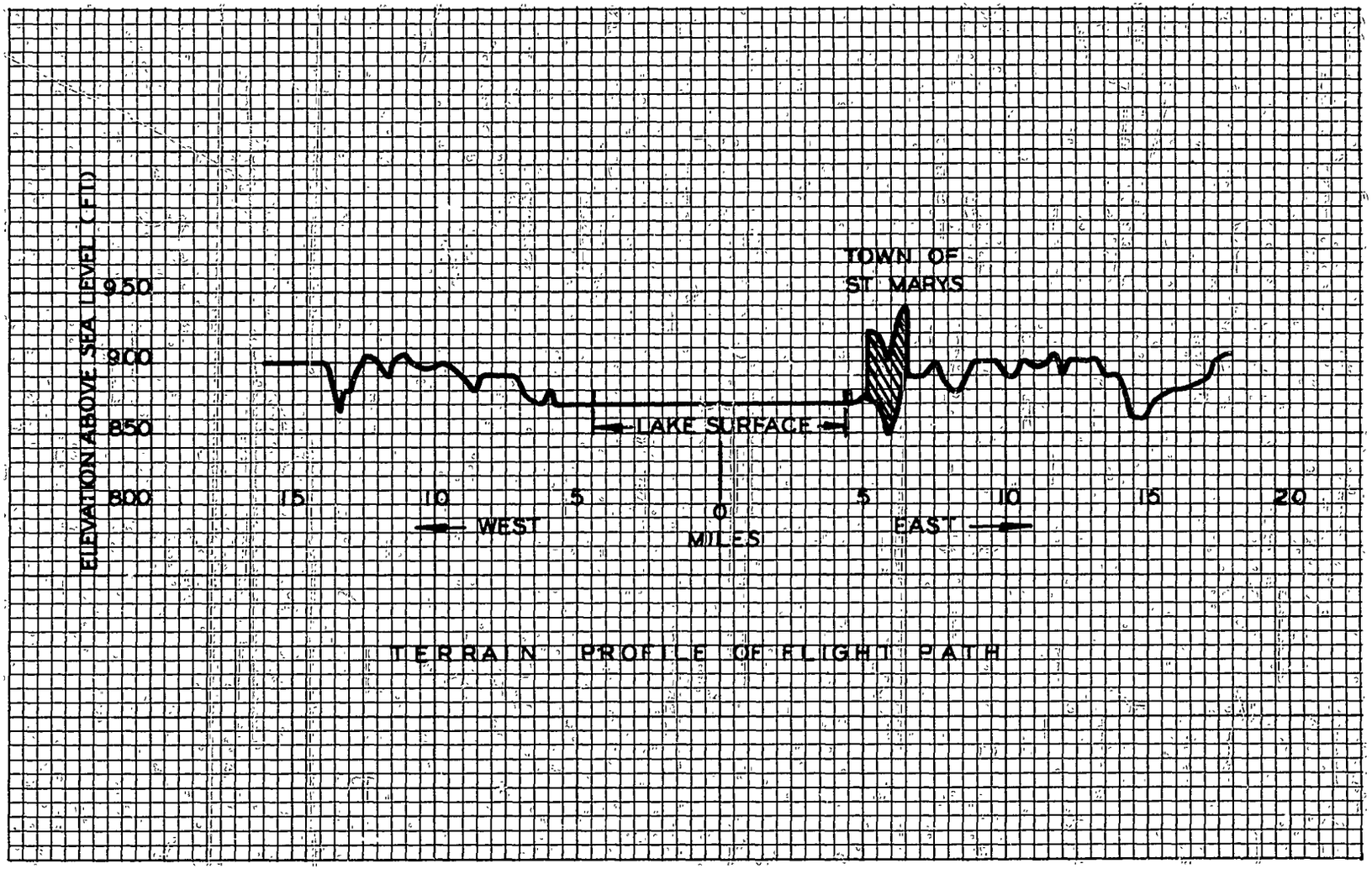
(6) The actual signal lobe rates follow in general the theoretical value for each operating frequency. The occasional scatter of actual rates is legitimately attributable to unavoidable vertical motion of the aircraft during the test runs.

(7) Reflection coefficients calculated from recorded signal maxima and

minima compare favorably with theoretical values for smooth fresh water. Small departures close in can stem from sudden vertical motion of the aircraft by changing the relative phase of direct and reflected rays. The major deviations, however, for low grazing angles (far ranges) result from an apparent reduction or loss in ground reflected ray. Possible causes of this are:

(a) Partial diffuse scattering of the earth reflected rays, and

(b) Actual physical obstruction of these rays coupled with anomalous refraction and shifting grazing angle.


ELEVATION ABOVE SEA LEVEL (FT)
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900
850
800
TOWN OF
ST MARYS
LAKE SURFACE
15
10
5
0
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10
15
20
WEST
MILES
EAST
TERRAIN PROFILE OF FLIGHT PATH

FIGURE 5

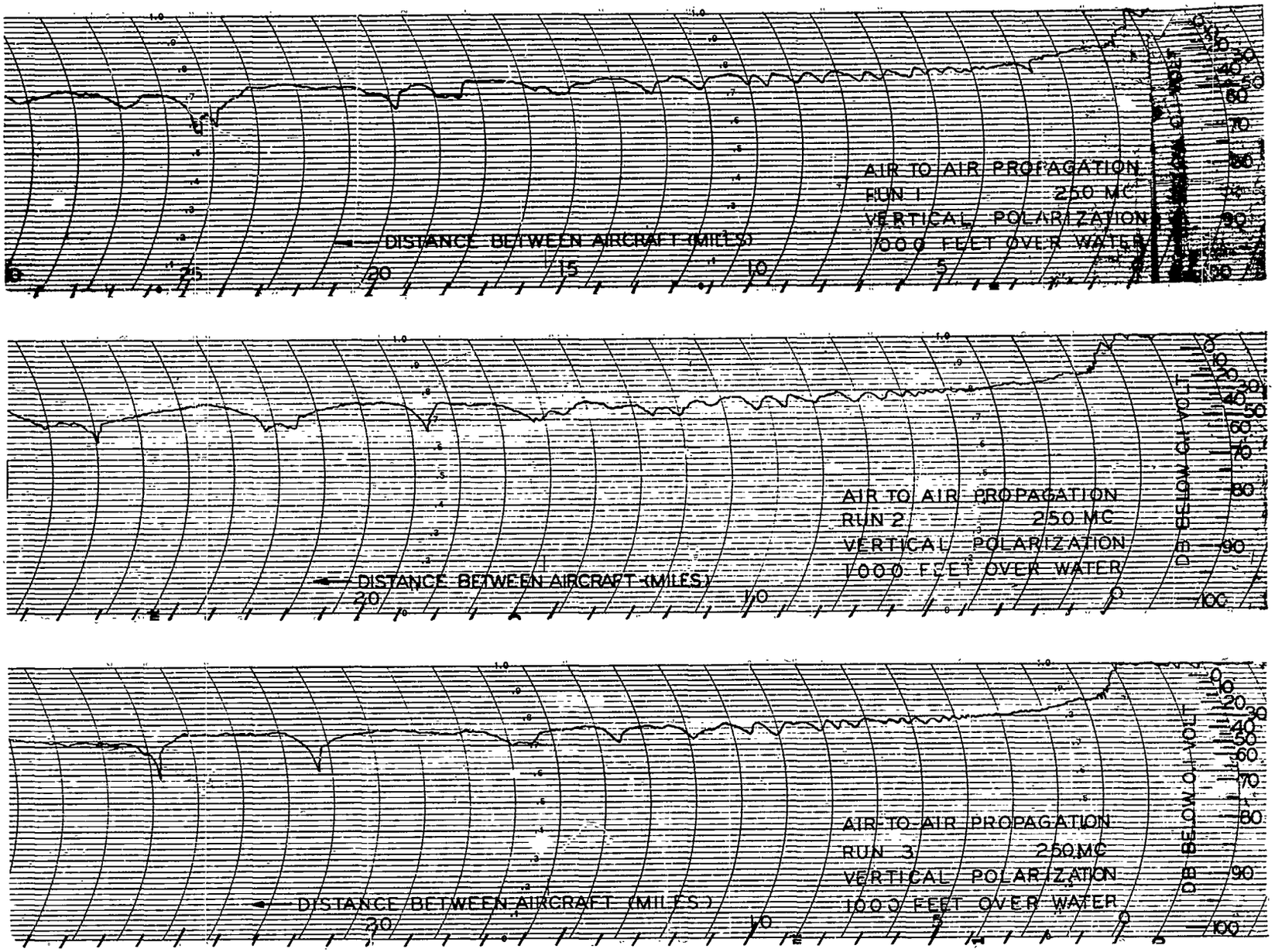

FIGURE 6. Recorded Data, 250 mc.

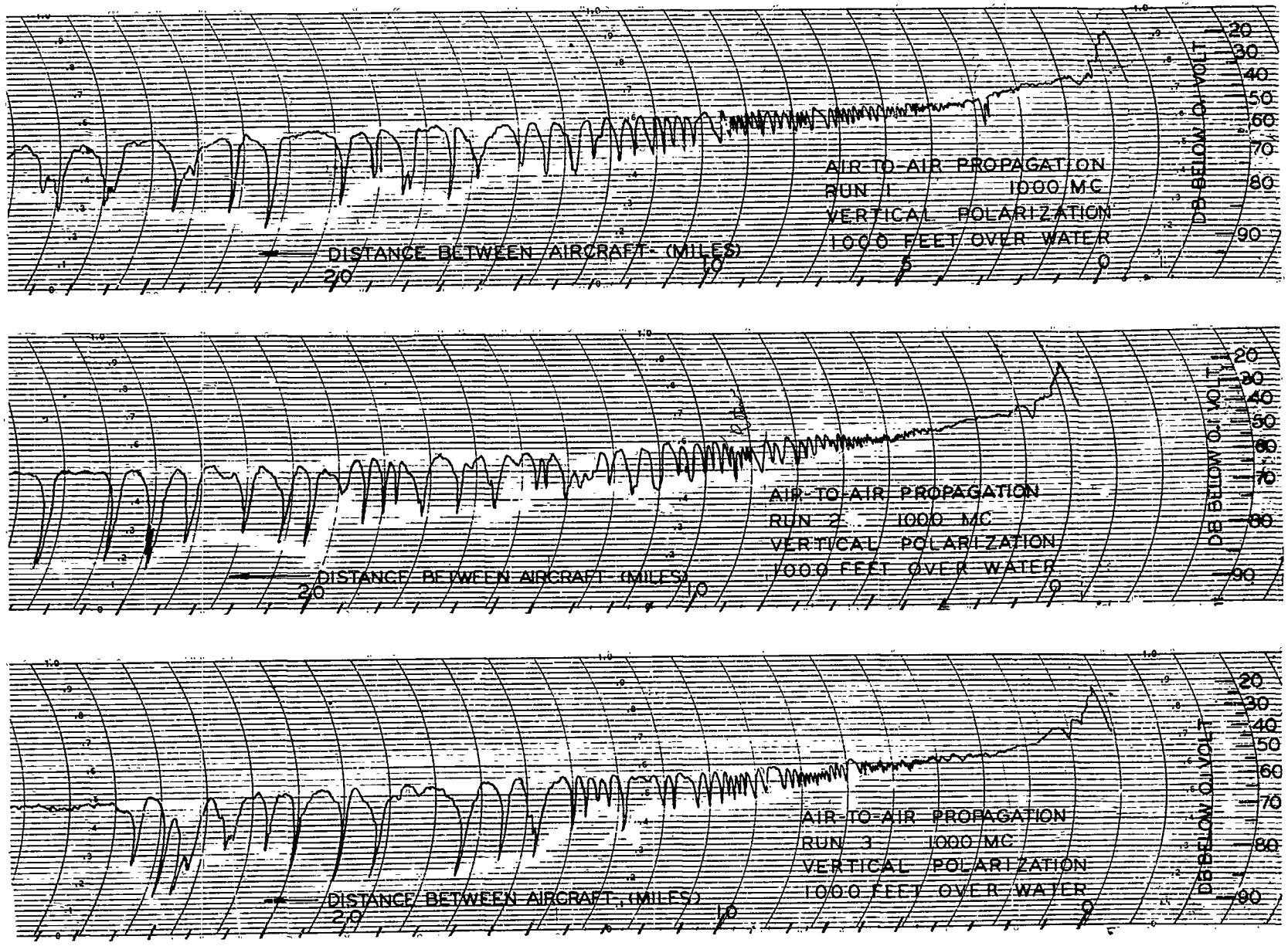

FIGURE 7. Recorded Data, 1000 mc.

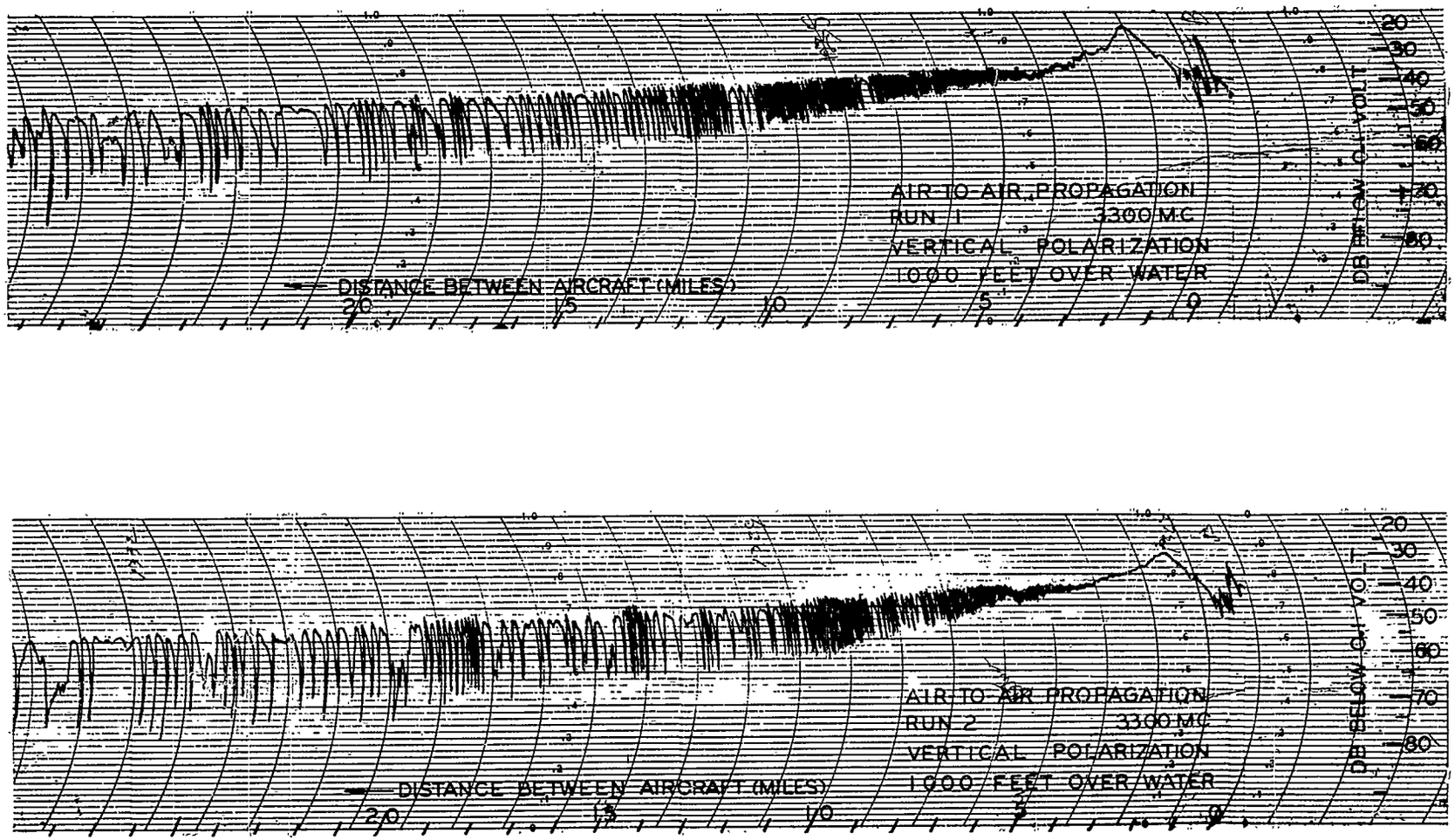

FIGURE 8. Recorded Data, 3300 mc.

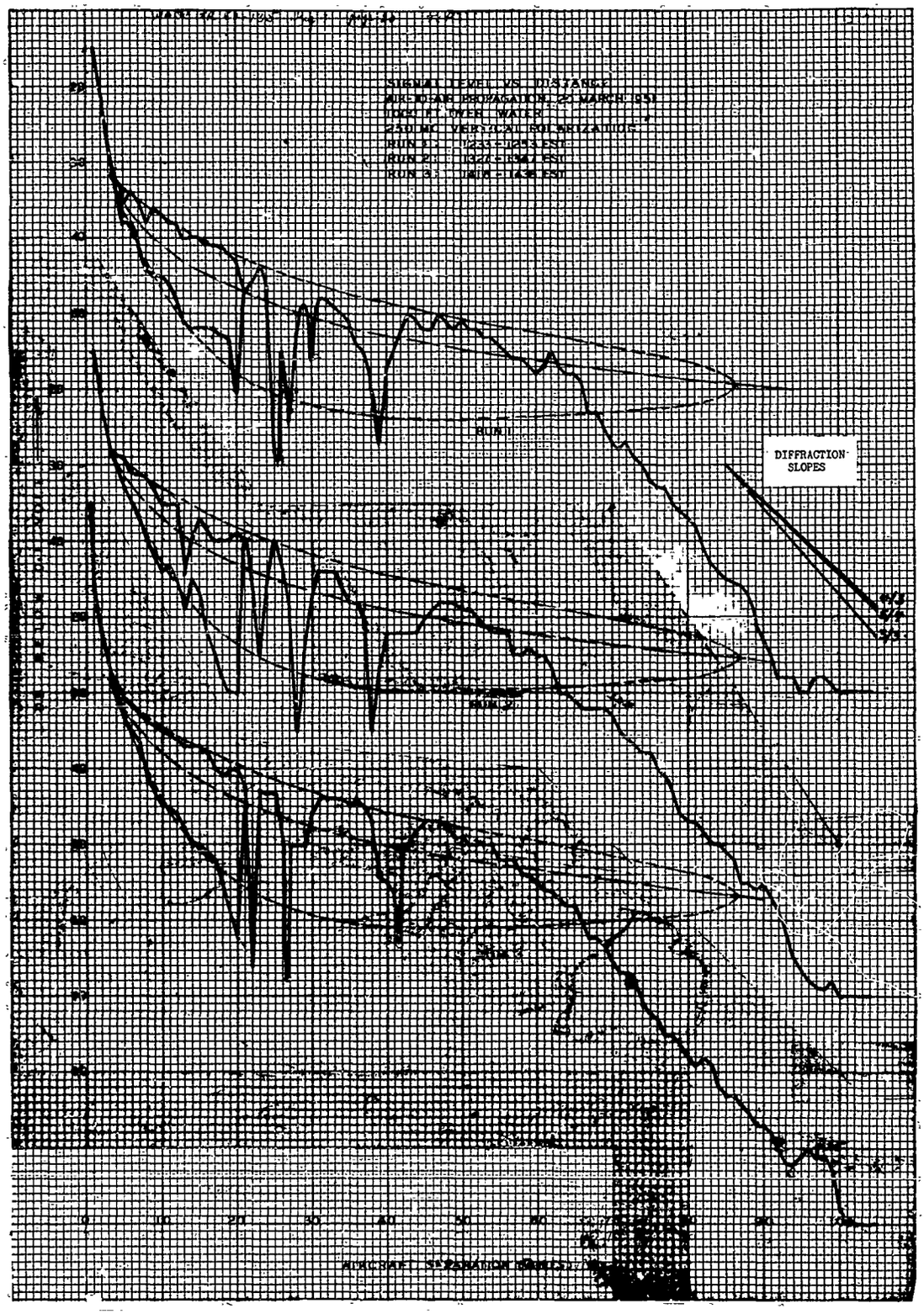

FIGURE 9. Signal Level vs Distance, 250 mc.

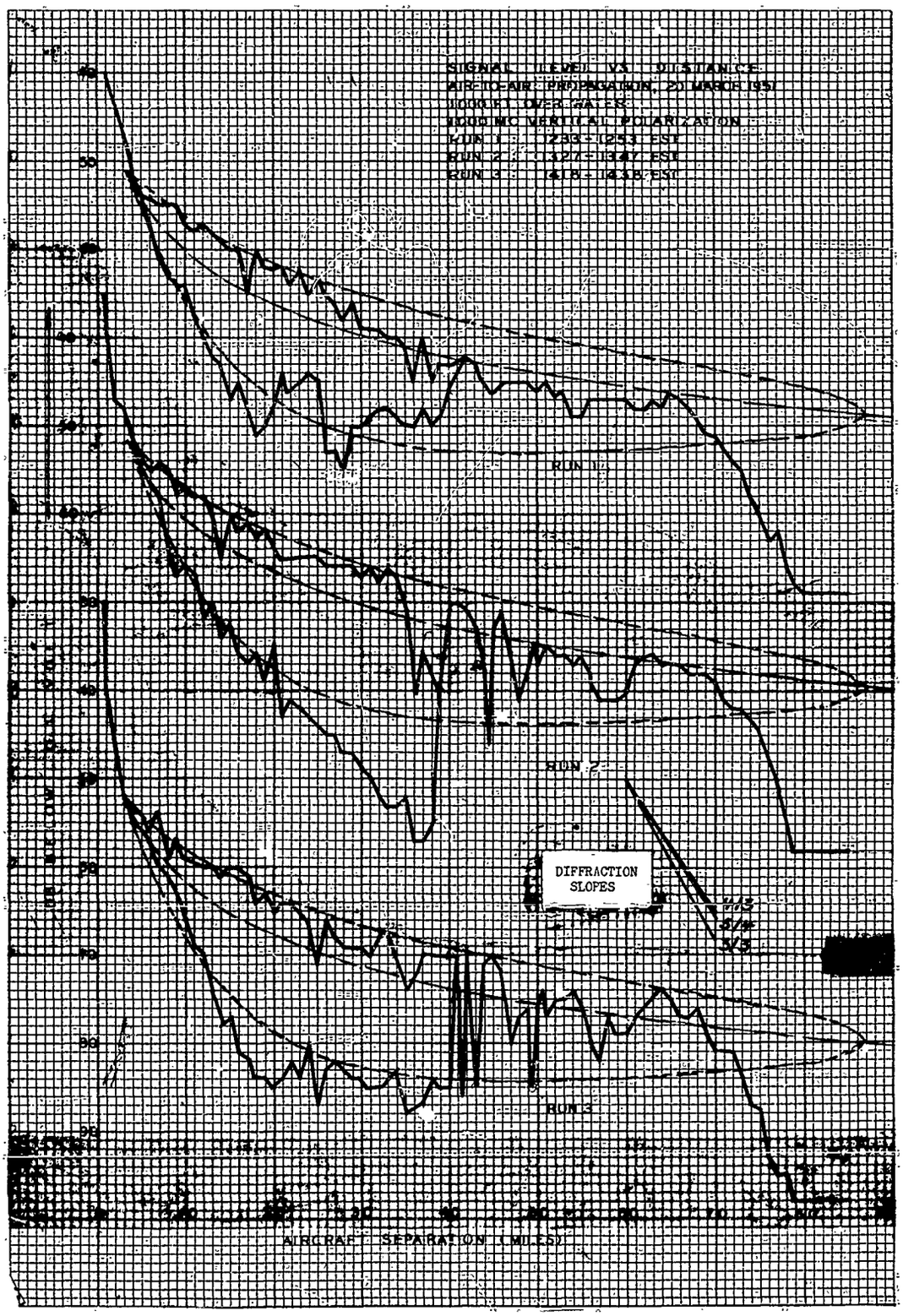

FIGURE 10. Signal Level vs Distance, 1000 mc.

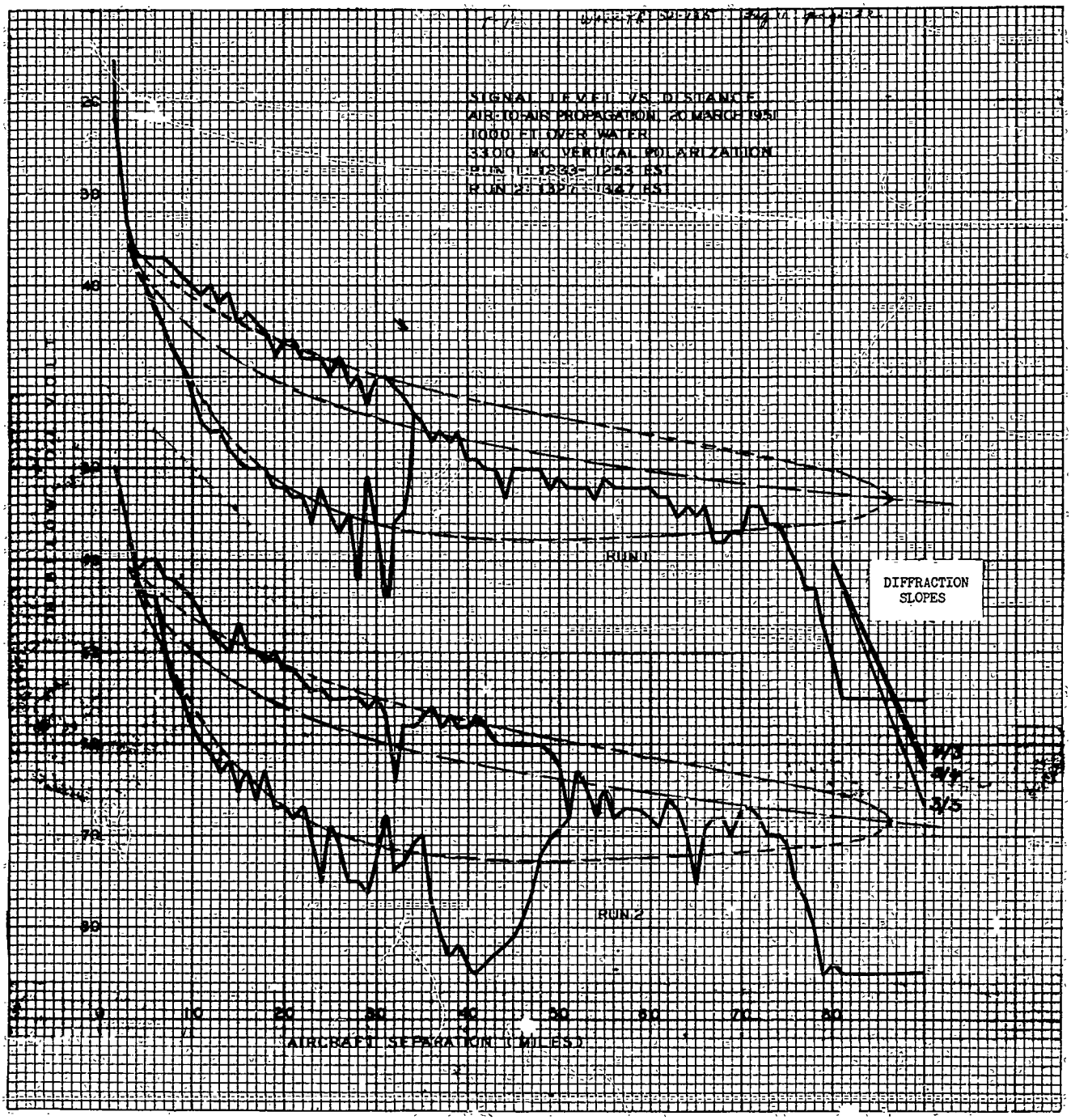

FIGURE 11. Signal Level vs Distance, 3300 mc.

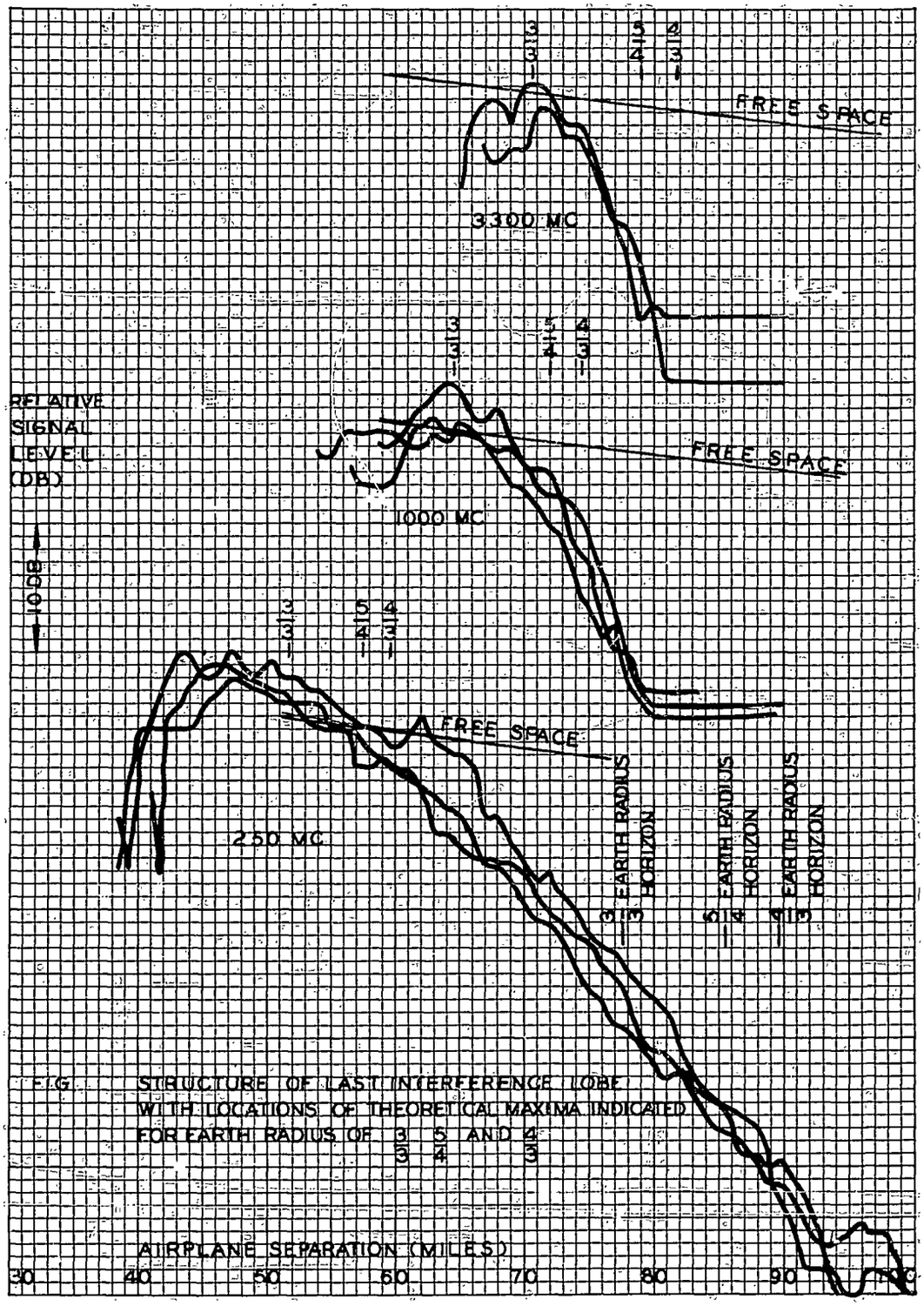

FIG. STRUCTURE OF LAST INTERFERENCE LOBE WITH LOCATIONS OF THEORETICAL MAXIMA INDICATED FOR EARTH RADIUS OF 3/3, 5/4 AND 4/3

FIGURE 12. Structure of Last Interference Lobe

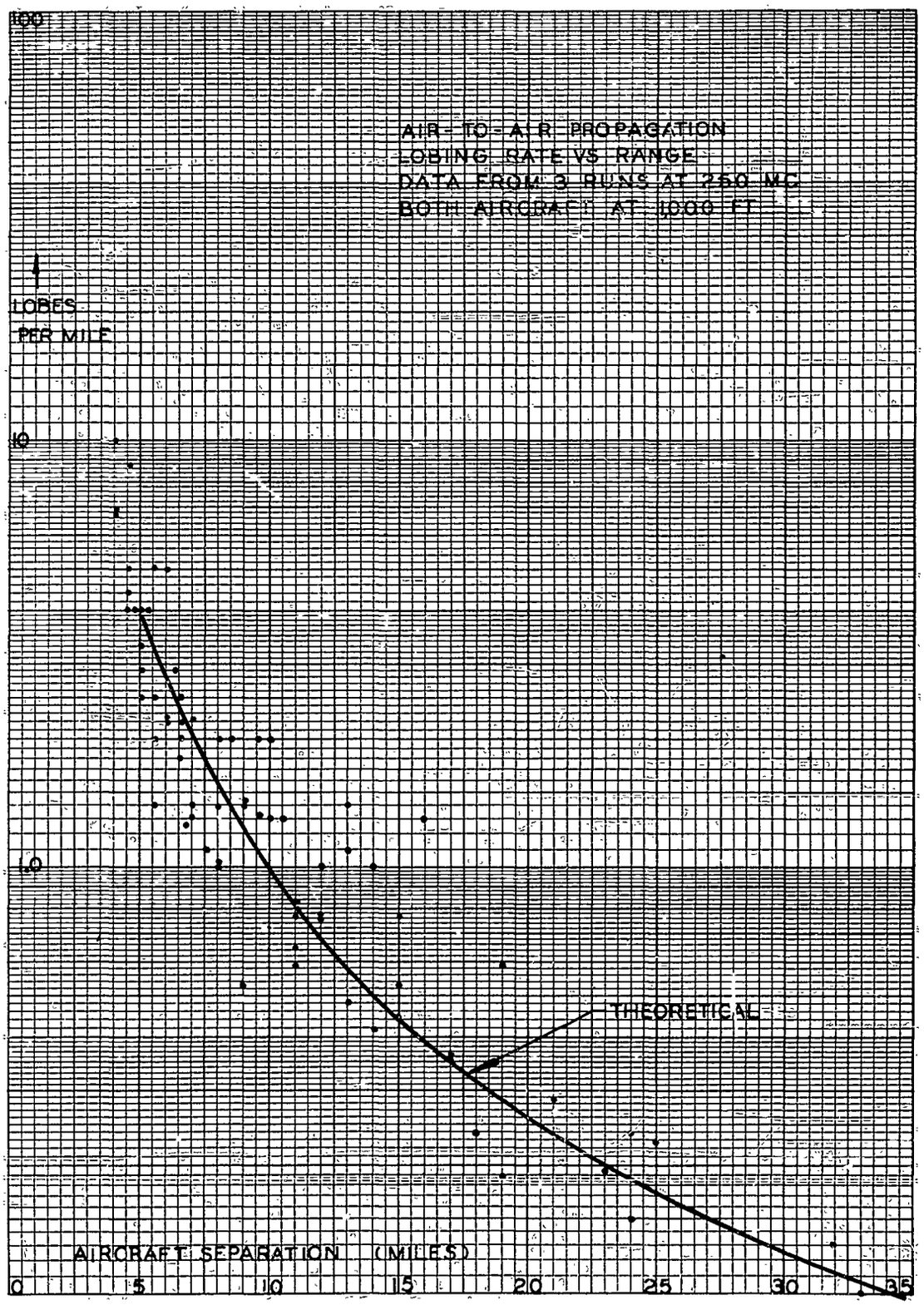

FIGURE 13. Lobing Rate vs Range, 250 mc.

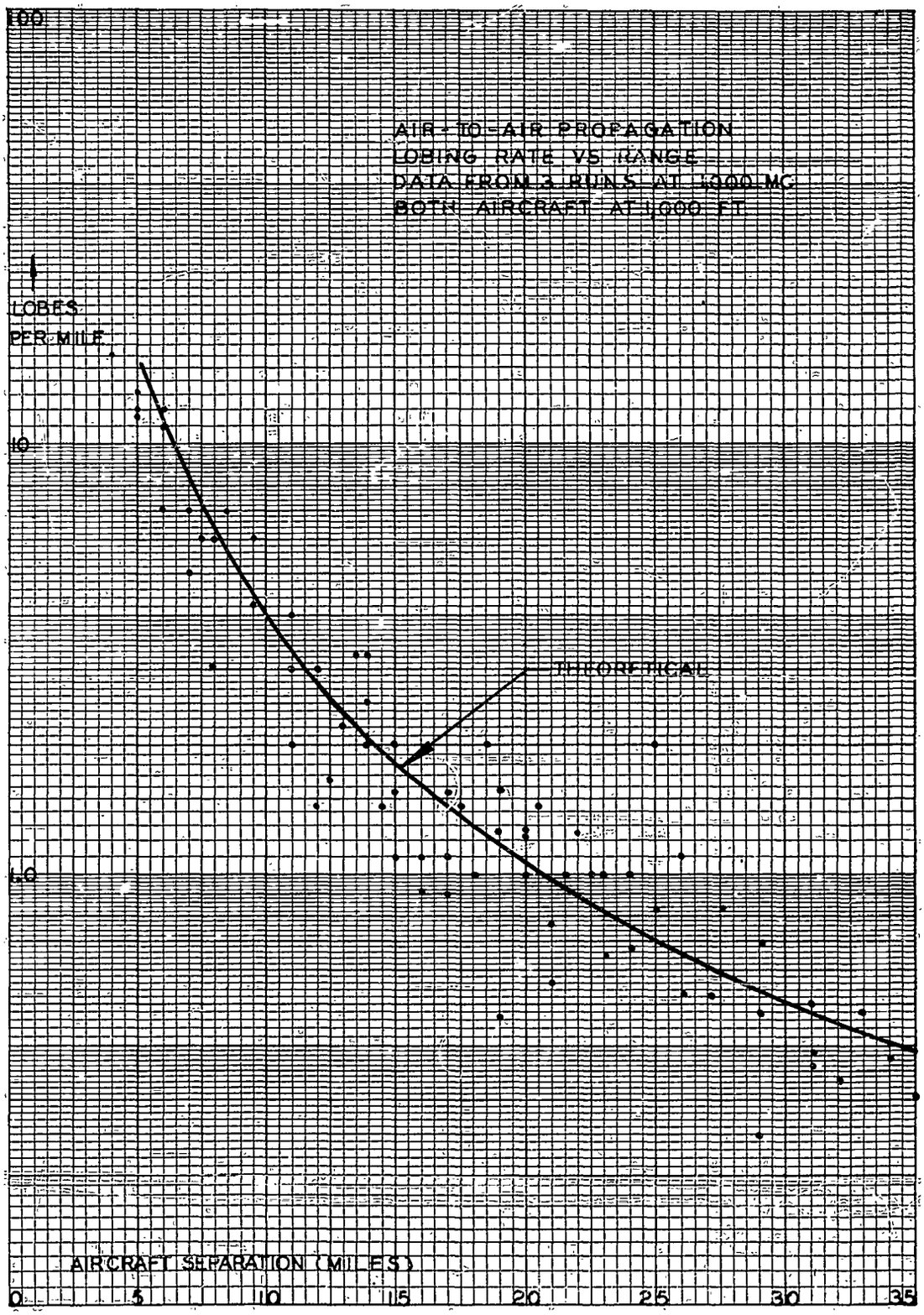

FIGURE 14. Lobing Rate vs Range, 1000 mc.

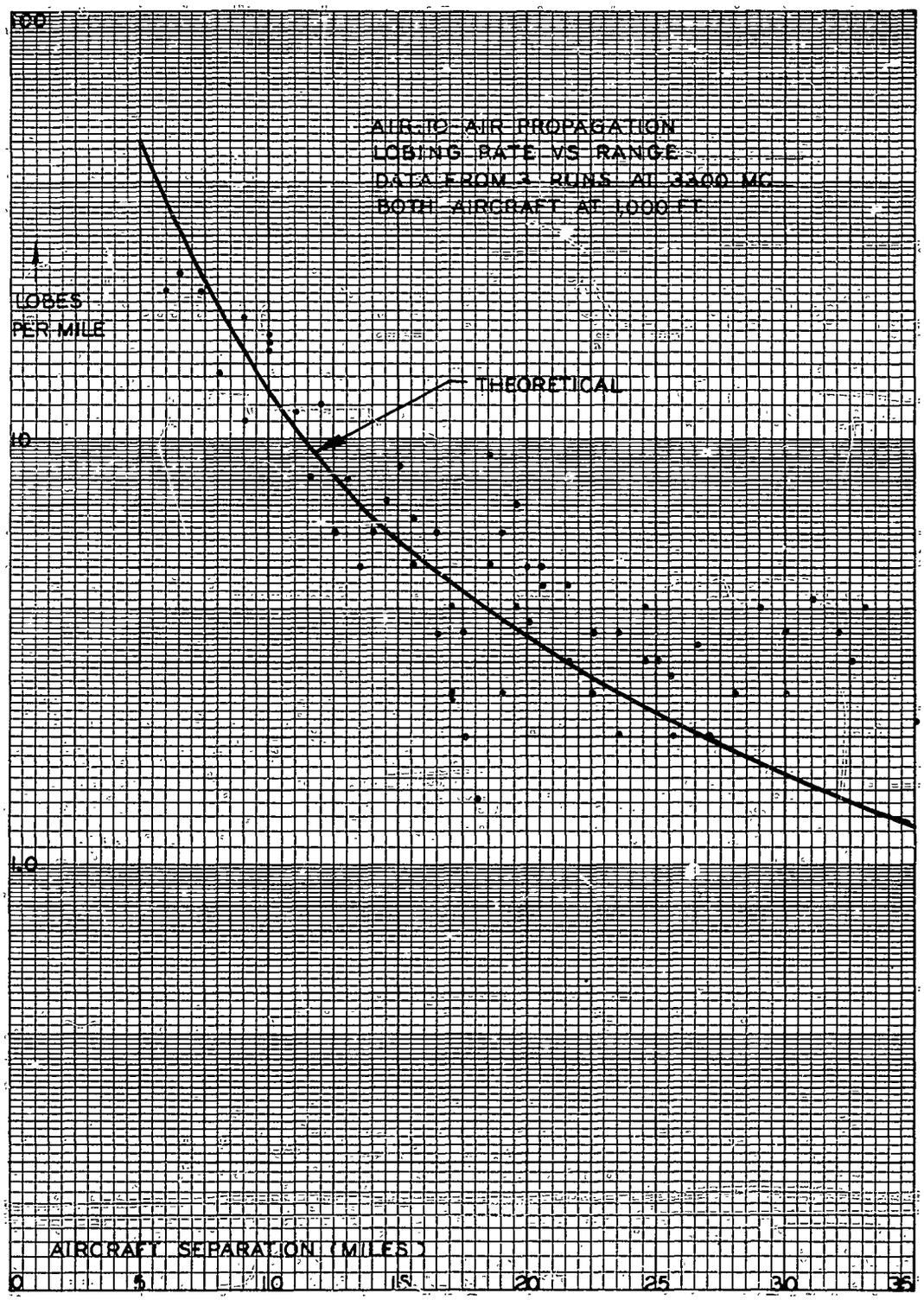

FIGURE 15. Lobing Rate vs Range, 3300 mc.

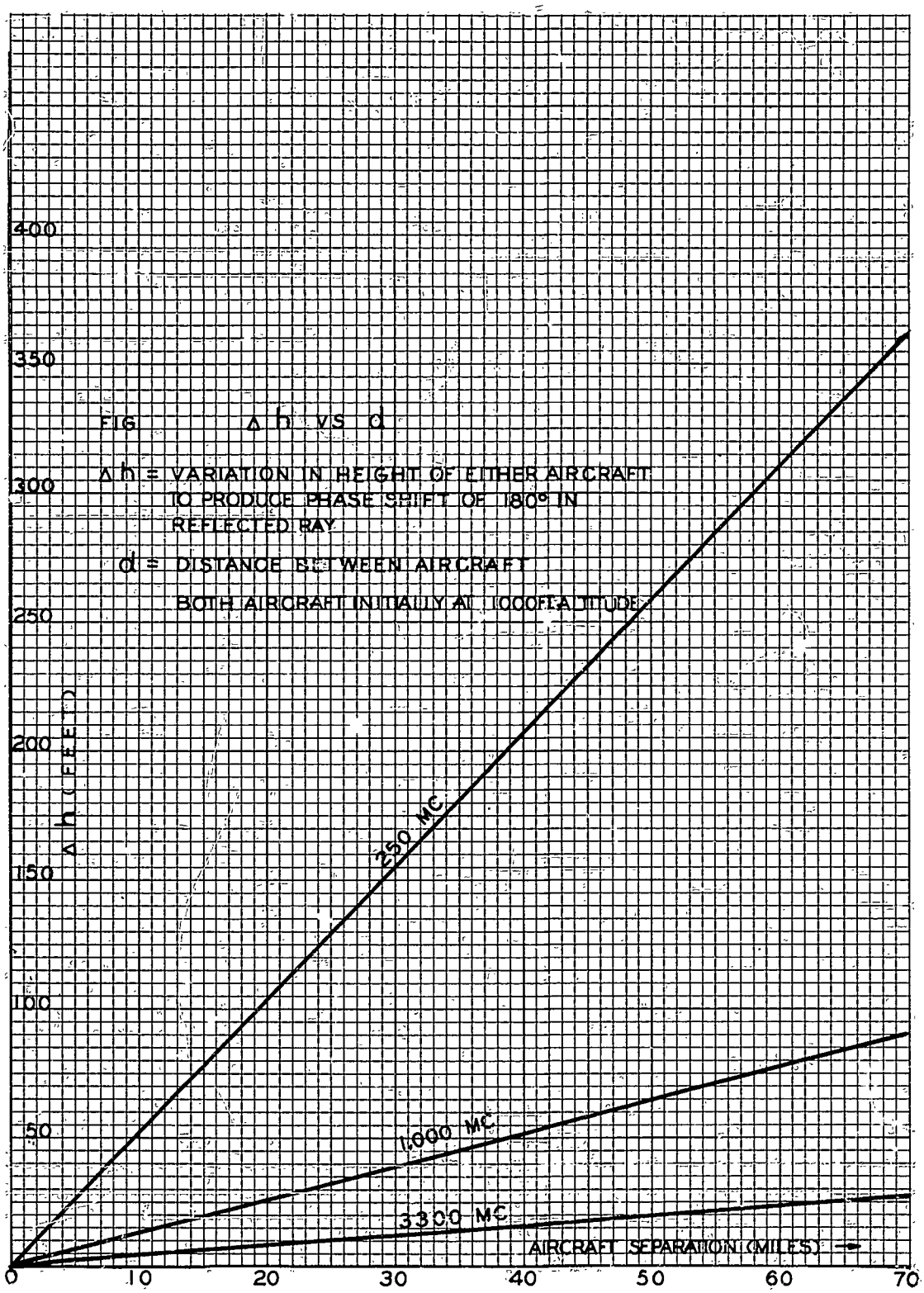

FIGURE 16. Delta h vs Range

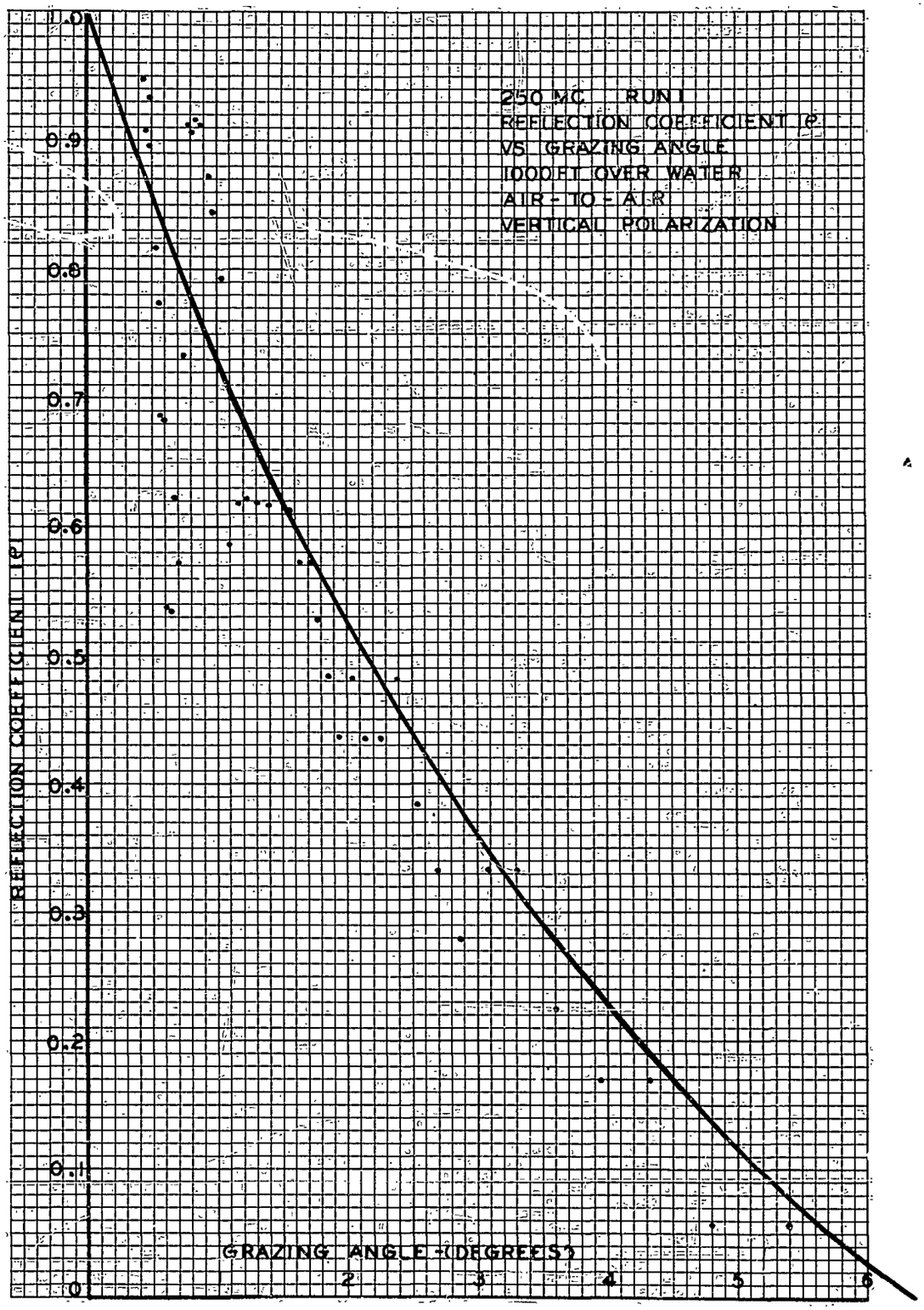

FIGURE 17. Reflection Coefficient vs Grazing Angle, 250 mc. (Run 1)

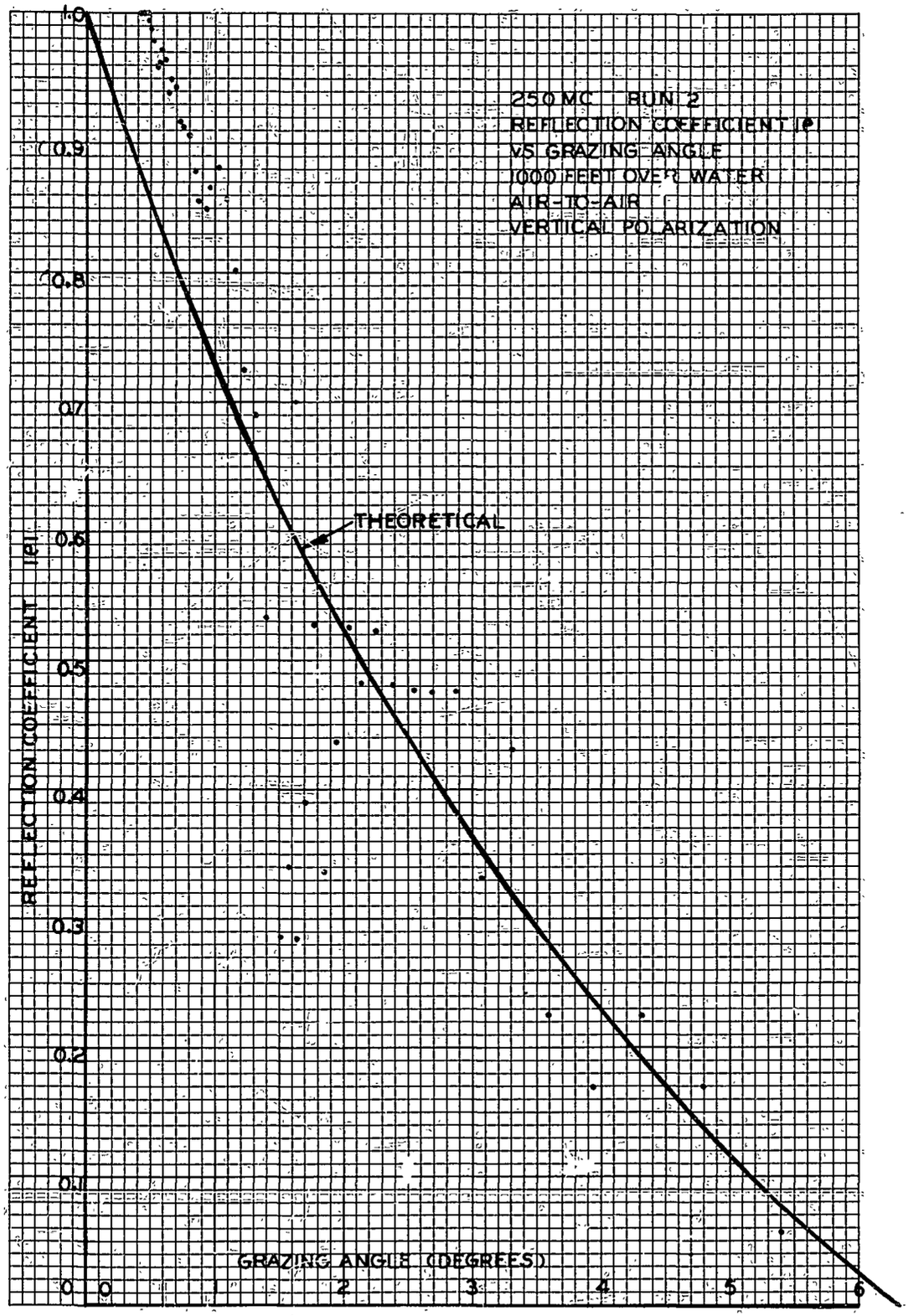

FIGURE 18. Reflection Coefficient vs Grazing Angle, 250 mc. (Run 2)

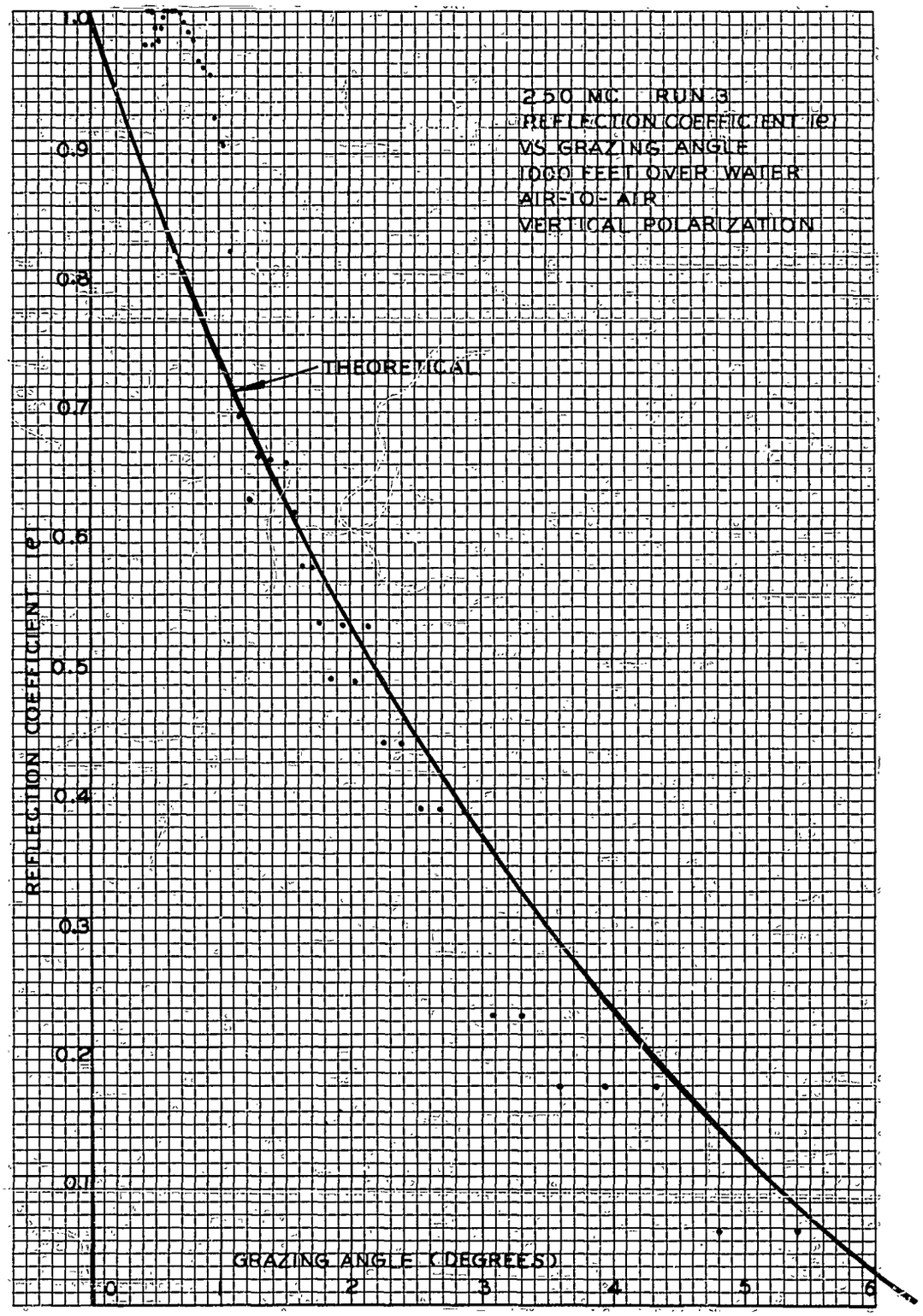

FIGURE 19. Reflection Coefficient vs Grazing Angle, 250 mc. (Run 3)

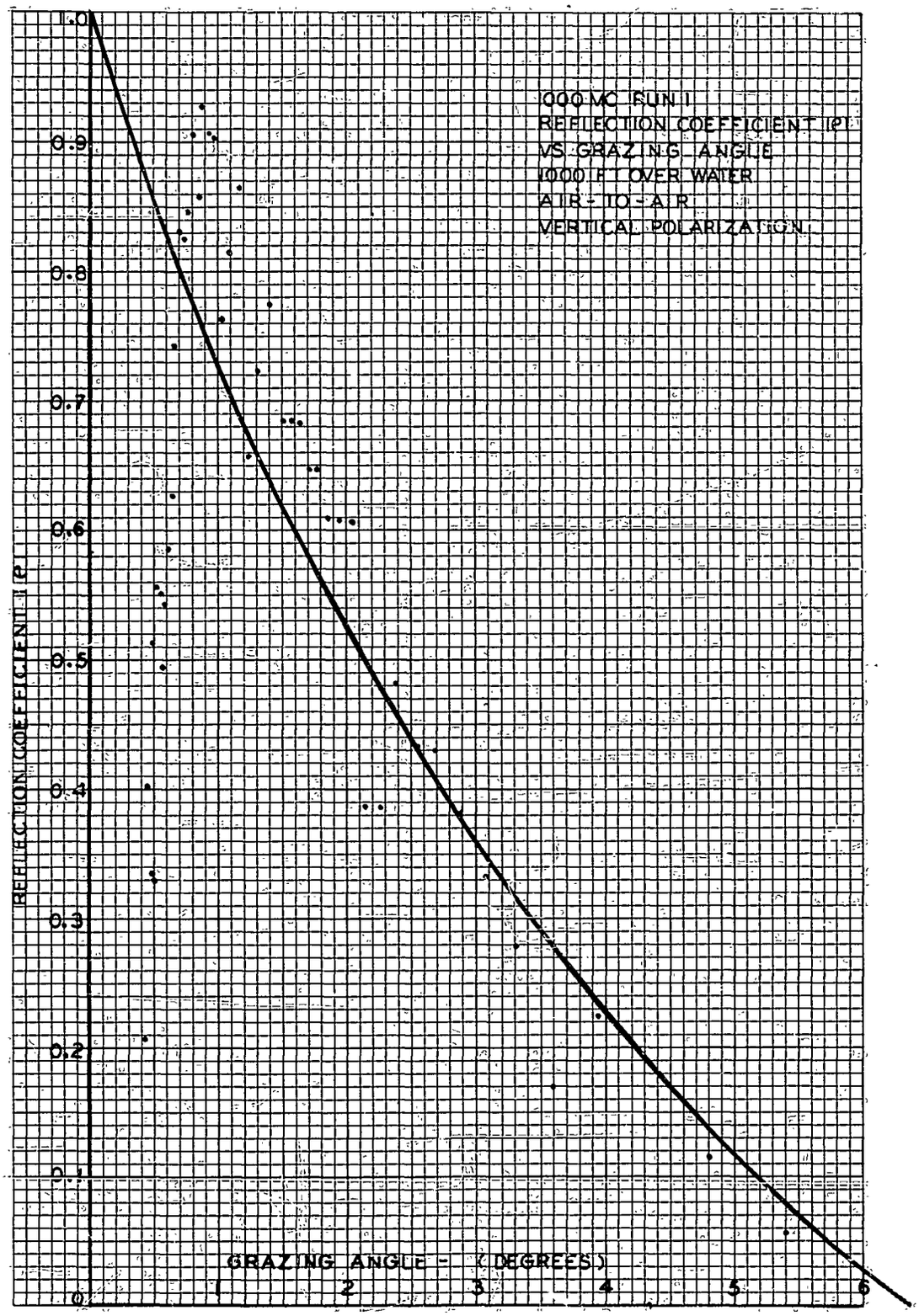

FIGURE 20. Reflection Coefficient vs Grazing Angle, 1000 mc. (Run 1)

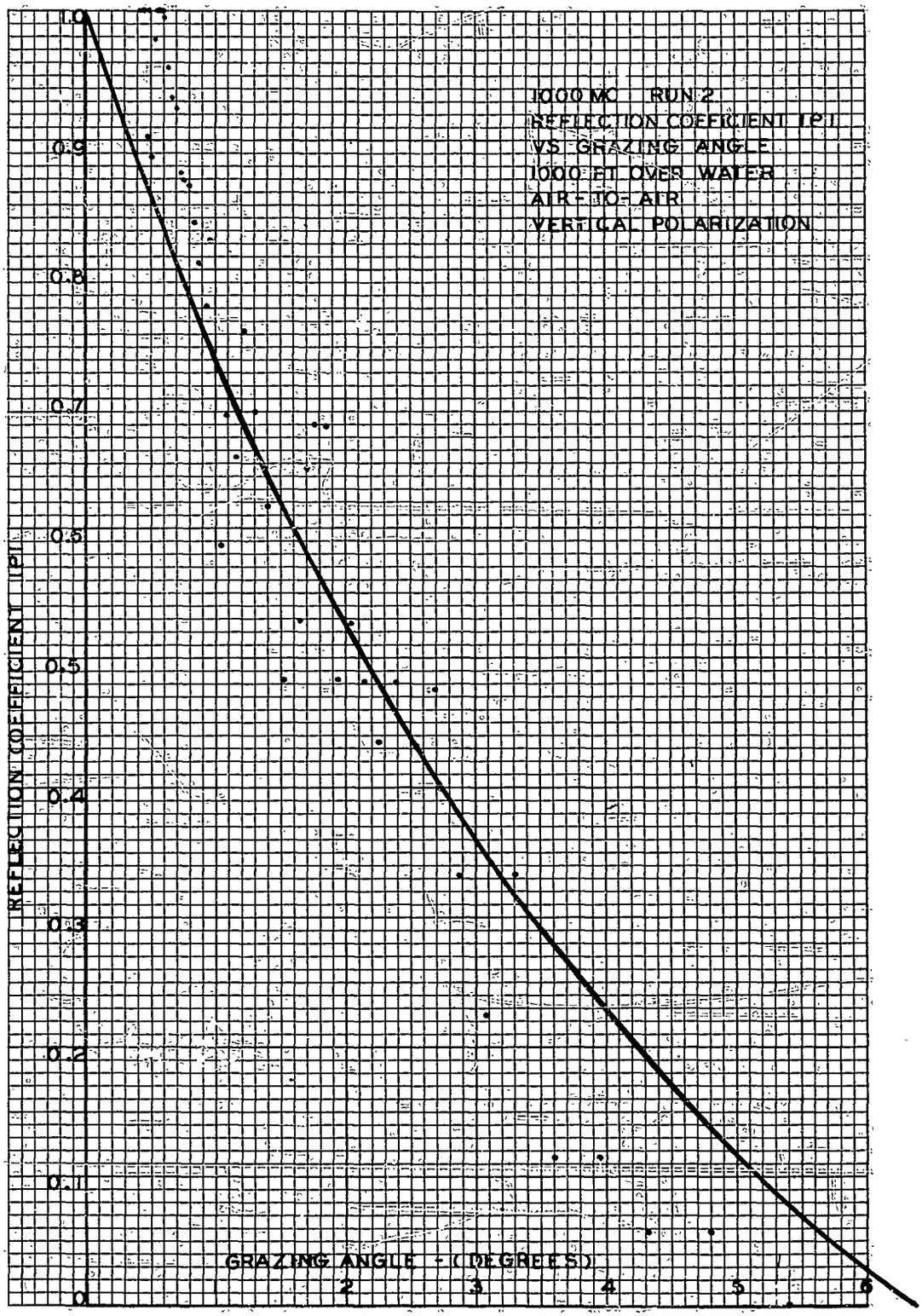

FIGURE 21. Reflection Coefficient vs Grazing Angle, 1000 mc. (Run 2)

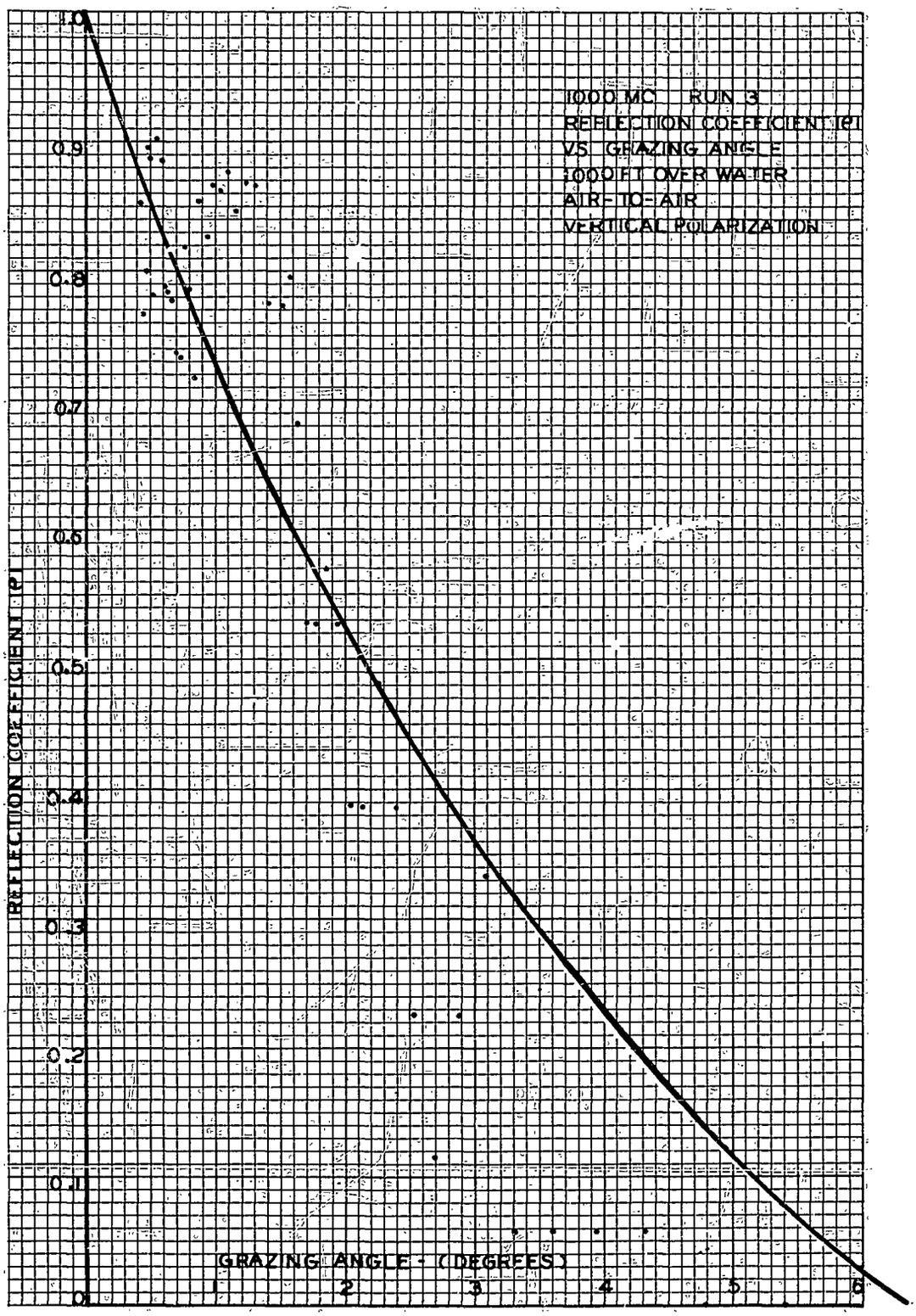

FIGURE 22. Reflection Coefficient vs Grazing Angle, 1000 mc. (Run 3)

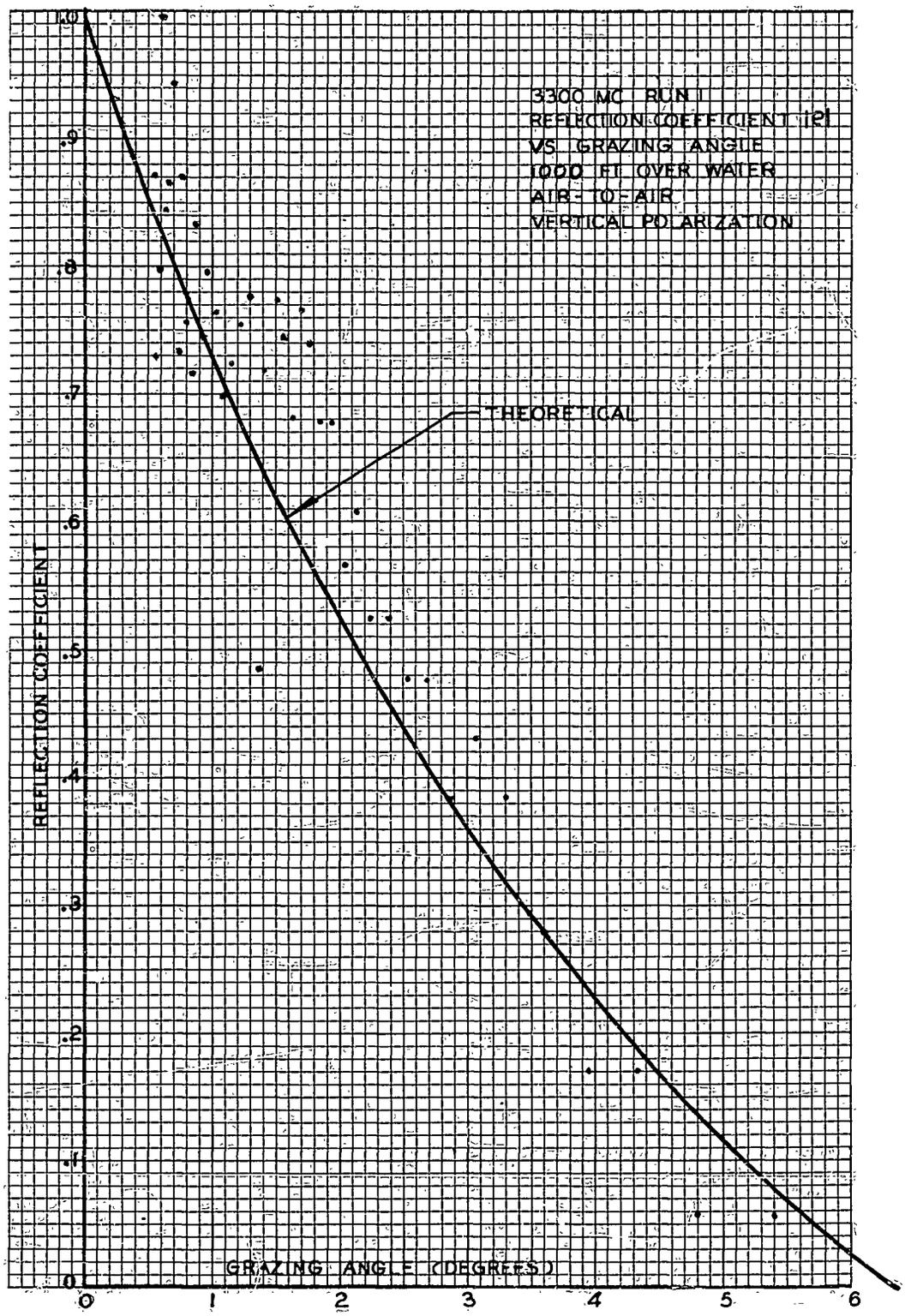

FIGURE 23. Reflection Coefficient vs Grazing Angle, 3300 mc. (Run 1)

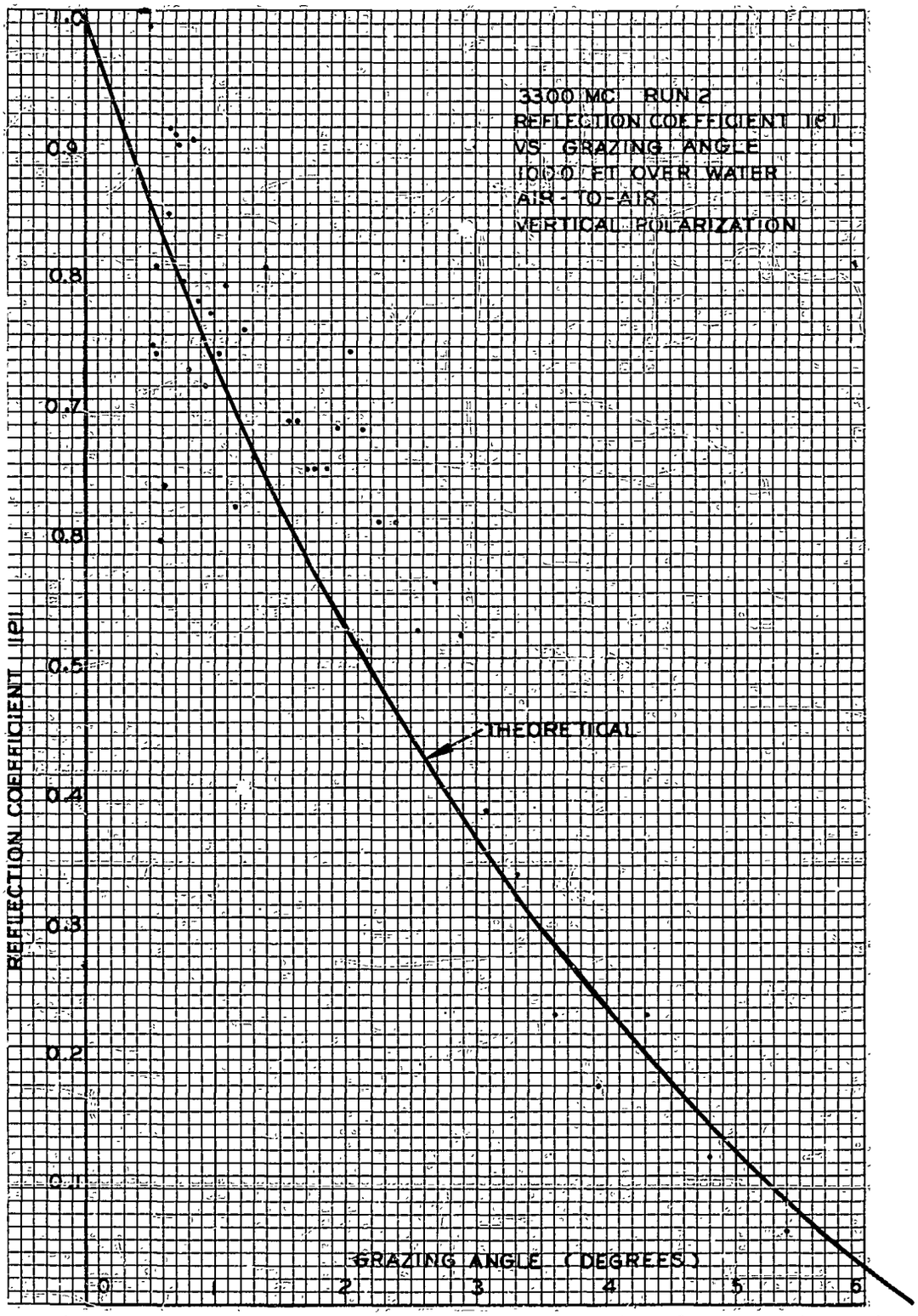

FIGURE 24. Reflection Coefficient vs Grazing Angle, 3300 mc. (Run 2)

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10. Reference No. 1, Section 2.

11. Reference No. 1, Section 5.1.

12. Reference No. 6, p. 709.

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