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(LO)1448-48
26 October 1948

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148

OPERATIONS EVALUATION GROUP

STUDY NO. 368

VISUAL DETECTION IN AIR INTERCEPTION

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Prepared by
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OPERATIONS EVALUATION GROUP
STUDY NO. 368

VISUAL DETECTION IN AIR INTERCEPTION

- Reference:
- (a) OEG Study No. 263, "Search and Screening: Visual Detection", Restricted, 9 April 1946.
 - (b) OEG Study No. 256, "Search and Screening: Target Detection", Restricted, 18 March 1946.
 - (c) NAS, Patuxent River, Md., Final Report on Part II of Project No. TED No. PTR-2556, "Visibility Tests of Specular and Non-specular Exterior Aircraft Surfaces", Restricted, 14 May 1945.
 - (d) NAS, Patuxent River, Md., Final Report on Part I of Project No. TED No. PTR-2556, "Visibility Tests of Specular and Non-specular Exterior Aircraft Surfaces", Restricted, 19 June 1944.

ABSTRACT

This study concerns the probability that a single fighter aircraft will make visual contact on a single target aircraft under daylight conditions of illumination. Quantitative results are presented which permit the computation of the probability of sighting by any given range as a function of each of a number of parameters. Some typical examples are worked out in detail showing the effects of such parameters as relative speed, angle of view, uncertainty in azimuth and in elevation. The sighting probabilities decrease with size of aircraft and with increase in relative speed. Neither head-on nor tail chase gives the best chance of detection. Best results are obtained when the target is viewed from between 110° and 140° from bow on, or correspondingly between 220° and 250° .

INTRODUCTION

At the present stage in the development of C.I.C. and fighter direction equipment and procedures, it is not

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26 October 1958

possible for an aircraft to complete an interception (position itself for firing its weapons) on the basis of information from C.I.C. alone. The final detection, or "tally-ho", must be made from the interceptor aircraft by visual, radar or other means. This study is concerned with visual detection of enemy aircraft by the interceptor aircraft under daylight conditions of illumination. The radar detection problem will be the subject of a later study.

It should be appreciated at the outset that the C.I.C. and "tally-ho" problems are closely interrelated; the requirements which must be met by one being predicated on the results to be expected from the other. For example, the size of the sector which must be scanned by the interceptor pilot is dictated in large part by the accuracy with which it is vectored. Because of the interrelations just described and variations to be expected in such parameters as elevation and relative bearing of the sun, enemy aircraft size and visual camouflage, and relative speeds and angles of approach, the detection problem should be studied for a relatively wide range of conditions rather than for a single typical one.

If a sufficiently large sample of operational data were available to provide a fair representation of all the conditions to be expected, this detection problem could, presumably, be solved by statistical methods alone. Because of the large number of parameters involved, such an analysis is not possible with the data now available. Earlier work on visual detection, based largely on laboratory performance of the human eye, is available, however, and has been used as the basis of analysis. This study is concerned chiefly with visual detection of a single enemy aircraft by a single interceptor aircraft under daylight conditions of illumination. While the problem of visual detection of multiple air targets will be the subject of a later study, some preliminary results are included here. The parallel problem for radar detection will be the subject of a later study. The operational data are employed to establish the values of certain of the constants involved in the analysis, and as a check on the final results obtained.

PHYSIOLOGICAL BASIS FOR VISUAL DETECTION

The physiological basis for visual detection is described in some detail in reference (a). For purposes of brief account is repeated here.

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2

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26 October 1948

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While searching a visual field, the human eye does not scan continuously, but moves in jumps and can see only during the pauses or "fixations" between jumps. The time from the beginning of one fixation to the beginning of the next is about 0.25 seconds. There is good evidence for the belief that from 6 to 8 successive fixations are made in the same general direction before another direction is investigated so that effectively the fixation time is from 1.5 to 2 seconds (reference (a)).

The least visible targets can be seen only on the fovea or central part of the retina of the eye. This region is only one or two degrees across, so that a relatively large number of fixations is required for a reasonable chance of imaging the target on the fovea where it can be seen. As the target becomes more visible, it can be seen farther from the visual axis or direction of best vision. In other words, the more visible target can be seen over a greater fraction of the total area of the retina. As this fraction increases, the number of fixations required for a reasonable chance of detection decreases.

DETECTION LOBES

For our present purposes the human eye can be thought of as carrying with it a "detection lobe", or surface of revolution about the visual axis, within which the target can be seen and outside which it can not. This concept is a convenient approximation rather than an exact statement of fact. Some targets which fall within the detection lobe, as represented here, will be missed and others which fall outside will be detected. However, the detection lobe is drawn on the basis of a convention which assures that the number of targets detected is the same as though all which fall within are detected and all which fall outside are missed. This detection lobe can be described by the equation (reference (a))

$$(1) \quad C = 1.15 \theta^3 + 45.6 \theta R^2/a,$$

where θ is the polar angle in degrees and R is the range or polar radius in miles. This formula neglects small effects due to changes in target shape and background brightness. For the cases studied here, this simplification is justified (reference (a)). C is the contrast of the target as seen at the eye, expressed as a per cent. It is 100 times the ratio

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(50)1448-48
26 October 1948

of the apparent difference in brightness between target and background and the background for which the eye is adapted (reference (A)). A is the area of the target expressed in square feet. Equation (1) does not hold for values of θ less than 0.8 degrees or greater than 90°.

The foveal or maximum range is obtained by setting the polar angle θ equal to 0.8 degrees, the approximate angular radius of the fovea. Making this substitution in Equation (1) leads to the following expression for the maximum range.

$$(2) \quad R_m = 0.1655 \sqrt{(C-1.565)A}$$

The maximum range, as expressed in Equation (2), is a mathematical abstraction which is employed for convenience. Not all targets at ranges less than maximum which are imaged on the fovea are seen. Similarly not all targets at ranges greater than maximum which are imaged on the fovea are missed. Here again, the number of targets imaged on the fovea which are seen is equal to the number that would be seen if all inside the maximum range were seen and all outside were missed.

Haze in the atmosphere has the effect of reducing the apparent contrast of the target. If the near or intrinsic contrast is designated by C_0 , then

$$(3) \quad C = C_0 e^{-3.44 R/V}$$

where V is the meteorological visibility, or range at which large targets such as mountains or a high coastline can be seen (reference (a)). The constant in this formula is slightly different from that quoted in various reports resulting from NDRC work at the Tiffany Foundation. The Tiffany constant assumes that meteorological visibilities are observed on targets having 100% intrinsic contrast. The figure (3.44) employed here refers to typical targets used to determine meteorological visibility, i.e., mountains or high coastline.

The substitution of Equation (3) in Equation (1) gives a complete description of the detection lobe under daylight conditions of illumination:

$$(4) \quad C_0 e^{-3.44 R/V} = 1.75 C_0^{1/2} + 48.6 C_0 R^2/A$$

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26 October 1948

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The visibility V is a characteristic of the atmospheric conditions which prevail, A is a characteristic of the target alone and C_0 a characteristic of the camouflage and the uniformity of illumination. If the illumination is not uniform (for example, in a direction 10 or 20 degrees from the sun), the eye adapts to a level of brightness higher than that of the immediate target background, so that the intrinsic contrast is reduced (reference (a)).

It is clear from Equation (1) that, so long as the contrast remains constant, the shape of the detection lobe remains the same regardless of the size of the target. The effect of change in target area is simply to scale the range up or down. In order to express the detection lobe in dimensionless form, a scale factor R_0 is introduced. This is the maximum range in the absence of haze and is given by:

$$(5) \quad R_0 = 0.1655 \sqrt{(C_0 - 1.565)} A.$$

In these terms the polar angle θ becomes

$$(6) \quad \theta = F \left\{ \sqrt{G/F + 1} - 1 \right\}^2.$$

where

$$F = 0.49(R_0/R)^4 / (C_0 - 1.565)^2$$

and

$$G = 0.80 C_0 e^{-3.44R/V} (R_0/R)^2 / (C_0 - 1.565).$$

The formulation above differs from that of reference (a) in that R_0 rather than R_m is employed as a scale factor. With the new formulation fewer steps are required in the computation of the polar angle θ . Furthermore, in some of the terms, fewer significant figures are needed for the same accuracy of the resulting value of θ . Since R_0 is essentially a characteristic of the target alone, while R_m is complicated by the fact that it takes into account the existence of haze in the atmosphere, the presentation of the results is somewhat clearer in terms of R_0 .

The detection lobes described in this section have been computed for a wide variety of conditions. Tables giving the polar angle θ as a function of the dimensionless polar radius R/R_0 are presented in the Appendix for various combinations of the parameters C_0 and V .

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26 October 1913

the value of n_0/R_0 is given at the bottom of the table. For purposes of illustration, two detection lobes, plotted on polar coordinates, are presented in Figure 1. Curve A shows the lobe shape for a representative intrinsic contrast C_0 under haze free conditions. Curve B illustrates the fore-shortening of the lobe brought about by moderate amounts of atmospheric haze.

Maximum Range R_0

In order to employ the detection lobes for the solution of any particular problem, one scale factor, the maximum range R_0 under haze free conditions, is required. A nomograph connecting R_0 with the parameters C_0 and A is given as Figure 2 of the text.

VISUAL SEARCH AS EMPLOYED BY CIC

It follows from earlier sections of this study that the probability that the interceptor will detect the target is simply the probability of placing the detection lobe so that the target is within it during at least one visual fixation. Visual scanning is the act of placing the detection lobe successively at various angles in space, with the eye of the observer as the origin of coordinates.

The distribution of successive lobe positions which should be selected in search depends, of course, upon where the target is likely to be. This problem has an intimate connection with the "tally-up" and "I.C." problems. In order to avoid an infinite number of computations and a correspondingly infinite set of results, it is necessary to make certain assumptions, at the outset, concerning the information to be expected from C.I.C.

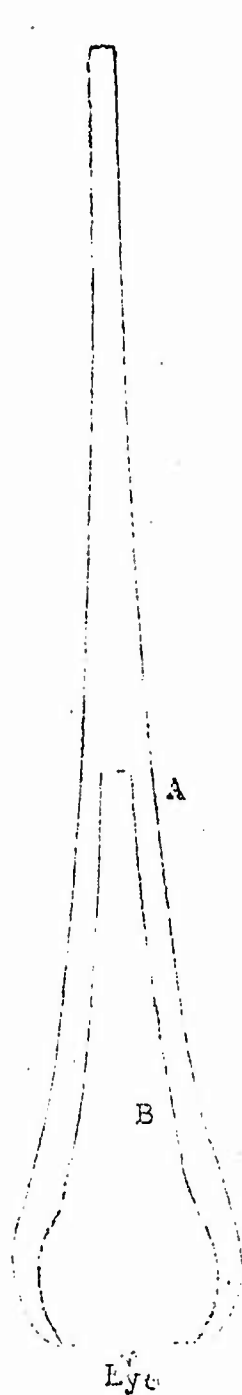
Since I.C. tracks both the target and interceptor in plan, it can determine the relative speed of each, and hence can provide the intercept point in the plan projection of the relative movement into the horizontal plane. Visual search of the intercept point is centered on this relative movement. The intercept point is plotted from C.I.C. to the interceptor and may be plotted by the visual search expected at C.I.C. The intercept point is plotted on what is known as the "intercept point" and the "intercept point" is plotted.

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26 October 1948

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(A) $\frac{R_0}{V} = 0$

(B) $\frac{R_0}{V} = 1.0$

$C_0 = 50\%$

Range Scale = R/R_0

Polar Angle = 0

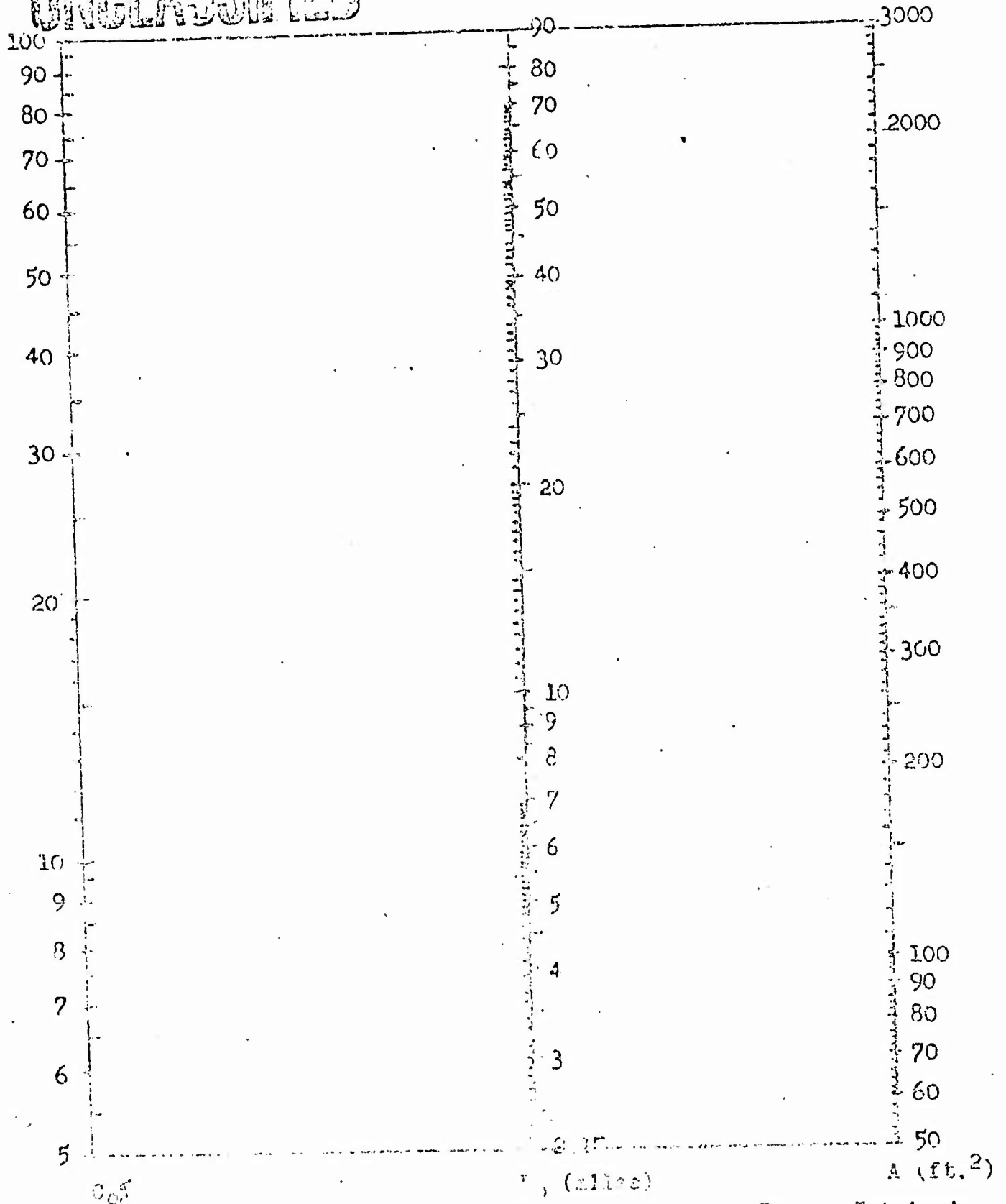
FIG. 1 TYPICAL DIRECTION LOBES

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26 October 1948



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While it is doubtful if the absolute altitude of the target can be determined with any degree of precision, it should be possible, when both target and interceptor are on the altitude determining scope together for C.I.C. to determine the magnitude and direction of the altitude difference to within about a thousand feet, so that the information from C.I.C. to the interceptor can include a statement of target position in thousands of feet above or below the interceptor. On the basis of past experience it is assumed that the altitude uncertainty is of the order of one to three thousand feet.

The center of a pip on a radar scope can be determined with fairly high accuracy, i.e., to within a fraction of a mile. However, to determine the distance, in plan, between the target and the relative movement line is a less straightforward problem. The accuracy of this determination depends not only on the accuracy with which the center of each pip can be located but also on the duration of the period during which tracking has been carried out. There is a further uncertainty introduced by the possibility that the target may change course during the final stages of the interception. It is doubtful, therefore, if C.I.C. can predict the distance between the target and the relative movement line closer than from 3 to 5 miles. For purposes of this study, therefore, it is assumed that the uncertainty in the distance of the target from the relative movement line is large compared with the altitude uncertainty.

If the altitude difference were known to be zero it would be sufficient to scan in azimuth only. If, on the other hand, the uncertainty in relative altitude were the same as the uncertainty in the target distance from the relative movement line, it would be necessary to scan the solid angle enclosed by a circular cone. In this study, solid angle scan is assumed, but with the scanning angle in elevation much smaller than the scanning angle in azimuth.

VISUAL SEARCH FROM INTERCEPTOR AIRCRAFT

In the earlier sections of this report, the various factors on which the probability of visual detection depends have been presented. In this section, these factors are combined to provide a functional relationship connecting them with the probability of detection. Let the angular travel

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(LO)1448-4B
26 October 1948

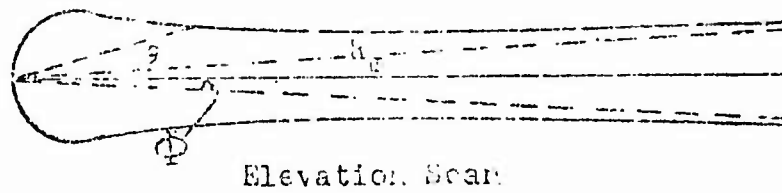
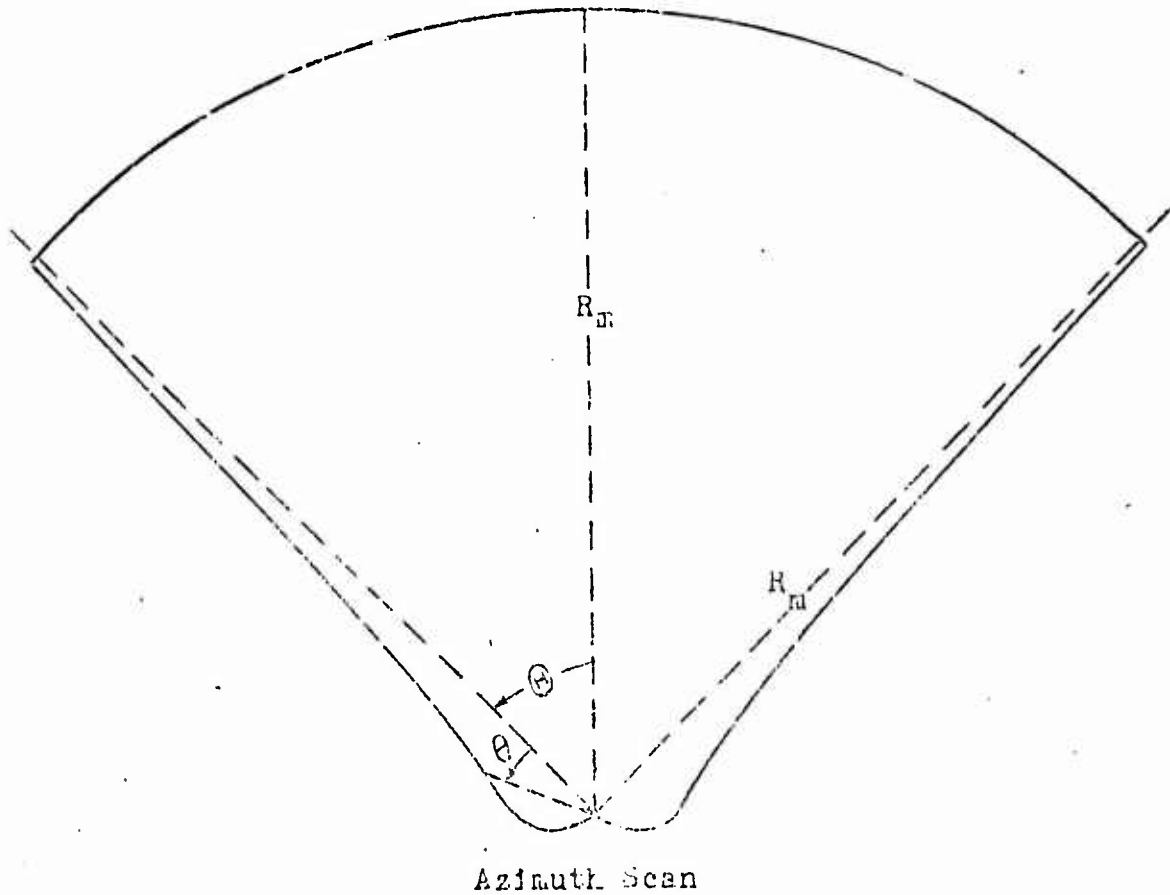


FIG. 3 REGION WITHIN WHICH DETECTION CAN BE MADE

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of the visual axis during scanning be limited in azimuth to an angle Θ on either side of the estimated relative movement line, and in elevation to an angle Φ above or below the expected elevation of the target. If the target is within the solid angle covered the probability of detection g in one glimpse is simply the ratio of the solid angle covered per glimpse, and the total solid angle, i.e.,

$$(7) \quad g = \Theta^2 / (\Theta^2 + \Phi^2) (\Phi^2 + \Theta^2).$$

One glimpse can be thought of as a number of successive fixations all made in approximately the same direction. From the material in reference (a) it is estimated that the time required for one glimpse is about 1.65 seconds.

It is to be remembered in computing the glimpse probability g that the constants given above are for a single observer. If there are two observers in the aircraft, they can divide the total azimuth angle Θ between them, each taking half. In this case, the single glimpse probability for the pair is the same as that for one scanning an azimuth angle half as large.

It remains, now, to combine the probabilities of detection on the various glimpses to obtain the probability of detection P by the time t following the beginning of the search. First, some system must be adopted for searching the given solid angle in order to insure that the number of glimpses in any given direction will be the same, per unit time, for any direction within the given solid angle. This scanning system must satisfy two requirements: first, the time required to complete one scan must be small compared to the total search time; and second, the distribution of fixations should be reasonably uniform over the solid angle scanned. One suggested scheme is, line scan in azimuth at a rate of about 10° per second, with elevation coverage by means of successive azimuth scan lines. Having adopted such a system, one can proceed by either of two methods, both of which lead to the same result. First consider the probability of detection, P_g , on one complete scan of the solid angle. If there are k glimpses during the scan, then,

$$(8) \quad P_g = 1 - \prod_{i=1}^k (1 - g_i).$$

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26 October 1948

If now the various probabilities, P_{sj} , are combined for l scans,

$$(9) \quad P = 1 - \prod_{j=1}^l (1 - P_{sj})$$

If Equations (8) and (9) are combined,

$$(10) \quad P = 1 - \prod_{i=1}^n (1 - g_i)$$

where $n = kl$. In other words, the result is the same as though the probability of detection had been computed directly from the single glimpse probability, using the total number of glimpses n , rather than by going through the intermediate stage of computing the scan probability, P_s .

Equation (10) can be rewritten in the following form.

$$(11) \quad P = 1 - e^{-\sum_{i=1}^n g_i}$$

which is exact provided the glimpse distribution is known. If the exponent in Equation (11) is averaged over all possible glimpse distributions,

$$(12) \quad P = 1 - e^{-\frac{1}{T} \int_0^T \sum_{i=1}^n g_i dt}$$

where T is the time between successive glimpses.

Consider now the special case in which the interceptor is on a collision course with the attacking aircraft. Then Equation (12) can be rewritten as

$$(13) \quad P = 1 - e^{-\frac{R_0}{v} \int_{R_2/R_0}^{R_1/R_0} 2.21 (10^3) \ln(1-g) d(R/R_0)}$$

or

$$(13a) \quad P = 1 - e^{-R_0 I/v}$$

where v is the relative velocity in knots, R_1 is the range at which search begins and R_2 is the range to which

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28 October 1948

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the interceptor has closed to obtain the probability of detection P . The integral (I) of Equation (13) is presented in Figure A1 of the Appendix as a function of the lower limit of integration, with the upper limit equal to R_m/R_0 for various values of the parameters C_0 ; R_0/V ; θ and δ . R_m/R_0 is used for the upper limit of integration since the glimpse probability g is zero beyond this point.

Since there probably will be some error in the information given to the interceptor by C.I.C., it is important to consider the probability of detection in the case where the interceptor is not following an exact collision course. If the interceptor is on a course parallel to a collision course but some distance to the right or left, or above or below the assumed relative movement line, the integration should then be carried out, not in R/R_0 as indicated in Equation (13), but in y/R_0 , where y is the distance parallel to the relative movement line from the target to the point of closest approach. Some integrations for this case have been completed, and the values of the detection probabilities obtained compared with those for the collision course. For values of the scanning angles θ and δ which are of practical interest, points on the surfaces of constant probability are nearly equidistant from the reference aircraft (either aircraft can be used as the reference one since the problem is one in relative rather than absolute movement). The points at the greatest angular distance from the relative movement line are actually more distant than the one on the relative movement line. In actual operations, the points of equal detection probability can be expected to be more nearly equidistant from the reference aircraft than the computations would indicate, for the following reasons:

- (a) The pilot is likely to scan the center of the solid angle more thoroughly than he does the edges;
- (b) Even with strict adherence, within practical limits to the uniform scanning procedure, the edges of the solid angle scanned are not likely to be sharply defined.

On the basis of the above considerations, because the procedure is conservative and in order to avoid the introduction of two additional parameters to an already formidable list, it may be assumed that the points of equal probability of detection are equidistant from the reference aircraft. It

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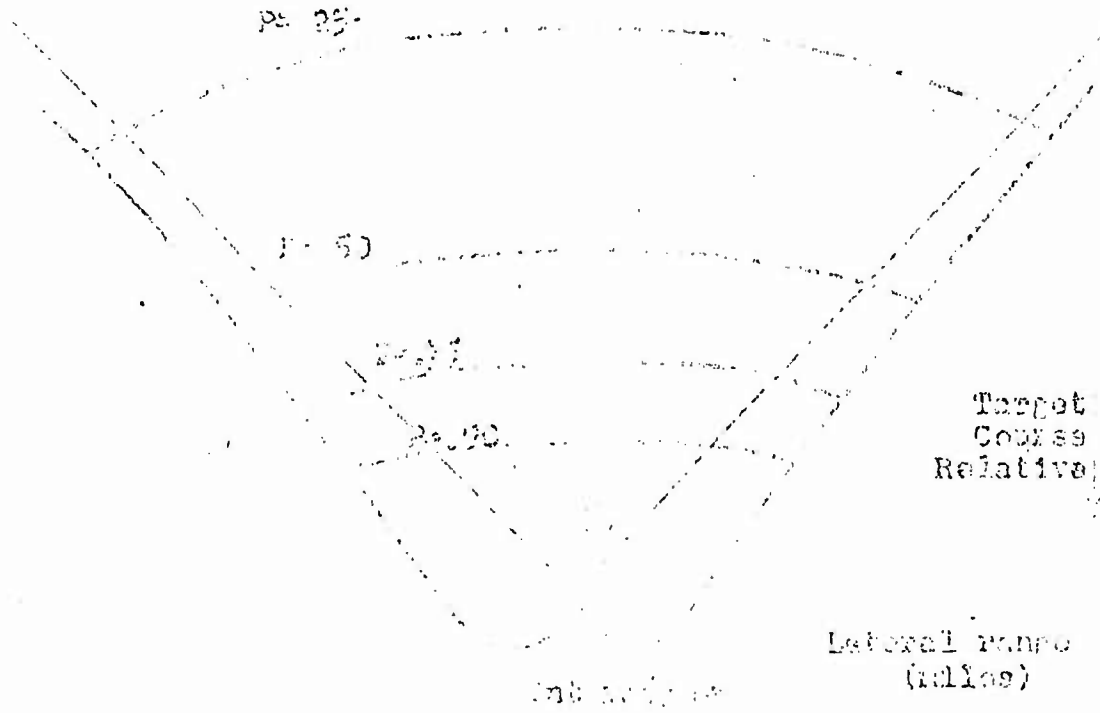
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(IO)1440-48
26 October 1948

Scan Angle = 45°



Horizontal scale gives lateral range of target in miles
Radial lines give true range (in miles) at which specified
probability (P) is obtained.
Data for P=25, 50, 75 from Fig. 3.

FIG. 4 SURFACES OF CONSTANT PROBABILITY
(Azimuth-Range Section)

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... that the surfaces of constant detection probability are bounded in azimuth by $(H) \pm \theta$, and in elevation by $(E) \pm \epsilon$ (see Figure 3).

If instead of a collision course the interceptor follows a pursuit course, C.I.C. must keep the interceptor constantly informed as to where, relative to him, the target is to be expected. During high G turns, of course, the interceptor can not be expected to search effectively, so that this part of the relative track can be neglected so far as any contribution it may make to the probability of detection is concerned. In other parts of the relative track the integrals appropriate for the collision course can be employed in conjunction with the average relative velocity for substitution into Equation (13). The values of the various parameters to be employed in particular cases are the concern of later sections of this study.

FORMATIONS AND STREAMS OF TARGET AIRCRAFT

This study, so far, has dealt with the interception of single target aircraft. In actual combat, raids consisting of large formations or even continuous streams of enemy aircraft, as well as single snoopers, can be expected. The problem of multiple targets will be the subject of a later study. In anticipation of this study a qualitative discussion in the present study seems appropriate.

The factors involved in the solution of the multiple target problem can best be visualized by considering two limiting cases: a single tight formation of enemy aircraft, and a stream of enemy aircraft spaced a considerable distance apart.

Before going into the first of the two cases, it is desirable to reexamine the concept of a visual detection lobe. For any given fixation of the eye there is, in general, a definite probability of detecting a given target which depends upon the range of the target from the eye and its angular separation from the most direct line of sight. The detection lobe was so described in space as to give the same probability of detection, on a random fixation as would be obtained if all targets inside the detection lobe were seen and all outside missed. Actually some targets inside are missed and some outside are seen. If there is more than one target aircraft in the close formation, there is more than one opportunity

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26 October 1948

for detecting an aircraft in a given fixation. A detection lobe to describe this improved situation, therefore, must be increased in size. Since the probability of tally-ho, by any given range depends directly upon the size of the detection lobe, this probability must increase with number of aircraft in the target formation.

In the second case, that of a stream of aircraft spaced a considerable distance apart, the detection lobe is that for a single aircraft since no more than one aircraft is ever in a region of high detection probability during any given fixation. The number of targets within the solid angle scanned, however, is increased so that the quantity g , the glimpse probability, which occurs in Equation (7) must be altered so as to apply to a distribution of targets rather than to a single one. This distribution is a function of range. It is clear, from what has been said, that the probability of detecting at least one target by any given range is greater for the target stream than for the single target. One further qualitative conclusion seems indicated. The probability of detecting at least one aircraft in the target stream should not be sensitive to changes in the scanning angle θ , since any decrease in intensity of search effort through spreading over greater azimuth angle is nearly or even more than compensated for by an increase in the number of targets inside the angle scanned.

Actual cases to be considered will include, undoubtedly, combinations of the two limiting cases just discussed. One might have streams, not of single planes, but of close formations of planes each separated by some considerable distance, or even a continuous stream with adjacent aircraft close together. While the general principles involved in the solutions to the various multiple target problems seem clear, the detailed computations will, no doubt, be tedious.

The probabilities of detection for the case of target spacings (S) far enough apart that two targets cannot be seen in a single fixation has been computed for an interception off the beam. The results are presented in Figure 5.

In this case the single glimpse probability is n times the single glimpse probability for a single target where n is the number of targets included in the scan angle. It is clear that a is a function of range. If x denotes the total linear width of azimuth scan at range R then x

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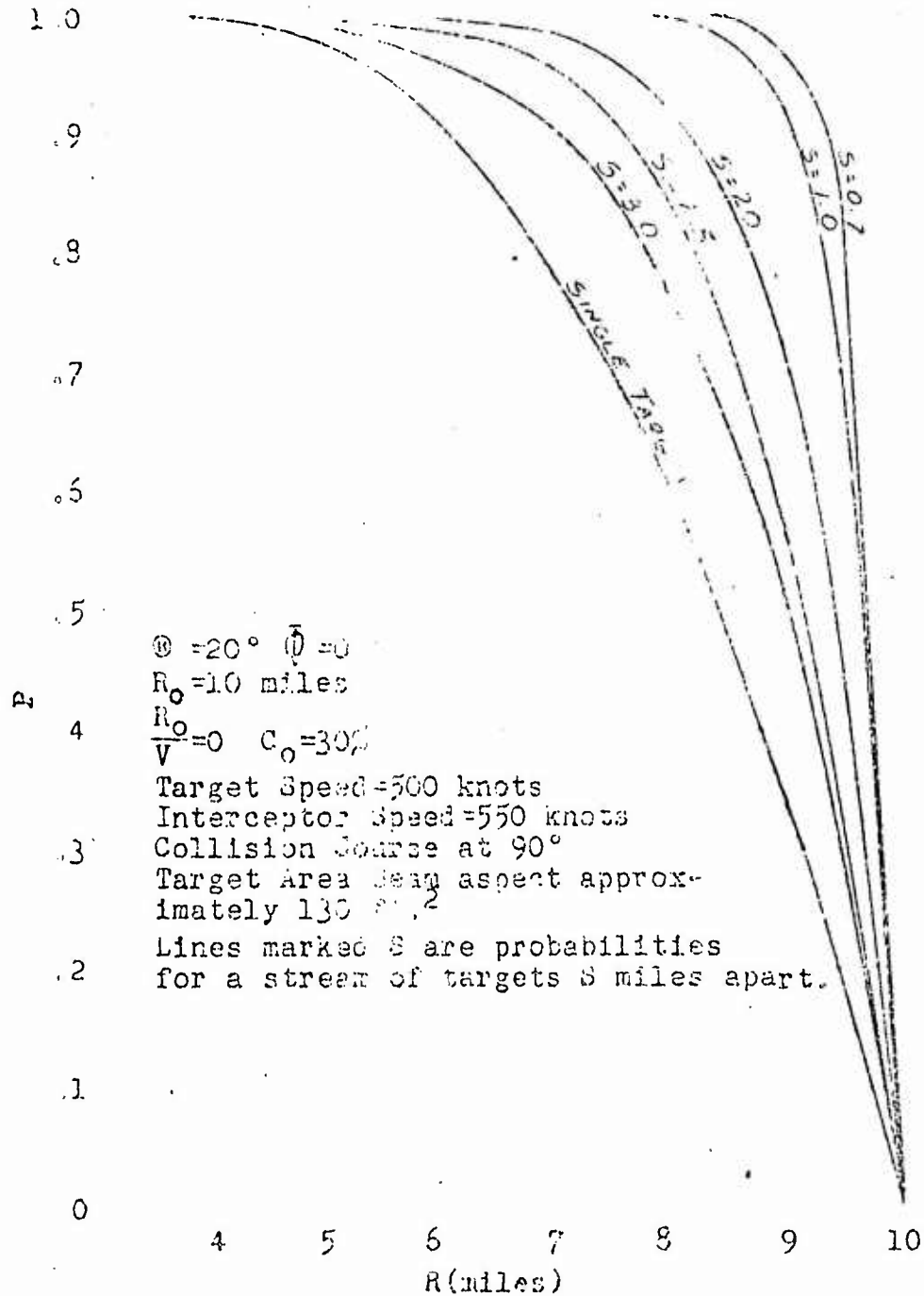


FIG. 5 PROBABILITY OF DETECTION TO RANGE (R)

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(a) $x = 2 R \sin (\theta + \theta)$

and the number of targets within the scan angle is:

(b) $n = \frac{x}{s}$

In constructing Figure 5, S was chosen large enough that not more than one target could be contained in the detection lobe at anytime. Expressed analytically this condition is:

(c) $S \geq 2 R \sin \theta$

Using the n from (b) as a multiplier for I obtained from Figure A1 in equation (13) gives the value of the probability of detection.

SEARCH PARAMETERS

In the preceding sections of this study, the theory of visual detection has been presented, using laboratory measurements to describe the performance of the human eye, and certain parameters to describe the aircraft, its physical surroundings, and the operational situation. In order to apply the analytical results and obtain a solution for any given operational situation, it is necessary to know the values of these various parameters, and to have some idea of the reliance which can be placed on the results obtained using them. These two questions are the concern of this section.

While equation (5), giving the maximum range R_0 , has been tested in other signaling problems, it is desirable to check its validity against actual aircraft. For this purpose, some useful reconnaissance raids at Pabkent during the war are available (reference (c)). These measurements were made to determine the maximum range at which the beam aspect of an SMO aircraft could be seen. If the area and intrinsic contrast of the aircraft are known, then R_0 can be computed using equation (5). The beam area of the aircraft, 110 sq ft., was obtained from a scale drawing of the aircraft. It was painted the usual navy blue. The reflectivity of the paint, as used at Pabkent, was 3%. If it is assumed that the light which was reflected diffusely from the aircraft was from the sky rather than directly from

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the sun, the intrinsic contrast C_o is 97%. Substitution of these two quantities, area and intrinsic contrast, in Equation (3) yields 17.6 miles for the maximum range R_o .

Unfortunately the measurements of reference (c) did not include accurate determinations of the meteorological visibility V so that an exact test of Equation (5), which is appropriate for haze-free conditions, could not be made. However, there were a number of measurements made in the category "above denser haze layer". In this category and away from the sun by at least 90° , the observed foveal ranges varied from 7.1 to 17.1 miles. Since the measurements were made over a period of several months, it is reasonable to suppose that some of them represent relatively haze-free conditions. If, in Equation (4), the obvious substitutions are made ($\theta = 0.3^\circ$; $A = 119$ square feet; $C_o = 97\%$ and $R = 17.1$ miles), the meteorological visibility V is 955 miles. The fact that no ranges greater than 17.6 miles were observed, and that one within 3% of this value was observed, provides considerable confidence in the validity of Equation (5), although of course they do not verify the equation. Since the equation has been verified in other sighting cases the evidence just presented is considered ample justification for using Equation (5) here.

An earlier series of tests made under the same Patuxent project (reference (d)) compared an unpainted aluminum aircraft with a navy blue one. Since these tests consisted of direct comparison runs, the meteorological visibility was the same for both aircraft. Using the values obtained with the known blue aircraft as a control, it is possible to solve Equation (4) for the meteorological visibility V . Substituting this value and the observed range for the aluminum aircraft, the intrinsic contrast, C_o , can be obtained for the aluminum aircraft. Unfortunately, reference (d) gives only the average foveal range for each aircraft, and not the results obtained from the individual runs. The use of the average ranges gave $C_o = 24\%$, subject of course to errors introduced by the averaging process. In reference (c), individual runs are given in the category "overcast", the category for the runs on which the averages of reference (d) were obtained. From the distribution in the ranges in category "overcast" from reference (c), the error introduced by the averaging process was estimated. Correcting for this error gives, as a most probable value, 27% as the intrinsic contrast of the aluminum aircraft. This would indicate a reflectivity of 73% for this aircraft. This is within the

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26 October 1948

range of measurements for aluminum, in various stages of polish, recorded in the published literature.

It is doubtful that any camouflage will render an aircraft less visible, when viewed from approximately the same altitude against a clear blue sky, than an aluminum aircraft, nor more visible than a Navy blue one. The aluminum does have the disadvantage that, in some preferred directions, there are occasional flashes resulting from specular reflection of the direct rays of the sun which increase the maximum range. While these flashes are neglected in this study, it should be pointed out that a mat rather than a polished finish is to be desired, from the camouflage point of view, to avoid these occasional flashes.

When viewed from above, the Navy blue is more difficult to detect against the sea than is the aluminum. When viewed against a white cloud, both Navy blue and aluminum have higher contrasts than when viewed against the clear blue sky. This gain in contrast is more apparent with the aluminum than with the navy blue since the contrast of the latter is already 97%.

Data concerning the influence of angular altitude and relative bearing of the sun on the intrinsic contrast of aircraft are somewhat sketchy. Some idea of the effect of sun's altitude and relative bearing can be obtained from the data of reference (c). These data show there is no significant difference between the ranges (and hence the intrinsic contrast) for the cross and down sun directions. Furthermore there is good reason to assume little or no reduction in contrast even as far as 45° into the up sun sector. Since it is usually possible to so plan an interception as to keep the sun in the aft sector relative to the line of sight, the effects of angular altitude and relative bearing of the sun are neglected here.

The operational data employed to check the final results were all obtained at relatively low altitudes. Some alterations may be anticipated at high altitudes. For example, it is quite possible that the background of rarefied atmosphere against which the aircraft is viewed may be darker than at low altitudes whereas the aircraft, illuminated partly by direct sunlight and partly by scattered light from below, may appear to be as bright as at lower altitudes. This effect will result in a change in intrinsic contrast C_0 .

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Not infrequently, aircraft flying at high altitudes leave vapor trails which can be seen for great distances. These, of course, increase the probability of detection. The effects of vapor trails on the probability of detection have not been included in this study so that the results presented are conservative for those cases under which vapor trails are present. Reports from England indicate that ranges of up to 20 miles are sometimes encountered.

The effect of relative motion, during a fixation, has been neglected in this study. Though a small physiological effect is believed to exist, the main effect is believed to be a psychological one, i.e., the calling of attention to a target which is really seen anyhow.

Before leaving the meteorological parameters, there is one further case which should be mentioned. If the target is viewed against a clear sky but with extensive white clouds in the sector aft of the line of sight, the target may actually appear brighter than the background because of added illumination from the white cloud. At the present stage in the sighting art it is not possible to give a quantitative description of this effect in terms sufficiently simple to be of practical use. Like specular reflection flashes, the effect just described is of occasional occurrence and hence is neglected in this study.

In planning any given interception it is necessary to know something about the aircraft to be intercepted and the conditions under which the interception is likely to be made before the maximum range parameter R_0 can be selected. It can be assumed that both target and interceptor will be at approximately the same altitude so that valley-ho will be made against sky or cloud in approximately the plane of flight. The apparent area of the target will vary with aspect angle, i.e., the angle between the target heading and the line of sight.

It is possible, of course, to present tables of R_0 for various aspect angles for each of the various conceivable aircraft, from which the value appropriate for a given interception could be selected. Unfortunately such a table would be so extensive that it would be cumbersome and time-consuming to use. It is desirable, therefore, to look for generalizations which will simplify this process.

An examination of the effect of target aspect shows that the ratio of the area as viewed from the beam and

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26 October 1948

from bow or stern is 2.4 ± 0.5 . This relationship holds for aircraft, jet or propeller driven, of conventional design varying in size from the Navy F4U to the Army XB-36. The relationship does not hold for aircraft of the flying wing type. If it is assumed that the apparent area at aspect angle α is the sum of the projections of bow and beam aspects, the aspect effect can then be expressed by the following equation:

$$(14) \quad R_{0\alpha} / R_{00} = \sqrt{\cos^2 \alpha + 2.4 \sin^2 \alpha}$$

where $R_{0\alpha}$ is the value of R_0 at aspect angle α , R_{00} the value of R_0 at aspect angle 0° and the absolute values of the sine and cosine are used. A plot of Equation (14) is presented in Figure 6. It shows that the maximum range R_0 is considerably greater if the angle between the target course and the line of sight lies between 50 and 130 degrees or between 230 and 310 degrees rather than closer to either bow or stern.

If the area of any given aspect of an aircraft is known, the maximum range can be determined for any aspect and for any given camouflage. Unfortunately, the area is seldom given in aircraft specifications so that it is more convenient to express the maximum range R_0 in terms of some more usual characteristic of the aircraft. One such characteristic is the gross weight. Reasoning from a dimensional argument, one would expect the maximum range to be proportional to a linear dimension of the aircraft which, in turn, should be proportional to the cube root of the gross weight. A test of this assumption is presented in Figure 7. Here the maximum range R_0 is plotted as a function of the cube root of the gross weight for both bow and beam aspect. The values given are for aircraft varying in size from the Navy F4U to the Army XB-36 finished with unpainted aluminum. The crude proportionality is apparent in the figure, and the assumption of proportionality appears sufficiently accurate for operational purposes. In Figure 8 the maximum range R_0 is presented for bow aspect, as a function of gross weight for each of a number of values of intrinsic contrast.

There are no aircraft sighting data available for testing Equation (3), which gives the dependence of the contrast C on the meteorological visibility V . This equation, known from its discoverer as Koschmidder's law, has been verified many times in other circumstances and hence may be considered

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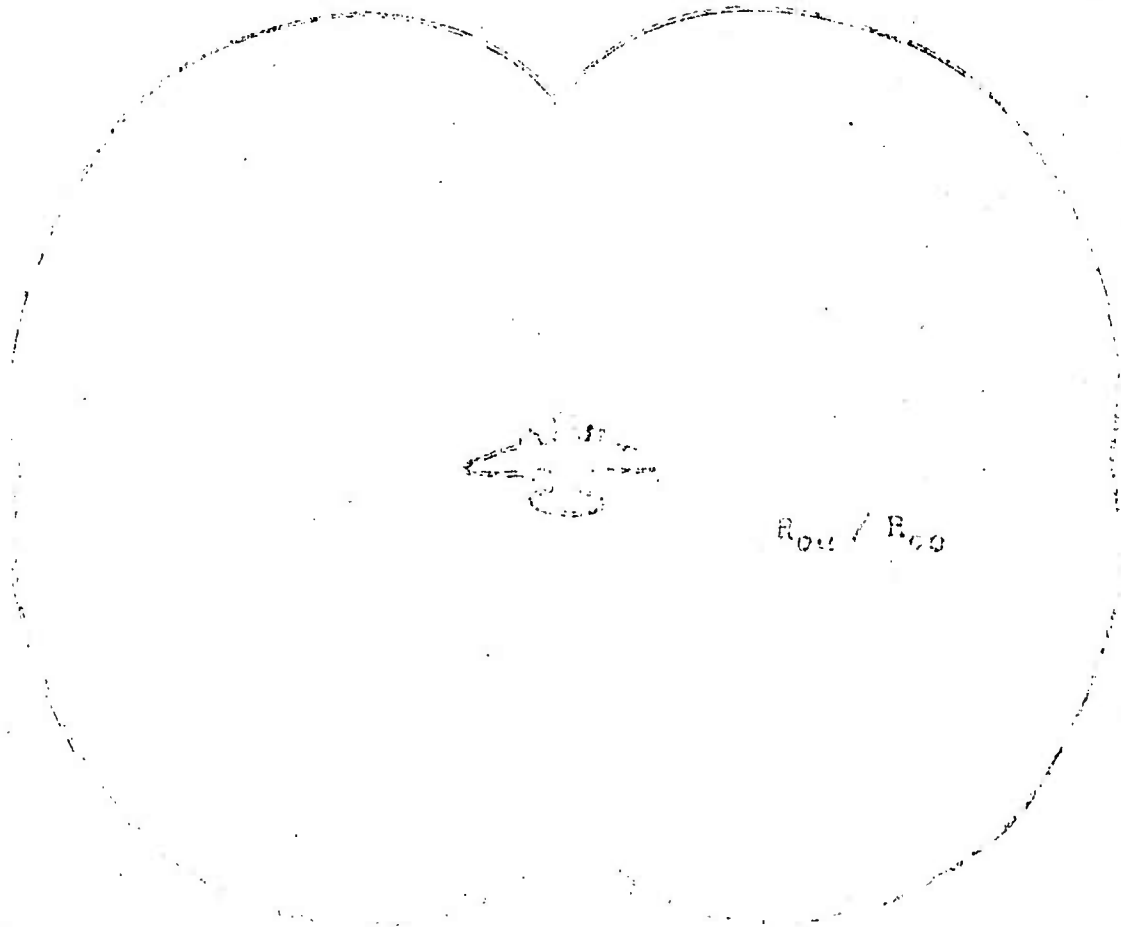


FIG. 6 EFFECT OF ACID ON ...

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(Gross Wt.) $1/3$	(Gross Wt.) K.Ds
20.0	8,000
22.5	14,060
25.0	15,625
27.5	20,800
30.0	27,000
32.5	34,330
35.0	42,675
35.5	44,740
40.0	64,000

Maximum Range = 10 (miles)

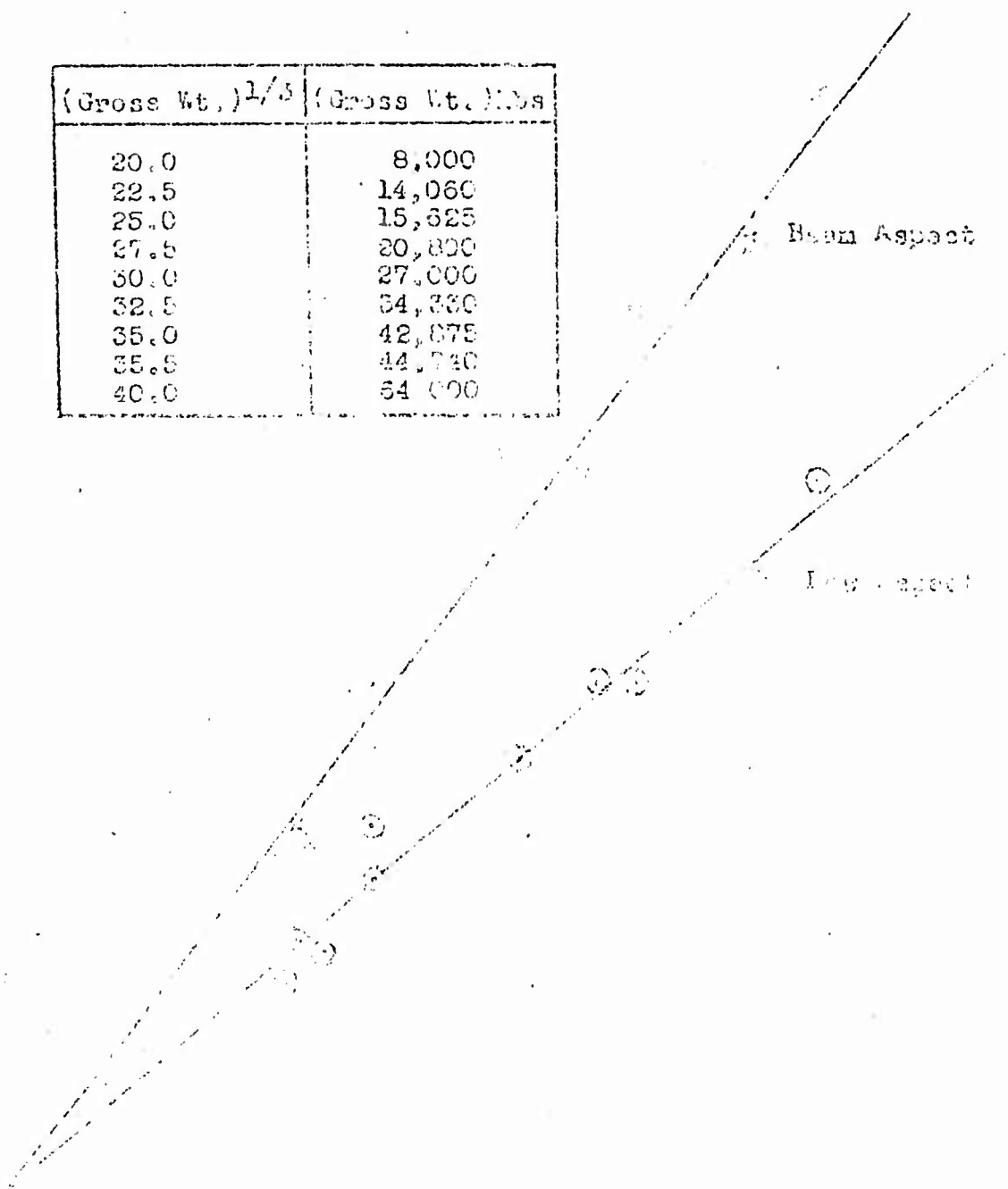


FIG. 7 CONTINUED FROM APPROXIMATE GROSS WEIGHTS (K.Ds)

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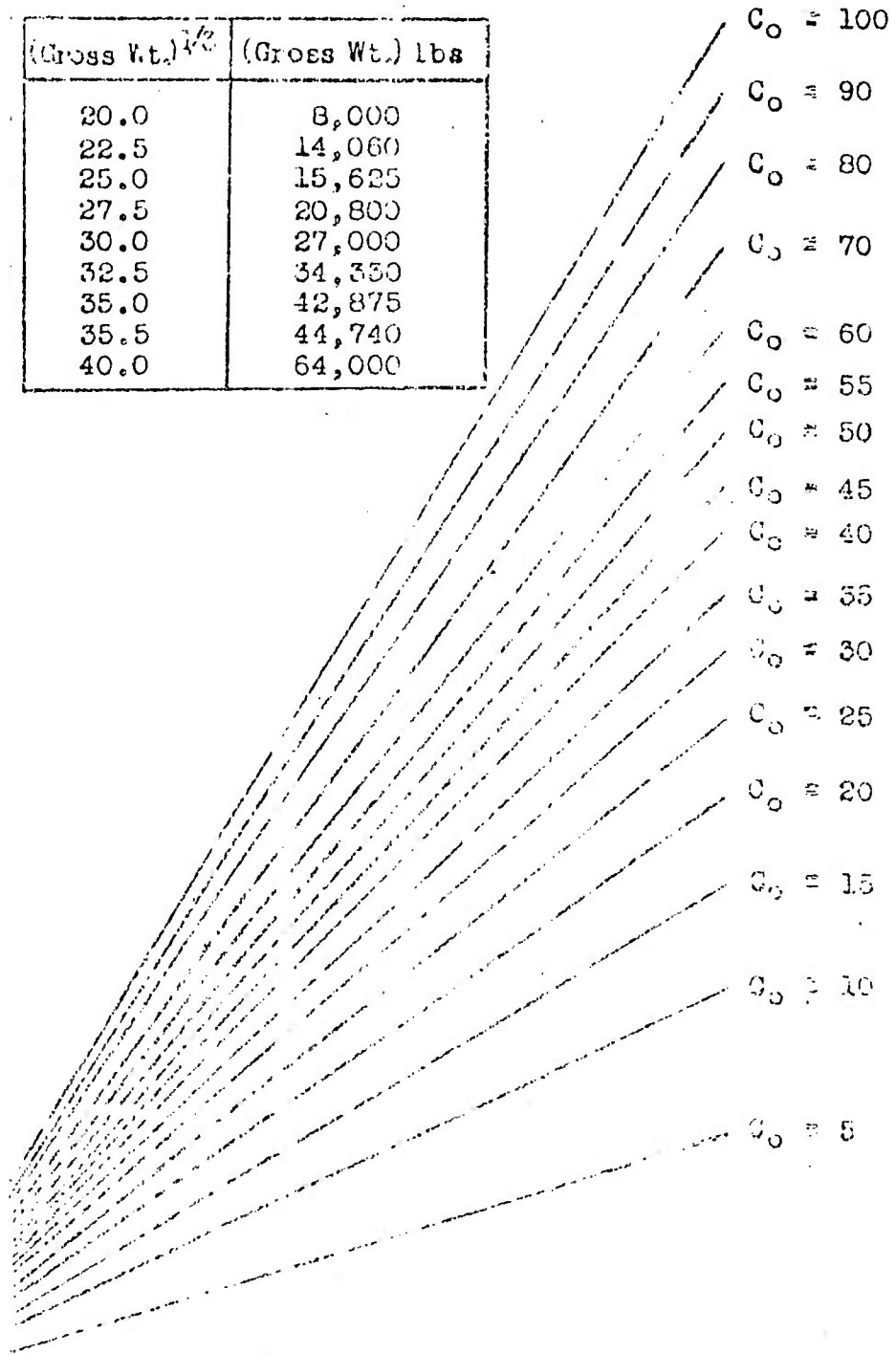
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 20 October 1948

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(Gross Wt.) ^{1/3}	(Gross Wt.) lbs
20.0	8,000
22.5	14,060
25.0	15,625
27.5	20,800
30.0	27,000
32.5	34,350
35.0	42,875
37.5	44,740
40.0	64,000

Maximum Range = R₀ (miles)



(Gross Weight)^{1/3} (pounds)^{1/3}

FIG. 3 BOW ASPECT

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26 October 1948

as well established. The other constants involved in computing the glimpse probability p and the number of seconds required for one glimpse have been verified in the laboratory and, to some extent, in other sighting problems. There are some few data available for making a direct check between measured and computed probabilities of detection. The check (based on reasonable assumed values of the meteorological visibility, size and camouflage of target, azimuth and elevation angles scanned, and relative speed) is good. This fact is irrelevant, however, since the actual values of these quantities are very uncertainly specified by the data; no further attention will be paid to these data in this study.

SOLUTIONS OF SPECIFIC AIR INTERCEPTION PROBLEMS

In the preceding sections of this study, sufficient information is presented for the solution of any visual air interception problem which is likely to occur in naval operations. In this section, a typical example is worked out in detail to illustrate the methods employed, to give an idea of the quantitative results to be expected, and to study the quantitative effects of various combinations of the parameters which occur in the theory.

For purposes of this example, it is assumed that the target is a medium bomber of conventional rather than flying wing design; that its gross weight is 38,000 pounds; its camouflage unpainted aluminum, its cruising speed 500 knots, and that it flies above 20,000 feet where the meteorological visibility can usually be considered as unlimited. It is further assumed that the interceptor is a single seater fighter with a cruising speed of 550 knots; that it flies at approximately the target altitude and is attempting interception along a collision course.

In working out the specific example, need will arise for certain kinematical information involved in the motion of one of the two aircraft relative to the other. This relative motion problem is solved first and the results are presented in Table 1. The first two columns give the aspect angle for approach from port or starboard of the target. The next two columns give the corresponding differences between the headings of the two aircraft. The third two columns give the relative bearing of the target from the interceptor and the next column gives the relative speed in knots. This relative motion problem can be solved either by using the

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TABLE 1

RELATIVE MOTION — TARGET AND INTERCEPTOR

Target speed 500 knots; Interceptor speed 550 knots
 Target gross weight 33,000 lbs; meteorological visibility unlimited

Interceptor bearing from target minus target heading (degrees)		Interceptor heading minus target heading (degrees)		Relative bearing of target from interceptor (degrees)		Relative speed (knots)	Maximum range (miles)
						V	R ₀
0	360	180.00	180.00	0.00	0.00	1050	13.4
10	350	160.92	199.08	9.03	0.92	1036	15.8
20	340	141.88	213.12	18.12	1.88	993	17.7
30	330	122.96	237.04	27.04	2.96	923	19.2
40	320	104.24	255.76	35.76	3.24	830	20.3
50	310	85.86	274.14	44.14	3.86	716	21.0
60	300	68.07	291.93	51.93	3.07	590	21.4
70	290	51.32	308.68	58.68	1.32	457	21.5
80	280	36.46	323.54	63.54	2.46	332	21.3
90	270	24.62	335.38	65.38	2.62	230	20.7
100	260	16.46	345.54	63.54	2.46	158	21.3
110	250	11.32	348.68	58.68	1.32	115	21.5
120	240	8.07	351.93	51.93	3.07	88	21.4
130	230	5.86	354.14	44.14	3.86	73	21.0
140	220	4.24	355.76	35.76	3.24	63	20.3
150	210	2.96	357.04	27.04	3.24	57	19.2
160	200	1.88	358.12	18.12	3.12	53	17.7
170	190	0.92	359.08	9.08	3.02	51	15.8
180	180	00.00	360.00	0.00	360.00	50	13.4

$$\sin \alpha = \frac{\text{Interceptor speed } (V_I)}{\text{Target speed } (V_T)} \sin \beta = 1.1 \sin \beta$$

$$v = (V_T^2 + V_I^2 - 2 V_T V_I \cos \alpha)^{\frac{1}{2}}$$

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26 October 1948

usual trigonometrical relations or by means of the manouvering board. It is assumed that the reader is familiar with either or both methods.

The next step in the solution of the problem is to find out how far the target can be seen, i.e., to find the maximum fovsal range R_0 . This is done by first looking in Figure 8 to find the maximum range R_0 for a 38,000 pound aircraft, intrinsic contrast $C_0 = 27\%$, aspect angle $\alpha = 0$. Next the maximum range R_0 for other aspect angles is computed using Equation (14). The results are presented in the last column of Table 1.

We are now in a position to compute contours of probability of detection for any specified set of conditions. The probabilities selected are 25, 50, 75 and 90 per cent. The following conditions, in addition to those given earlier, are assumed: The interceptor comes to a collision course outside maximum range R_0 , and continues on this course. The pilot searches 45 degrees in azimuth on each side of the relative movement line ($\theta = 45$) and 3 degrees in elevation above and below the expected target altitude ($\beta = 3$). The meteorological visibility is unlimited, i.e., $R_0/V = 0$.

For 25, 50, 75 and 90 per cent probabilities of detection, the exponent in Equation (13) must be -0.288, -0.693, -1.306 and -2.303, respectively. The values of the integrals in Figure A1 ($C_0 = 27\%$, $R_0/V = 0$) must be the products of these exponents and v/R_0 , where v is the relative velocity in knots. For convenience these products are listed in Table 2, for each of the 4 probabilities given above, as a function of aspect angle α .

Once the values which the integrals must have are obtained, the values of R/R_0 can be found in Figure A1. These, when multiplied by the appropriate value of R_0 , give the ranges in miles at which the various probabilities of detection occur. The results are presented in Figure 9 as polar plots of range as a function of aspect angle for the 4 probabilities of detection considered. Because of the change in relative speed with aspect angle, the effect of changes in R_0 with aspect angle is not clearly apparent in this figure. Examination of this point, keeping relative speed constant, shows that as R_0 is increased the range for any given probability increases more than proportionally. A marked effect of relative speed on the probability contours is apparent in Figure 9. This was expected because of the form of Equation (13).

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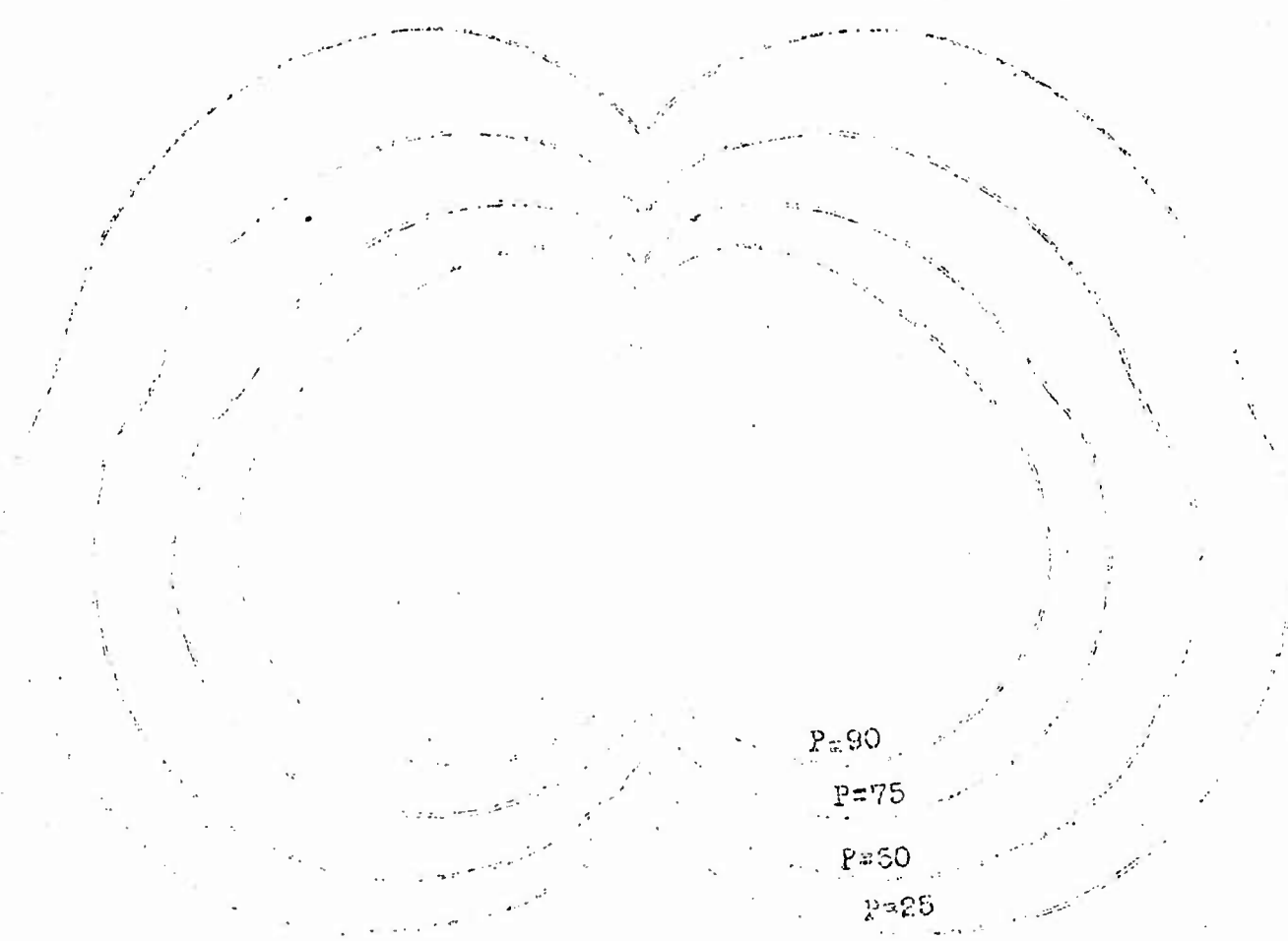
TABLE 2
REQUIRED VALUE OF INTEGRAL I
TO OBTAIN SPECIFIED PROBABILITY P (P).

<u>α</u>	<u>P = .25</u>	<u>P = .50</u>	<u>P = .75</u>	<u>P = .90</u>
0°	22.6	54.7	106	180.5
10°	18.9	45.6	93.9	151.0
20	16.2	38.8	77.8	129.2
30	13.8	33.3	66.5	110.7
40	11.3	28.3	56.7	94.2
50	9.82	23.6	47.3	78.5
60	7.94	19.1	38.2	63.5
70	6.12	14.7	29.5	49.0
80	4.49	10.6	21.6	35.9
90	3.20	7.70	15.4	25.6
100	2.14	5.14	10.3	17.1
110	1.54	3.71	7.42	12.3
120	1.18	2.85	5.70	9.49
130	1.00	2.42	4.82	8.01
140	.893	2.15	4.30	7.14
150	.855	2.06	4.12	6.84
160	.834	2.03	4.16	6.91
170	.830	2.03	4.48	7.44
180	1.07	2.55	5.17	8.59

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26 October 1948



P=90

P=75

P=60

P=25

Target: Medium bomber (gross wt. 38,000 lbs.)
Direction of movement: 100 deg
Speed: 100 kts.

Intercept: Single engine fighter
Speed: 150 kts.

Weapon: 4.2 inch automatic cannon
Search: 400 ft
Visibility: unlimited

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RANGE (nautical miles) vs. ASPECT ANGLE

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26 October 1948

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As can be seen from Table 1 the maximum range R_0 is quite large - of the order of 20 miles. If an interception is begun from outside maximum range, particularly in a stern chase, many miles may be covered by target and interceptor before the interceptor can overtake the target. In certain cases, therefore, it is desirable to begin the interception, i.e., to come to a collision course, at a point inside maximum range. In order to show the effect of changes in starting position, the limiting cases of head-on and stern chase of the examples of this section have been selected for illustration, and are presented in Figures 10 and 11, respectively. In each figure the range for each of the 4 probabilities is presented as a function of the range at which the search is begun. The procedure employed for computing these ranges is exactly the same as that already outlined, with one exception. The values used in the integrals for computing Figures 10 and 11 are the values obtained from Table 2 as in the previous case, plus the values of the integrals at the starting ranges.

It will be noticed in Figures 10 and 11 that a decrease in the starting range decreases the range for each of the detection probabilities. The decrease which can be tolerated is set, of course, by the firing point range desired. A similar effect to the one just described is observed at each aspect angle. These are not worked out in detail here.

If the angle over which scanning must be carried out can be reduced, then the ranges for each of the probabilities of contact should be increased. The effects of changes in scanning angle are presented for head-on and tail chase in Table 3, which shows the range for each of the 4 probabilities as a function of azimuth scanning angle α , and the elevation scanning angle θ . Figure 12 gives, for the head-on attack, the probabilities of detection up to given range for a variety of azimuth scan angles. In all cases, the range for the given probability increases with decreasing scanning angle, the effect being more marked for the higher relative velocity, i.e., head on attack.

The lower limit to the azimuth scanning angle is set, of course, by the accuracy with which C.I.C. can vector the interceptor on a collision course. The interceptor will, in general, be off a relative collision course by some lateral range. In Figure 12 the lateral range covered by the scan is given as a function of range for each of a number of scanning angles α . This lateral range in miles is, $L = R \sin(\alpha - \theta)$ which can be obtained by means of Table A1.

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31
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26 October 1948

$P = .25$

$P = .50$

$P = .75$

$P = .90$

$R_0 = 13.4$

Head on Approach

Conditions of Interception as in Figure 9
Aspect Angle = 0°

Range at Start of Search (miles)
FIG. 10 RANGE AT WHICH SPECIFIED PROBABILITY OF DETECTION OCCURS, AS
FUNCTION OF RANGE AT START OF SEARCH

32 DOWNGRADED TO

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$P_0 = 25$
 $P_0 = 50$
 $P_0 = 75$
 $P_0 = 100$

U. 13.4

P_0

FIG. 11. BEHAVIOR OF P_0 AS A FUNCTION OF P_0 FOR DIFFERENT VALUES OF P_0 . (AS)

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30 October 1948

REPORT OF THE COMMISSION ON
THE RACE AND ETHNIC PREJUDICES OF
THE ARMY AND AIR FORCE

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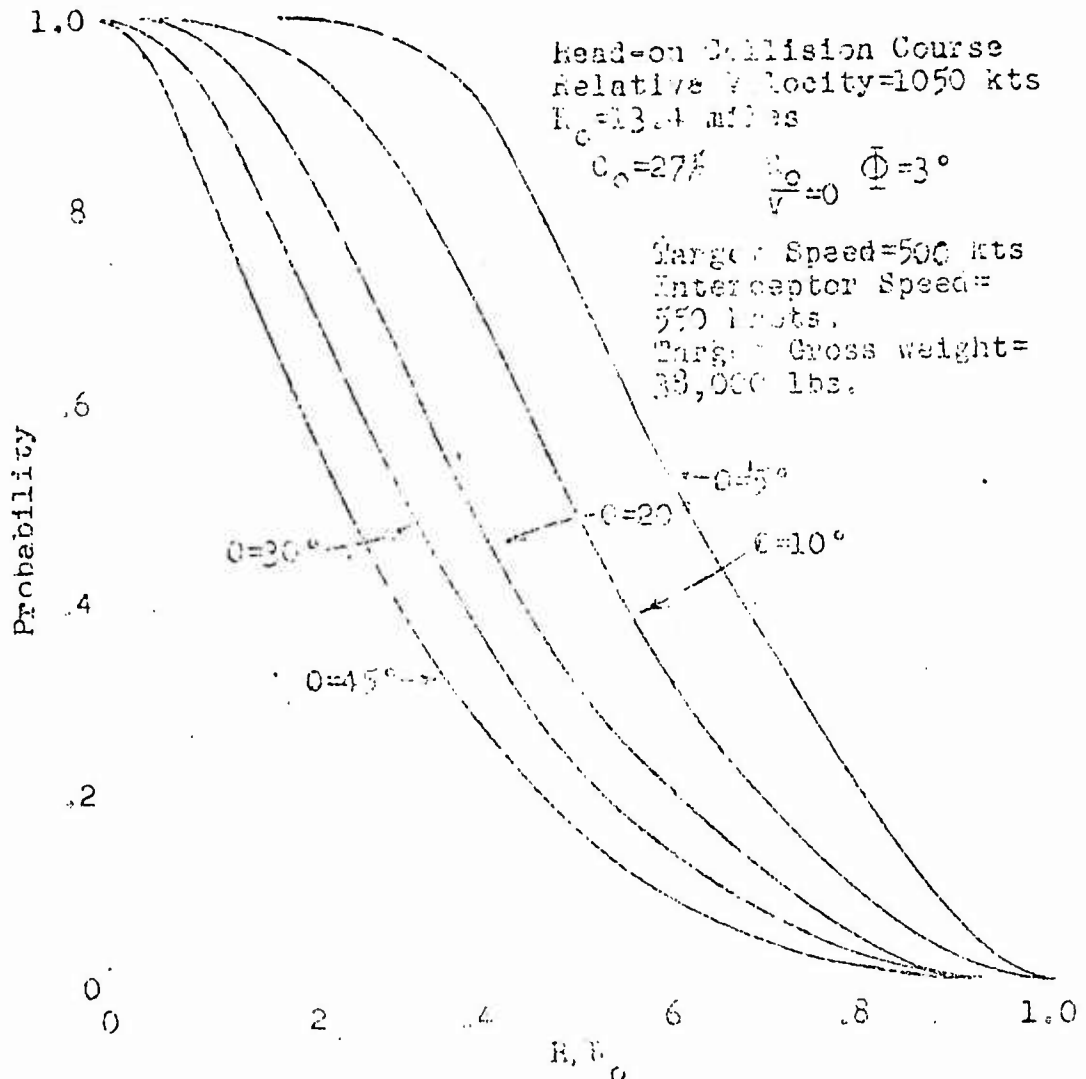


FIG. 12 PROBABILITY OF DESTRUCTION AS A FUNCTION OF SCAM ANGLE

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26 October 1948

As the interceptor may be off in lateral range, so he may also be off in altitude. In Figure A3 the altitude covered by the scan is given as a function of range for each of a number of scanning angles, θ . The altitude difference Δh is given by $R \sin(\theta \pm \phi)$.

It should be noticed in Figures A2 and A3 that there is much less decrease in off track coverage with decreasing range than in the corresponding radar case. This is especially noticeable for small scan angles. For the very small scan angles in elevation, there is in fact an increase in off track coverage with decreasing range (for high contrast values). The reasons for this lie in the shape of the detection lobe which, unlike radar, is broad at the base and narrow at the ends. It is because of this difference in lobe shape that the scanning circles for visual search will probably be smaller than those for radar.

CONCLUSIONS

1. Against single high speed enemy aircraft, visual tallying in the form of target trails in a head-on attack will occur at considerably shorter ranges than is the case for attacks from the rear and side trails.
2. Against a single high speed aircraft, those approaches which give the best chance of visual tallying are those for which the relative movement line is roughly on the target's quarter, i.e., between 150° and 210° or between 220° and 280° .
3. The greater the necessity of vectoring, the greater is the chance of successful interception of a single enemy aircraft since the angle over which visual search must be carried out is reduced.
4. The larger the target, the greater is the range for any given probability of detection.
5. The greater the relative speed, the less is the range for any given probability of tallying.
6. The greater the number of aircraft in the target formation, the greater the probability of detecting at least one by any given range.
7. Flashes resulting from specular reflection of sunlight from the aircraft can be expected to increase the range,

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for any given probability of detection beyond that given in this study but will occur too rarely to change these results appreciably.

8. The existence of vapor trails can be expected to increase the range, for any given probability of detection, beyond that given in this study.

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(LO)1443-43
26 October 1948

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APPENDIX

Contents:

(I) Figure A1, pages (41, 43, 45, 47): Graphs giving the values of the integral I used in Equation (13a) page 12, for computing the probability (P) of detecting a single target. I is the vertical scale of the graphs. The parameter values used in computing these graphs are:

- (i) Azimuth Scan Angles $(\theta) = 20^\circ, 45^\circ$.
- (ii) Elevation Scan Angles $(\delta) = 0^\circ, 3^\circ$.
- (iii) Intrinsic Contrast of Target $(C_0) = 5, 15, 50, 50, 100\%$.
- (iv) $R_c/V = 0$ and 1 .

The limits of integration are from the variable lower limit R/R_0 (abscissa of graphs) to the fixed upper limit R_m/R_0 . For the case of haze-free atmosphere ($R_0/V = 1$), $R_m/R_0 = R_0/R_0 = 1$. For atmospheric conditions other than haze-free the value of R_m/R_0 is, of course, less than unity. These values are given at the bottom of the table A1, for various values of R_c/V and C_0 .

(II) Figure A2, page 49: Lateral Range covered by Azimuth Scan.

(III) Figure A3, page 50: Altitude covered by Elevation Scan.

(IV) Table A1, pages (51 - 53): Tables giving, for the detection lobe, the polar angle θ as a function of the dimensionless range R/R_0 .

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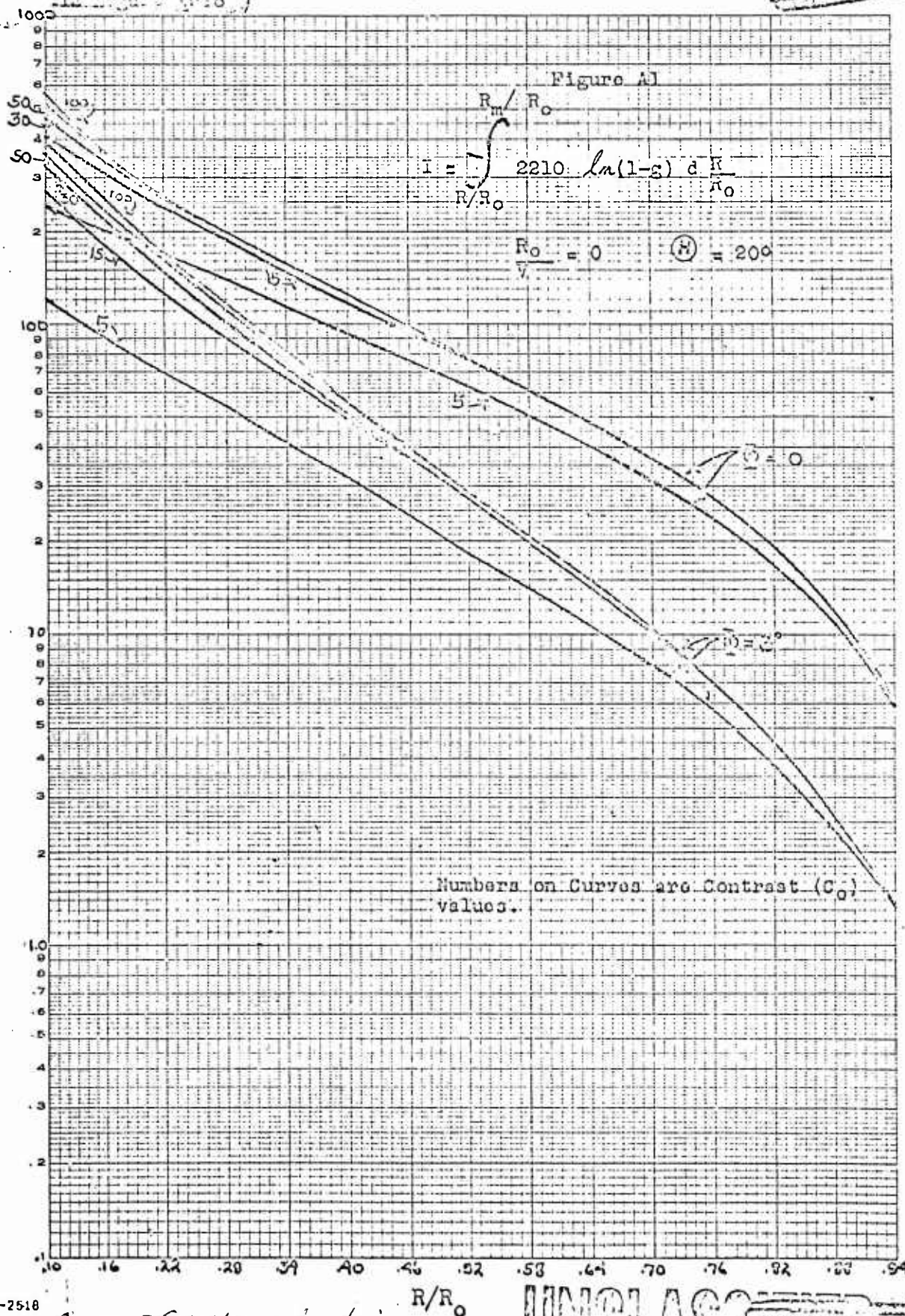
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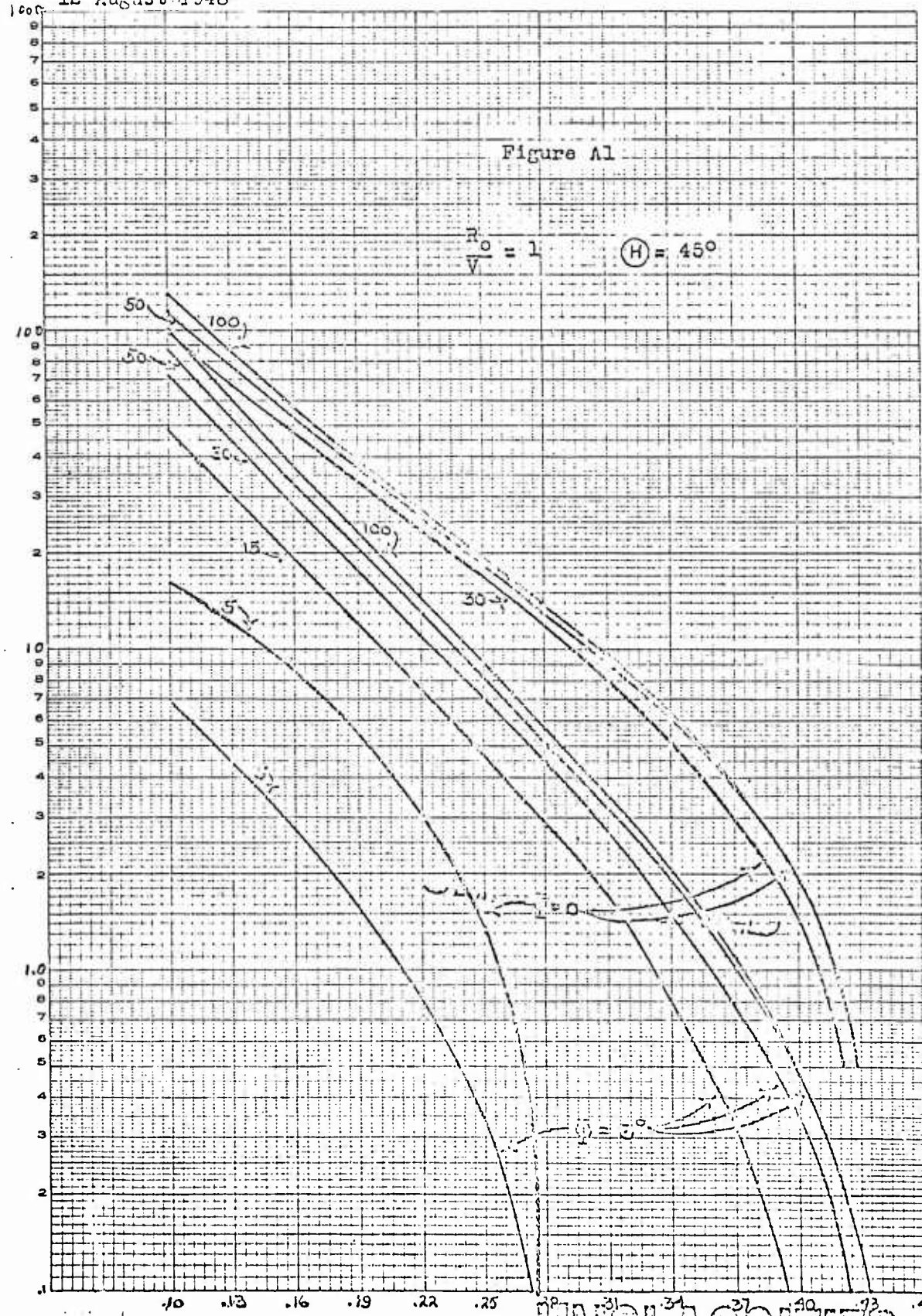
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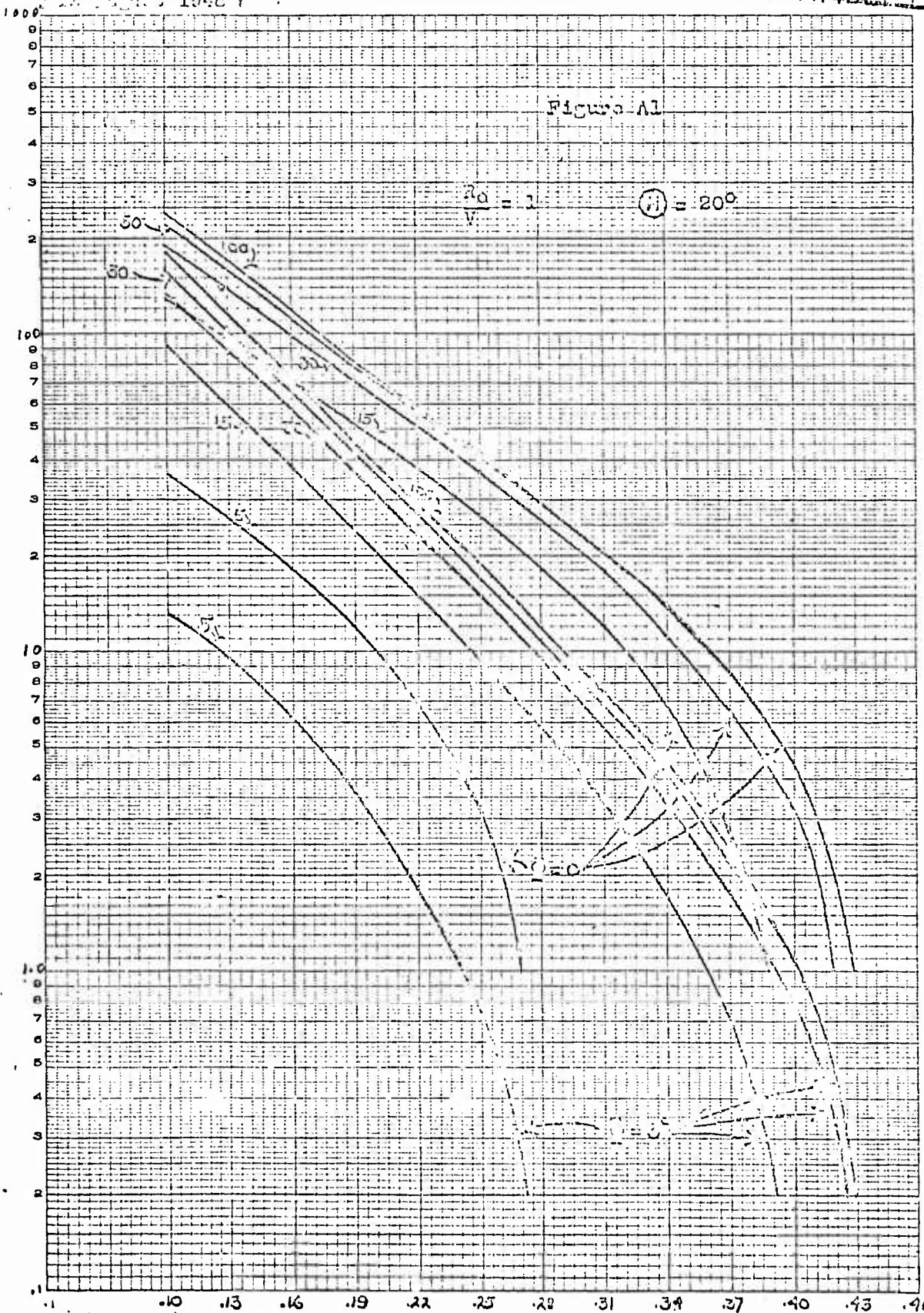
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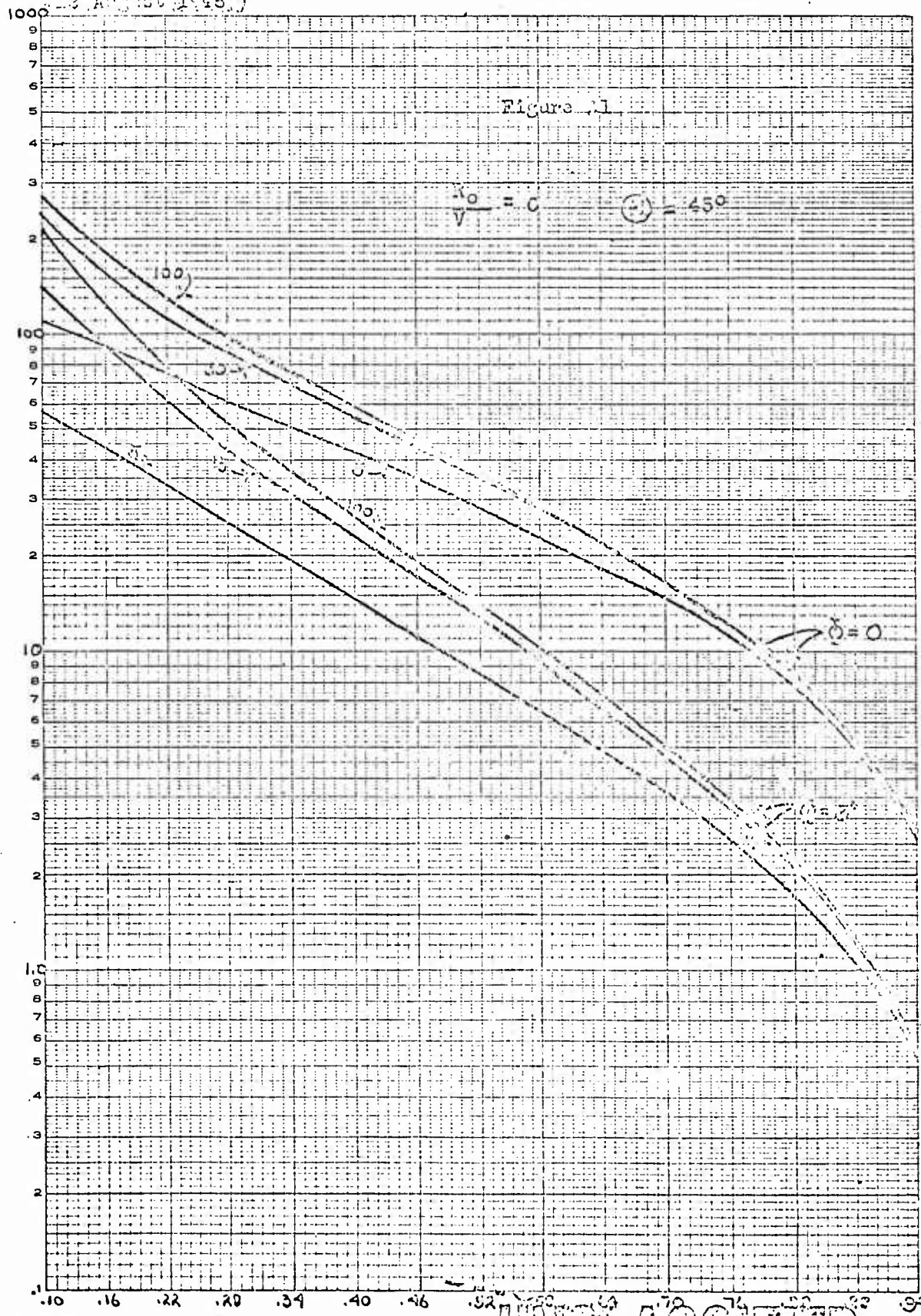
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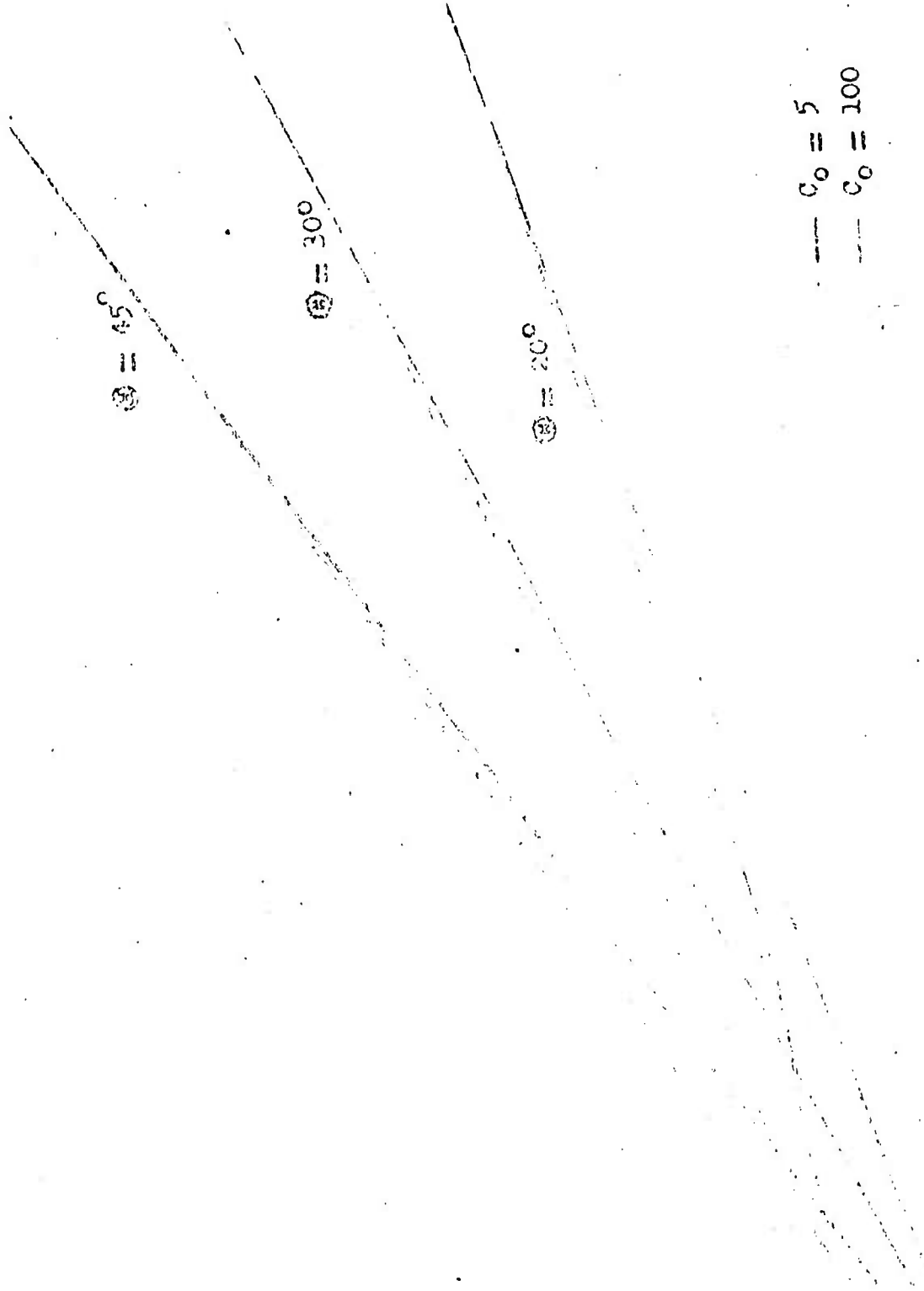
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LATERAL RANGE COVERED BY AZIMUTH SCAN



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ALTITUDE COVERED BY ELEVATION SCAN

$\theta = 5^\circ$

$\theta = 3^\circ$

$\theta_0 = 5$

$\theta_0 = 100$

$\theta = 0^\circ$

FIGURE A3

R/R₀

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TABLE A1

Polar Angle θ (degrees)

$h_0/V = 0$

C_D R/R_0	5	10	20	30	40	50	60	80	100
.0	3.2	32.7							
.01	3.1	32.4							
.03	3.1	30.8							
.06	2.8	26.4	67.6						
.10	2.2	20.2	41.3	49.7	56.0	61.4	63.1	67.0	69.3
.15	6.3	14.3	22.5	26.3	28.4	30.7	30.6	31.0	32.5
.20	5.4	10.4	14.5	16.2	17.1	17.7	18.0	18.7	18.8
.30	3.9	6.1	7.1	7.4	8.1	8.4	8.4	8.5	8.6
.40	2.9	3.9	4.4	4.5	4.7	4.7	4.8	4.9	4.9
.50	1.7	2.0	2.1	2.1	2.2	2.2	2.2	2.2	2.2
.60	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
1.00	.8	.8	.8	.8	.8	.8	.8	.8	.8
R_m/R_0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

$h_0/V = .2$

C_D R/R_0	5	10	20	30	40	50	60	80	100
.0	3.7	32.7							
.01	3.0	32.0							
.03	2.7	29.6							
.06	2.2	24.5	63.4						
.10	6.3	18.0	17.7	45.6	51.6	55.6	58.4	62.1	64.5
.15	5.2	12.1	19.8	22.9	25.2	26.5	27.4	23.5	29.2
.20	4.3	8.5	12.3	13.3	14.7	15.2	15.5	16.0	16.3
.30	2.9	4.8	5.3	5.3	6.5	6.6	6.7	6.9	6.9
.40	2.0	2.3	2.3	2.4	3.5	3.6	3.6	3.7	3.7
.60	1.0	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4
R_m/R_0	.63	.72	.75	.75	.76	.76	.76	.76	.76

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52

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$R_0/V = .9$

R_0/V	5	10	20	30	40	50	60	80	100
.0	32.2	32.7							
.01	7.7	30.7							
.03	6.8	26.2	89.5						
.06	5.0	19.5	71.1	73.0					
.10	4.3	12.8	25.7	35.0	40.1	43.5	46.1	50.4	51.5
.15	3.0	7.6	13.2	15.1	17.7	18.7	19.5	20.4	21.0
.20	2.1	4.7	7.4	3.6	9.2	9.7	10.0	10.3	10.6
.30	1.0	2.0	2.3	3.1	3.3	3.4	3.5	3.6	3.7
.40		1.0	1.3	1.4	1.5	1.5	1.5	1.6	1.6
R_m/R_0	.34	.43	.46	.43	.49	.45	.49	.50	.50

$R_0/V = 1.0$

R_0/V	5	10	20	30	40	50	60	80	100
.0	32.2	32.7							
.01	7.6	30.5							
.03	6.6	25.2	85.2						
.06	5.2	15.1	48.3	73.5					
.10	4.0	11.3	24.2	32.0	36.9	40.2	42.6	45.8	47.8
.15	2.5	6.4	11.5	14.2	15.7	16.7	17.5	18.3	18.8
.20	1.8	3.8	6.2	7.3	7.9	8.3	8.6	8.9	9.1
.30		2.5	2.2	2.5	2.6	2.7	2.8	2.9	2.9
.40			.9	1.0	1.1	1.1	1.1	1.2	1.2
R_m/R_0	.29	.33	.42	.43	.44	.44	.45	.45	.45

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