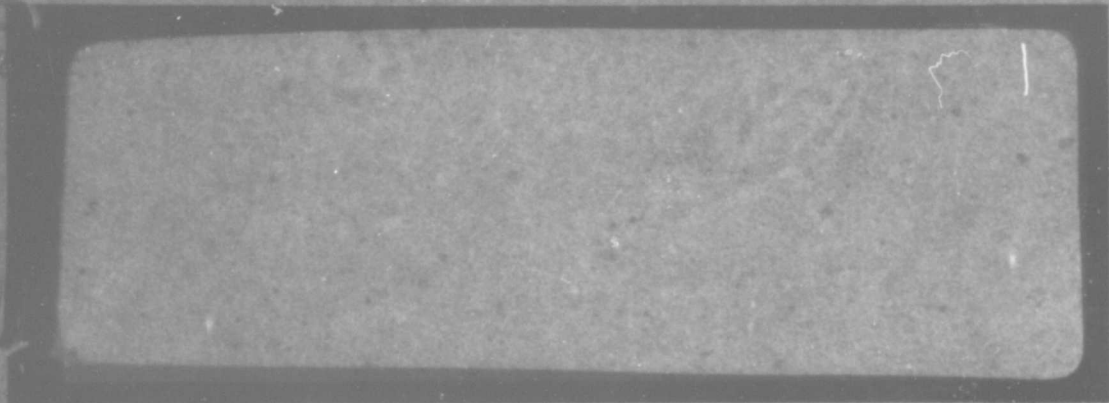


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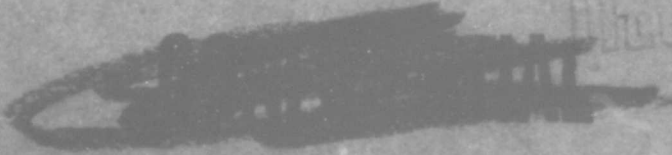
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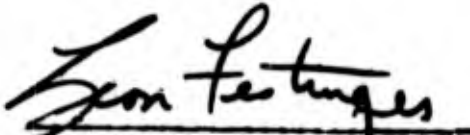
## ESTIMATES OF VISIBILITY FROM HIGH ALTITUDE AIRCRAFT

Report No. 151-1-14  
Project No. 20-M-1b  
15 April 1948

### Report prepared by:

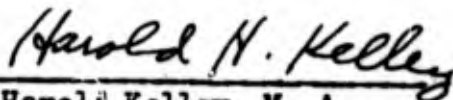
Division of Bio-Mechanics  
The Psychological Corporation, New York

John D. Coakley, Acting Director

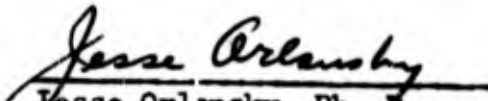
  
Leon Festinger, Ph. D.

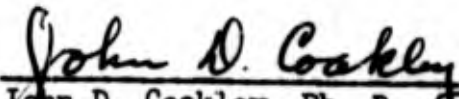
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Harold Kelley, M. A.

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3831, SD from the Office of  
Naval Research, Navy Department,  
Sands Point, Port Washington,  
Long Island, New York

  
Jesse Orlansky, Ph. D.

  
John D. Coakley, Ph. D.  
Project Director

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## Orientation

High speeds imply that unpursued targets remain visible for relatively short times. On the other hand, high speeds will probably require operation at rather high altitudes and at these altitudes a target may be visible at unusually great distances. Evaluation is, therefore, desirable. The specific question considered in this report is, "For various combinations of observer and target altitudes, how far away can a pilot see another object, such as a plane in the sky?"

This question may be answered in part by recourse to information reported in the literature. Since a large number of factors determine what can be seen by a human observer, it is convenient, wherever possible, to simplify the problem by eliminating certain specified variables. Visibility, as it is considered here, is measured by the extreme distance at which the mere presence of another object may be detected in a variety of viewing circumstances. The distances at which an object may be resolved and identified are not considered here. It is known that the distances for identification are less than those at which an object becomes just visible. The problem is further simplified by assuming that the observer is unencumbered in any manner and that both the observer and the target are motionless with respect to each other. This simplification is due to the lack of satisfactory information on the ability to detect moving objects. Further studies will be necessary to show the effects of removing these strictures.

Thus, attention may be devoted to the principal variables which determine visibility. Some of the major variables are contrast, target size, brightness level, sky brightness, solar illumination, and the attenuation of contrast by the atmosphere. Estimates of visibility at high altitudes

depend upon quantitative information about each of these variables. Since direct knowledge about flight and the attendant visual conditions is not available, it will be necessary to assume typical values for some variables and probable ranges for others. Thus, some presumed values -- which are always described explicitly as such and which are based on information gathered from the literature -- are combined with precise laboratory data to develop a fuller understanding of visibility at high altitudes. The results are expressed in terms of the distance at which a target may be seen. The basis upon which such estimates of distance may be made is explained in three major sections. The first section presents data about vision and the properties of the atmosphere which influence vision. The second section shows how the distance at which an object becomes visible may be computed by taking into account the influence of atmospheric attenuation. The last section presents estimates of visibility for a specific target at altitudes up to 300,000 feet when the observer is at various altitudes up to 200,000 feet.

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Summary

1. The distance at which an object becomes visible depends upon such factors as brightness contrast, target size, brightness level, and atmospheric attenuation. On the basis of evidence given in this report, numerical values are selected to represent the influence of these variables under the conditions of high altitude flight. Visibility is examined under the following conditions:

- a. Altitude of observer -- sea level, 50,000, 100,000, and 200,000 feet.
- b. Altitude of target -- from sea level to approximately 500,000 feet (60 miles).
- c. Background brightness conditions -- from 1 to 32 footlamberts.
- d. Contrast ratio between target and background -- for values of 1, 5, 10, and 100.

2. The computation of visibility is based on visual acuity data corrected for the effect of atmospheric attenuation at various altitudes. A round object with a diameter of 10 feet may be used as a representative target. When the altitude of this object is the same as that of the observer, the distances at which the object is just visible are as follow:

Contrast Ratio	Altitude	
	Sea Level	50,000 feet and above
1	3.6-3.9 miles	9-14 miles
5	3.9-5.3 miles	21-30 miles
10	5.3-6.7 miles	27-39 miles
100	—	83-138 miles

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The minimum and maximum values just given are determined by variation in the level of background brightness. Visibility above 50,000 ft is approximately the same as shown for the values of contrast examined at 50,000 ft because the effect of atmospheric attenuation is negligible above this altitude. Four graphs are presented in the text to show threshold visibility for all directions of view at altitudes up to 200,000 feet.

3. Described in the broadest terms, direct vision may permit an observer to detect another object in the sky at distances which may be travelled in one minute or less at high speed. It appears unlikely that an opportunity to permit leisurely inspection of another object will be available under these circumstances. Since fast moving objects may appear and disappear from view in sudden fashion, effective surveillance requires a willingness to respond to slight visual cues before it becomes clearly apparent that they are actual targets.

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## I. Some Factors Which Influence Visibility

The relevant facts about visibility on which the estimates are based are presented in this section. Certain technical terms used frequently in this paper will be defined at the outset:

- a. Footcandle - A measure of the intensity or level of illumination. One footcandle (fc) is the intensity of illumination at a point on a surface one foot from a uniform point source of one standard candle. The approximate intensity of illumination from certain sources is given for purposes of reference:

direct sunlight, at very high altitudes	13,600 fc
daylight, in shade	100-1000
daylight, at north window	50-200
good office lighting	50-50
street lighting	0.6-1.2
moonlight	0.02
starlight	0.0002

- b. Footlambert - A measure of the brightness of a surface which emits or reflects light. A perfectly reflecting surface illuminated by one footcandle has a brightness of one footlambert (fl), i.e., footlamberts = footcandles x reflection factor of surface. Other units for brightness are the candle per square inch (candles/sq in x 452.5 = fl) and the millilambert (ml x 0.929 = fl). Several representative brightness values are given below:

white surface in bright sunlight (at 40,000 ft altitude)	12,000 fl
sun-illuminated clouds, seen from above	6,200-10,000
horizon sky	2,600-3,000
clear blue sky, 30° above horizon	500-1,250
green grass in sun	700
black cloth in sunlight	225

- c. Reflection factor - The diffuse reflection factor of a surface is the ratio, expressed as a percent, of the light reflected from a surface to that incident upon it. Several representative values are given:

magnesium carbonate	94-98 percent
mirrored glass	80-90
white blotting paper	80-85
polished aluminum	60-70
black paint	3-5

In this paper, illumination will be described in footcandles and brightness

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in footlamberts regardless of the units employed in the original source.

A. Brightness contrast between target and background

One of the major factors which determines the visibility of an object is brightness contrast, that is, the difference between the brightness of the target and its background. Other factors, among which are the absolute brightness level, the size of the target, and the retinal patch upon which the light falls, must be taken into consideration; but visibility cannot occur without contrast.

The inherent contrast,  $C_o$ , of a target with a brightness measured at close range is defined as

$$C_o = \frac{B_t - B_b}{B_b} = \frac{\Delta B}{B} \quad (1)$$

where  $B_t$  and  $B_b$  are brightnesses of the target and background, respectively (12)\*. Contrast is indicated by a number which will be positive and range from zero to infinity for targets brighter than the background; or negative and range from zero to one for targets darker than the background. The positive sign is usually employed for all classes since present evidence indicates that where area is held constant there is equal visibility for targets of numerically equivalent positive and negative contrast\*\*. Of

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\* The subscripts "t" and "b" are used in this paper for designating "target" and "background". The reference from which the formula was taken uses "o" for "object" and "h" for horizon; Blackwell (5) uses "s" for "stimulus" and "o" for "observation screen"; Verplanck (38) uses the subscripts adopted in this paper. Except for the choice of subscripts, all define contrast in the same manner.

\*\*One exception occurs in the case of large target areas at low adaptation brightness where there is a 20 percent lower threshold for negative as against positive contrast (5). This combination is not likely to occur under the present conception of fast-moving objects at high altitudes.

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course, small amounts of contrast exist when the brightnesses of the target and background approach each other although the actual brightness level of the target may be high.

Basic data, which show the relation between brightness contrast and target area, are to be found in an article by Blackwell entitled "Contrast Thresholds of the Human Eye" (5); a complete table representing the same data appears in the NDRC Summary Technical Report, Volume 2 (41). The latter source provides precise values of the minimal required contrast for targets that vary in size from 360 to 0.129 minutes of arc under brightness conditions that range from 1000 to 0.00001 fl. Figure 1, which is reproduced from Blackwell's paper, shows the relationship graphically. The marked discontinuity in the curves at approximately 0.001 fl is attributed to the shift from cone to rod function as adaptation brightness is reduced. The least amount of contrast is required for perception of a brightness difference between large targets at high brightness levels, e.g.,  $C_0 = 0.0027$  for a target of approximately  $6^\circ$  at 1000 fl; the greatest amount is required for small targets at low brightness levels, e.g.,  $C_0 = 1530$  for a target of 0.8' at 0.00001 fl (41, Appendix A).

While Blackwell's data constitute the most substantial body of information available on visibility, it was considered advisable to check his findings against actual visibility on field trials. The contrast thresholds obtained at Tiffany Foundation (reported by Blackwell) are lower by 0.40 log units than those obtained at New London in extensive field tests of optical instruments (38). In another report based on the New London data, Coleman and Verplanck (11) find a "remarkable agreement between the computed (i.e., Tiffany based) and experimental range performance of the optical instruments". The differences which occur are minor, and they are considered

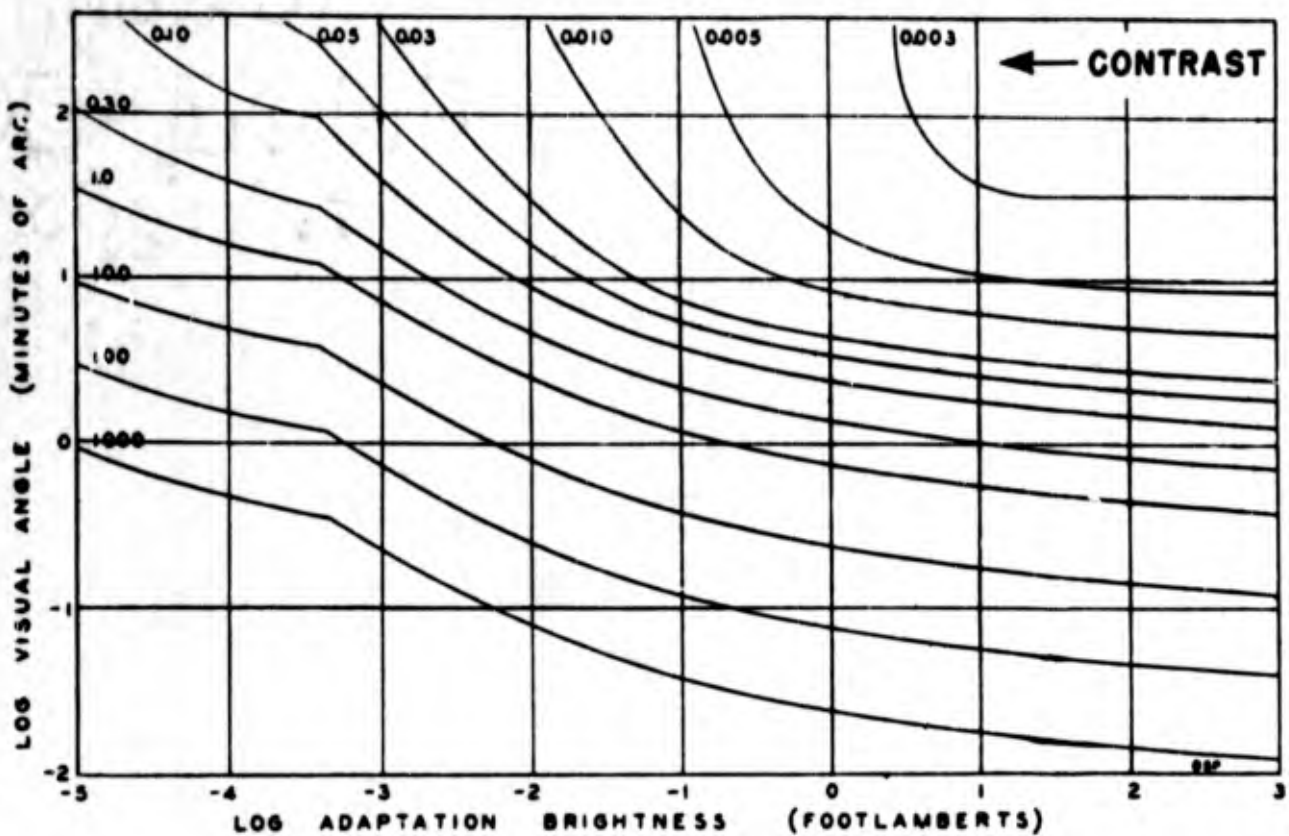


FIG. 1 THE RELATION BETWEEN STIMULUS AREA AND ADAPTATION BRIGHTNESS FOR STIMULI OF VARIOUS CONTRASTS. (FROM BLACKWELL (5), FIG. 18)

to be due to such factors as vibration and the relative ease of handling the various optical instruments when either mounted or hand held. Another factor which might explain the differences between the laboratory and field data is the possible lack of consistency among subjects in using a recognition, rather than a detection, criterion of visibility. Blackwell reports elsewhere a ratio of 1.14:1 between field and laboratory threshold values for two subjects (8). The field data were close to and did not vary systematically from the Tiffany results. However, this comparison is not conclusive because it was based on a few preliminary observations. Hecht (17) reported that silhouetted squares with sides of 2, 2.5, and 3.0 inches could be seen against a sky of about 929 fl (1000 ml)\* at a distance of 2458 feet. The increase in size from 2 to 3 inches resulted in increasing the frequency of correct answers from 74 to 99 percent. For equal probability of seeing (90 percent level of confidence), Hecht's data yield a value of 0.315 minutes, which is to be compared to Blackwell's 0.301 minutes as the angular subtense of a just visible target at 1000 fl. There is, again, a reasonably close agreement between field and laboratory data. The statistical significance of the disparity (which is not large) has not been tested because few field cases are involved and the criterion of visibility may have been different for the subjects in the two reports.

In his report to the Army-Navy-NRC Vision Committee, Blackwell (6) shows that there is an excellent agreement between the Tiffany data and other experimental data. Adjustments must be made between the Tiffany data and those from four other laboratories because different threshold criteria are utilized and because of differences in procedure. Blackwell presents four graphs to show the close agreement with other laboratory data after allowances

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\*See page 5 for a definition of millilambert.

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are made for the differences in experimental procedure.

Full verification of the Tiffany data by field trials is still to be achieved, and projects directed toward this end have already been established. The Tiffany data are in general agreement with and are more substantial than any other existing laboratory data. Such field test data as are available are confirmatory in nature, but they have not yet been carried far enough to permit full evaluation at this time. Accordingly, the Tiffany data are accepted as a basis for computation.

Suppose that a target with a brightness of 10 fl is viewed against a background with a brightness of 0.1 fl. The contrast ratio is

$$C_o = \frac{B_t - B_b}{B_b} = \frac{10 - 0.1}{0.1} = 99$$

When  $C_o = 99$ , Figure 1 shows that the threshold visual angle is equal to  $\log - 0.90$  or about 0.12 minutes of arc. That is, when the eye is adapted to a brightness of 0.1 fl, a bright object with an inherent contrast of 99 is just visible if it subtends 0.12 minutes of arc. A solution by trigonometric methods may then be applied to relate distance and size for targets of this angular subtense.

#### B. Visual angle

The size of an object and its distance from the observer influence visibility, but the combined effect may be expressed as the visual angle. According to this concept, the angular subtense of a target determines its visibility. Disregarding atmospheric attenuation, it is assumed that a small target at a close distance is as easily visible as a large target at a great distance when both subtend the same angle at the eye. The angular subtense which can be perceived is related to brightness, the ability to

perceive small targets improving with an increase in illumination (2). This fact points toward excellent visibility at high altitudes where targets may be highly illuminated and seen against a relatively dark sky even during the day.

1. Target area

When contrast is held constant, the visibility of targets is dependent upon their area but only when the area is about 200 square minutes or more. For targets less than 2 minutes in diameter, such as must be considered here, the amount of light (area x brightness) rather than area alone determines visibility (25). Very small targets reported visible out-of-doors in 75 percent of the trials against the sky at a distance of 2458 feet subtend visual angles of 14 seconds (2 inch sides) for a square and 0.45 seconds (0.066 inch diameter) for a wire (17).

2. Constancy of visual acuity with distance

The premise that the size of the retinal image determines visibility regardless of the manner in which target area and distance combine to yield a particular angular subtense requires examination. Visual acuity is known not to be constant over very short distances. That is, the minimum visual angle which can be discriminated changes over distances up to 72 feet as reported by two studies (4, 15). The present question is whether this effect applies as well to greater distances. Forbes and Holmes (14) found that for distances ranging from 330 to 1550 feet, visual acuity for dark letters on a white background increases slightly with distance. There was a 20 percent increase of acuity for a 370 percent increase in distance and they concluded that visual acuity was sufficiently constant for practical purposes. Beebe-Center and others (3) studied visual acuity at distances ranging from 12.5 feet to 2.83 miles and found that acuity for

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white letters on a black background did not change at distances greater than 30 feet. It appears correct, therefore, to follow present practice in predicting visibility over large distances on the basis of a constant visual angle.

### 3. Target shape

The Tiffany data indicate that visibility is equal for squares and circles having the same area. A theoretical expression for the effect of shape is derived:

"The liminal contrast of a rectangle is the geometric mean of the liminal contrasts of squares having sides equal in visual target subtense to the sides of the rectangle".  
(41, p. 59)

Experiments at 10 and at 0.00001 fl are reported to verify these predictions within the experimental error of observations (8). A wartime survey based upon British experimental sources suggests that, where area is constant, targets in the shape of circles, semi-circles, triangles, and rectangles with length to width ratios up to 3:1 are equally visible (24). The range of visibility of ship models was shown to depend only on the contrast and total area seen by the observer, except for a variation of 5 percent; this residual variation may possibly be due to differences of shape (31).

Rectangles of a constant area become more difficult to detect as their shape becomes elongated. This relationship was tested in a series where the ratio of length to width varied from 2:1 to 200:1 for rectangles with areas of 0.5 to 800 square minutes (25). A critical minimum quantity of light is required for detection of targets when both dimensions are less than 2 minutes. Field trials show that squares are more readily seen than lines, visual angular areas of 500 for the former and 1800 square seconds

for the latter being equally visible under daylight conditions (17).

A circular target is used in the calculations of visibility for this report. Thus, the estimates in this paper are directly applicable to circular targets; and, with negligible error, they hold for other compact targets of equal area though different shape. Computations based upon a circular target yield maximum ranges for all targets of that area. If the actual target is considerably elongated, its range will be less than the computed range. Use of a single target shape, though not strictly accurate for planes or missiles, simplifies the computations and at the same time provides satisfactory estimates.

### C. Adaptation level

The sensitivity of the eye varies with the brightness level to which it is exposed and to which it has become adapted. The adaptation level is regarded as equivalent to the brightness of the background set before the observer's eye. A certain amount of time is required before the eye becomes fully adapted following a shift from one brightness level to another. The longest amount of time is required when shifting from daylight (1000 fl) to starlight viewing conditions (0.0001 fl). About 30 minutes must elapse before maximum visual sensitivity is achieved. The shift from daylight to twilight (0.1 fl) requires only about 3 minutes, and the shift from a brighter to a less bright daylight level is accomplished quickly (within 1 minute). However, 1 minute is about the maximum time required for shifting from any darker to any brighter level.

In this paper, it is assumed that the observer is adapted to the brightness level at which visibility is considered. This assumption leads to no limitation of any consequence under conditions of normal daylight

flight. If a pilot is expected to see under night viewing conditions after exposure to daylight, it is assumed that 30 minutes elapse in order for him to achieve maximum sensitivity. No such limitation is imposed if he has been dark-adapted with red goggles prior to flight.

Adaptation level influences the size of the pupillary opening, the diameter of which is related to visual acuity. Visual acuity is roughly constant for pupil diameters between 3 and 6 mm, with a minimum threshold (best acuity) at 4 mm (10). Visual acuity decreases markedly for pupil openings smaller than 2 mm and slightly for those larger than 6 mm. Much of the existing laboratory data on visual acuity as related to intensity of illumination was collected with the use of a fixed aperture, i.e., artificial pupil, either 2 or 3 mm in diameter. Such data must be corrected if they are to be applied to visibility where the natural pupil changes size with variation in the intensity of illumination. No correction is required when the Tiffany data are employed because the naked eye was used for all observations in that study. However, a correction would have to be made for a prediction of visibility if binoculars or other optical instruments were used in operating high-speed craft. Formulas which may be used in making these corrections are given by Moon and Spencer (28).

#### D. Atmospheric Attenuation

Atmospheric attenuation is an important factor in reducing visibility at the earth's surface. The effect of the atmosphere upon light consists of two separate phenomena: the absorption and the scattering of light. The total result of these atmospheric effects can be represented as a reduction in brightness contrast. This reduction can be very severe when the air contains impurities, such as water vapor and dust particles, whereas the attenuation of pure air is relatively small. Thus, not only the density of

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the air but also the type and degree of impurity in the air at different altitudes must be taken into account. These topics are considered more fully in Section II.

An atmospheric phenomenon which may influence visibility, particularly if the line of sight passes close to the earth, has been demonstrated photographically. The image of a target may deviate over 3 seconds of arc from a reference scale when the light passes over level ground in bright sunshine (29). Presumably this phenomenon is due to atmospheric turbulence, which produces effects similar to those of prisms changing constantly in power, orientation, and size. It is a factor which influences the performance of binoculars and stereoscopic range finders on the earth's surface, but it is not of critical importance to this report.

#### E. The criterion of visibility

Objects observed under conditions which are close to the threshold of visibility appear to fluctuate between being seen and not being seen. Data from a series of target searches will show that the frequency of seeing increases from 0 to 100 percent as the distance between the target and observer decreases. The question which always faces the experimenter is which of the distances to accept as the threshold for visibility. This problem is not unique for vision, but is common to threshold determinations for the other senses as well.

The variability of the visual mechanism has received considerable attention, and there is general agreement that the relation between frequency of seeing and contrast is described by an S-shaped curve which may be the integral of the normal probability function (24). The threshold must be selected, somewhat arbitrarily, in terms of some probability of seeing.

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Blackwell (5) and others have defined the threshold as the contrast required for target detection with a probability of 50 percent, due allowance having been made for chance success\*. This particular value is selected because the steepness of the probability curve at this point results in maximum precision in the determination of the threshold. This definition does not introduce any special restriction because these thresholds can be converted to any desired level of probability by use of proper constants. For example, threshold contrasts corresponding to a 90 percent probability of detection may be derived when the thresholds presented by Blackwell are multiplied by the constant 1.62. The effect of this "correction" would be to reduce the range of visibility by requiring that a target approach more closely before it will be considered as "visible", i.e., noted more frequently. Blackwell's data are used in this paper with the threshold defined at the 50 percent level of probability. The distance for threshold visibility would be reduced about 10 percent if the 90 percent probability level were adopted.

F. Visual problems due to high altitude flight

The factors which have been discussed up to this point apply generally to visibility problems. Some special conditions associated with high altitude flight will now be considered. Anoxia and target motion are examples of problems which must be considered. The treatment of these and other topics must be conjectural in part because, at present, exact information

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\*"When there were eight possible positions of the target, coincidence of random guesses would be expected to yield one correct report out of every eight responses. The criterion of visibility adopted in this investigation required half of the remaining 87.5 percent of responses to be correct. These, in addition to the 12.5 percent attributed to chance, correspond to 56.25 percent correct responses, which was the score employed for the determination of liminal contrasts throughout this investigation". (41, p. 54).

[REDACTED]

is meagre about airplanes operating at very high altitudes. However, a useful purpose is served by making explicit reference to these possible influences upon visibility. Statement of the lack of information may identify areas which require further exploration.

Anoxia, which reduces visual efficiency, must be considered if the cabins of high-flying aircraft are not pressurized to sea level conditions. Carbon monoxide, small amounts of which are often found in aircraft, ultimately produces an anoxic effect, additive to that due to absence of oxygen (25, 26). These and similar deleterious influences may be considered simultaneously by use of the concept of "physiological altitude". This parameter is expressed in feet and by the physiological consequences, however induced, equivalent to those associated with breathing air at some actual altitude.

The degree of anoxia to which a pilot will be subjected depends, of course, upon the design characteristics of the particular airplane considered. Following McFarland's discussion (25, pp. 41-105), one may judge it undesirable to expose the pilot to anoxia greater than that which occurs at 10,000 ft. At a "physiological altitude" of 10,000 ft, there is a moderate degree of anoxia, sufficient to induce fatigue and impair visual function, but not so extreme as to involve the danger of unconsciousness for the normal pilot.

Moderate anoxia impairs the response of the rods but does not appreciably alter the sensitivity of the cones. Thus, for 10,000 ft altitude, Hecht(16) has shown that no increase of brightness contrast ( $\Delta B/B$ ) is required for visibility at a brightness of 9.29 footlamberts (10 ml) although 32 percent more brightness contrast is required when the brightness is 0.0009 footlamberts. This implies directly that no loss of visibility due to this degree of anoxia has been demonstrated when the eye operates at or above

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twilight brightness.

Anoxia reduces contrast discrimination, and the largest reduction in range occurs for targets which are visible at a great distance when the atmosphere is clear. Anoxia would only slightly reduce the visibility of a target already impaired by conditions of low atmospheric visibility, such as fog at low altitudes. At low illuminations, the reduction in range due to anoxia (10,000 ft) is of the order of 10 percent (7, 30). Figure 14, which appears in the Appendix, illustrates more fully the nature of this effect.

Some special visual problems which may exist at high altitudes will be given passing mention. Due to the absence of contaminating particles in the air, the sky appears darker at higher altitudes, whereas objects in the sky are more intensely illuminated. Therefore, there may be considerable glare, which may interfere with visibility if the field of view includes brightly illuminated parts of the airplane. The presence of brightly illuminated areas within the visual field may cause frequent shifts in the level of adaptation brightness and pose a problem in predicting the level of sensitivity from one moment to the next. Information already available concerning the effect of flash and glare may be useful in solving these problems when they arise.

Objects at high altitude may first appear as mere points of light. This is due, of course, to the contrast afforded by the intense illumination on an object seen at great distance against a dark background. The Tiffany data were collected in a situation where the observer had to note the presence (in one of eight positions) of a single stimulus and not of an additional one among others already there. When seen from high altitude, stars will appear in the upper portion of the sky even during the day. This

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must mean that a target appearing among the stars as a new point of light may not be detected quite as readily as the Tiffany data suggest. (In any case, this is a matter which may affect vision at high altitudes and concerning which further information is required.)

The shock wave which occurs in supersonic flight must be evaluated for the effect of image distortion which it may introduce. Also in need of evaluation are the related problems of image distortion and the loss of light due to the airplane's enclosure and the pilot's goggles. Relative target motion will also influence the detectability of the target.

A host of other medical factors associated with temperature, vibration, g, fatigue, and particular drugs, e.g., aspirin or benzedrine, may influence physiological equilibrium and thereby affect vision. These influences can be expected to introduce deleterious effects, especially when several of them are imposed in combinations. Visibility in the present paper is considered for the normal pilot free from any special stresses. With the various limitations noted in this section, the visibility ranges discussed below refer to those possible for an unencumbered individual at the several designated altitudes.

## II. Intermediate Calculations and Results

This section of the memorandum contains the data and intervening calculations which are prerequisite to the final visibility computations described in Section III. In Part A the geometric problems are set out and three lines of sight having special characteristics are described. The lengths of these lines indicate the absolute geometric limit of visibility. In Part B the geometric limits are modified to take into account the sensitivity of the eye. Atmospheric effects are introduced in Part C to serve as a further modification of the limits of visibility. Finally in Part D the variations in the intensity of sunlight and sky brightness as a function of altitude are incorporated to complete the series of corrections necessary for estimating visibility.

### A. Maximum viewing distances

Three of the directions in which one might look from high altitudes are selected here as representing limiting conditions of interest to the present topic. These are defined and figures presented to show the maximum possible distances at which an object may be seen in each of these directions without being obstructed by the earth.

#### 1. The downward line of sight

The distance between the observer and the surface of the earth (defined as sea level) in a direction directly downward (that is, making an angle of 90 degrees with the horizontal) is the altitude of the observer. This is the minimum distance between observer and the surface of the earth and, as such, the line of sight to the earth which encounters the least atmospheric interference.

#### 2. Line of sight tangent to the earth's surface

This represents the longest possible line of sight which touches the earth's surface. Continued outward, this line of sight determines the maximum distance at which another object, at some particular altitude, could be seen without having the earth block the view. This line of sight, by the time it touches the earth's surface, has encountered the greatest amount of atmospheric interference of any possible line of sight. The length,  $x$ , of a line tangent to the earth's surface is equal to

$$\sqrt{h(h + 2r)} \quad (2)$$

where  $h$  is the altitude and  $r$  is the radius of the earth's sphere.

### 3. Line of sight tangent to 30,000 feet altitude

If one assumes that pure air exists above 30,000 feet (because of the low density of the air at this altitude), one may come to the conclusion that the effects of atmospheric attenuation can virtually be ignored above such altitudes. Consequently, it is important to know how far one can see from a given altitude without the line of sight going below an altitude of 30,000 feet. For such lines of sight, one can then ignore atmospheric attenuation and, without further correction, can compute visibility from the data presented in Figures 1 and 3. The length of a line of sight tangent to the 30,000 feet altitude circle is equal to

$$\sqrt{h(h + 2r) - d(d + 2r)} \quad (3)$$

where  $d$  is 30,000 feet.

The earth is assumed to be a perfect sphere with radius of 3,958.89 miles. (The equatorial radius is 3,963.34 miles and the polar radius is 3,949.99 miles.) The radius chosen for use is the radius of a sphere having the same volume as the earth. Figure 2 presents the curves which relate altitude of the observer to his maximum viewing distance along lines of sight (a) tangent to the earth's surface and (b) tangent to the 30,000 feet

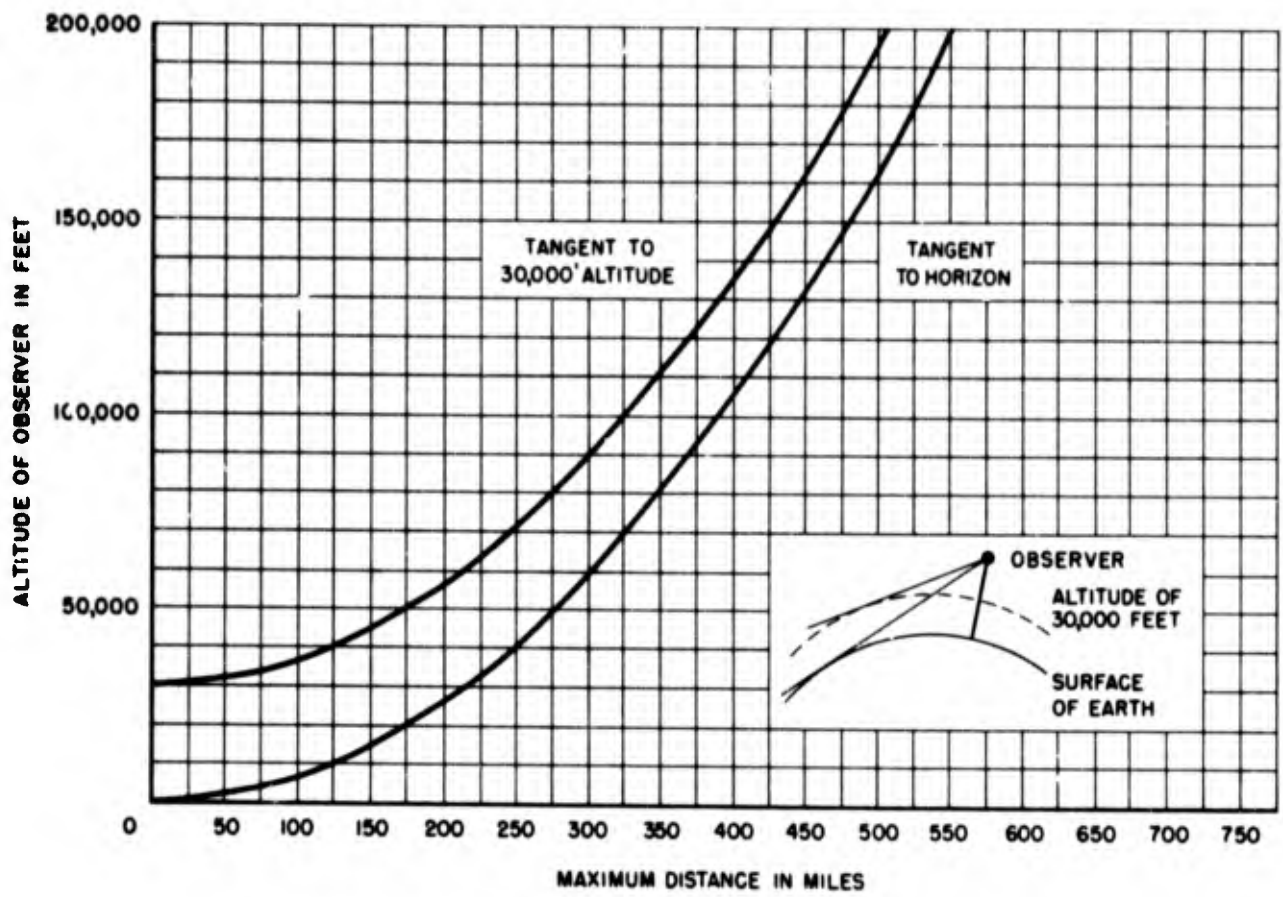


FIGURE 2: RELATION BETWEEN ALTITUDE AND MAXIMUM VIEWING DISTANCE TO THE HORIZON AND TANGENT TO A CIRCLE AT 30,000 FEET ALTITUDE

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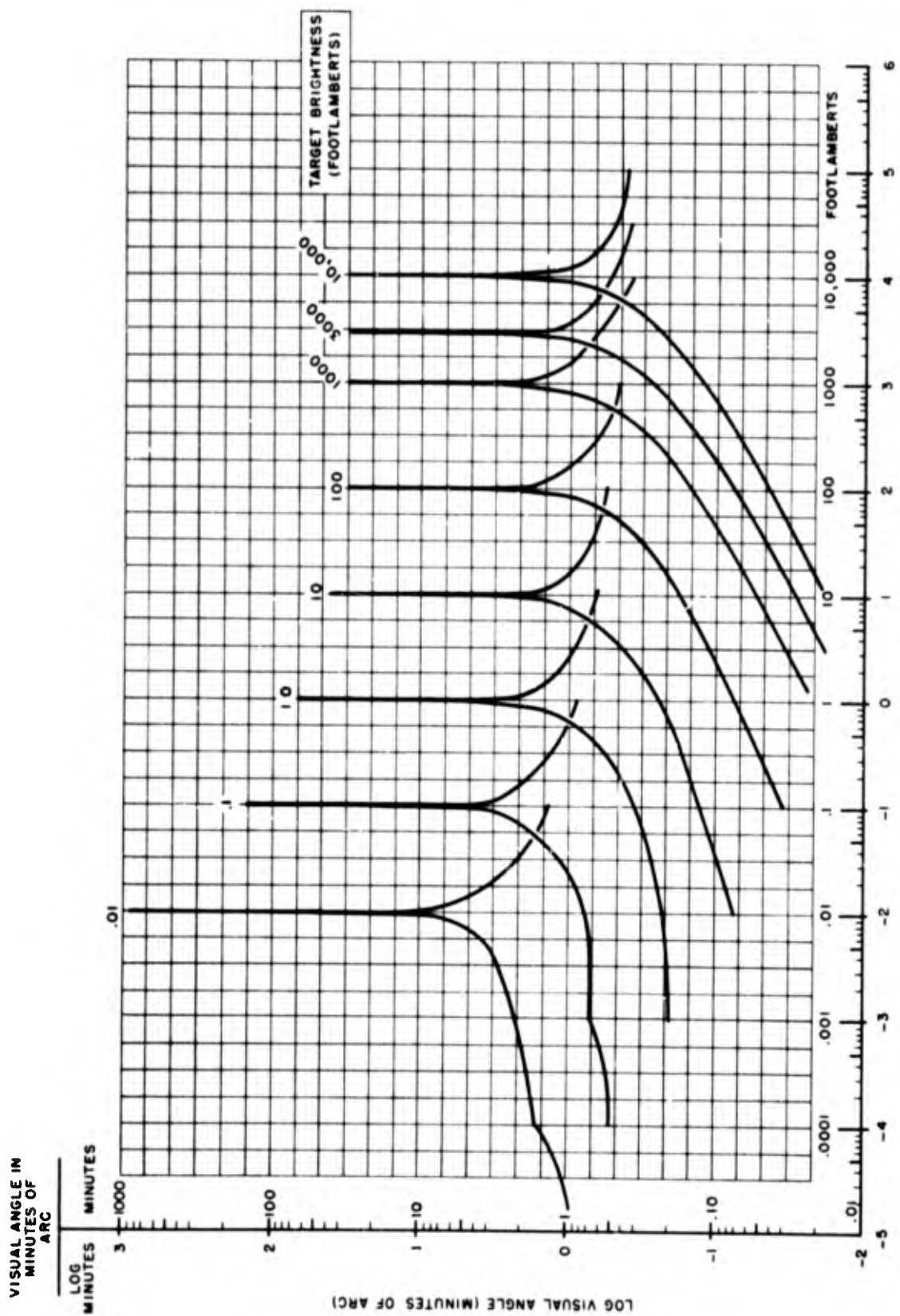
altitude level. The figure shows that, from an altitude of 200,000 feet, one could look along a 550 mile line which is tangent to the surface of the earth. From an altitude of 50,000 feet, the comparable distance is 275 miles. The maximum distance between two objects, one at 200,000 feet, say, and another at 100,000 feet without the earth interfering, would be 550 plus 390 miles, or 940 miles. The maximum possible distance between two objects of given altitude without the earth forming an obstruction could thus be obtained by adding together any two specified points on this curve. The same procedure can be applied to the curve for a line tangent to the circle drawn about the earth at the altitude of 30,000 feet. Thus, from 100,000 feet, the line of sight to the point of tangency to the 30,000 feet altitude level would be 325 miles long. Theoretically, an observer at 200,000 feet could see another object at 50,000 feet altitude almost 675 miles away without the line of sight going below an altitude of 30,000 feet.

**B. Visibility of a target before correction for atmospheric effects**

A preliminary estimate of visibility may be obtained by referring to Figure 3, which is based upon Blackwell's data for visual acuity thresholds. The effect of the atmosphere, which would be to reduce these ranges, has been disregarded for the moment in order to emphasize the visual relationships. Threshold visual acuity is plotted against background or adaptation brightness for targets of various brightness in such a manner that it is not necessary to compute the contrast ratios.

The conditions which are described in Figure 3 are:

- |  |                            |
|--|----------------------------|
| a. background brightness                                     | 0.00001 to 10,000 fl       |
| b. target brightness   | 0.01 to 10,000 fl          |
| c. target size (diameter of the angular subtense of the eye) | 0.01 to 100 minutes of arc |



LOG ADAPTATION BRIGHTNESS (FOOTLAMBERTS)

FIGURE 3: RELATION BETWEEN ADAPTATION BRIGHTNESS AND THRESHOLD VISUAL ANGLE FOR TARGETS OF VARIOUS BRIGHTNESSES.

EQUIVALENT DISTANCE IN MILES FOR 3 ROUND TARGETS	
DIAMETER (FT.)	
10	200
.03	.65
.05	.96
.07	1.41
.10	2.07
.15	3.03
.22	4.45
.33	6.53
.48	9.58
.70	14.09
1.03	20.66
1.51	30.34
2.22	44.50
3.26	65.3
4.8	95.8
7.0	140.9
10.3	206.6
15.1	303.4
22.2	445.0
32.65	653.0
48.0	958.0
70.0	1409.0
103.0	2066.0
151.0	3034.0
222.0	4450.0
326.5	6530.0

A scale is provided to permit interpretation of the threshold visual angle in terms of distance in miles for round targets with a diameter of 10, 50, and 200 feet. The choice of the range of target brightness and background brightness is somewhat arbitrary but is broad enough to cover anticipated daylight conditions.

Suppose, for example, that a target with a brightness of 1000 fl appears against a sky background of 100 fl. This level of target brightness may be expected with sunlight illumination of 10,000 fc falling upon an object with a reflectance of 10 percent. The contrast ratio, which need not be calculated when this figure is used, is

$$\frac{1000 - 100}{100} = 9$$

The threshold visual angle is about 0.14 minutes of arc. This is equivalent to a distance of approximately 21 miles for an object with a 10 ft diameter or a greater distance for larger targets, as is evident from the appropriate scale on the figure. Objects may be expected to be visible at great distances in daylight at high altitudes because the targets will be bright due to intense illumination and will appear against a relatively dark background. This combination may yield unusually large contrast ratios which, in the extreme case, approximate a point source of light against a dark background, and lead to exceptional visibility distances, as the figure attests. Under such conditions a distant airplane might have the general appearance of a star. The maximum distance is less for a target darker than the background because in this case the maximum contrast cannot be greater than unity.

Figure 3, of course, cannot be employed to estimate actual visibility except in the special case where there is no atmospheric attenuation. Since,

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however, atmospheric attenuation is an important determinant of visibility, the data presented in this figure must be modified to take account of atmospheric effects. Attention will now be directed to this problem.

C. Effect of the atmosphere on visibility

The atmospheric conditions which require treatment here are those which have an effect on light and consequently on the visibility of targets. A discussion of the composition of the atmosphere and the manner in which its composition influences light follows.

1. Composition of the atmosphere at various altitudes

The density of the air and the presence of impurities such as water vapor and dust particles are the major causes of atmospheric effects. The ultimate effect is a reduction of contrast.

Air density decreases in an exponential manner with increase of altitude. This knowledge is based on direct observation made by means of balloon-carried instruments for altitudes up to about 100,000 feet (39). Beyond that level the tentative tables established by NACA are useful (36). However, it must be recognized that the NACA data are subject to revision when the field results of the V-2 rocket experimental program are available (19).

The effect of impurities in the air can be estimated by considering conditions known to exist on the surface of the earth. The amount of impurity, regardless of its nature, may be characterized in terms of the magnitude of its attenuation of light. Beta, the coefficient of atmospheric attenuation, is related to contrast in the following formula (41):

$$C_x = C_0 e^{-\beta x} \quad (4)$$

$C_x$  is the contrast of a target at distance,  $x$

$C_0$  is the contrast of a target at 0 distance

$e$  is the base of the natural logarithm

$\beta$  is the coefficient of atmospheric attenuation

$x$  is the distance

The magnitude of Beta is shown by the following representative values (39, No. 13):

<u>Conditions of Atmosphere</u>	<u>Beta Coefficient Per Foot</u>
Pure air	$4.5 \times 10^{-6}$
Very clear day	$6 \times 10^{-5}$ to $4 \times 10^{-5}$
Clear day	$1 \times 10^{-4}$ to $8 \times 10^{-5}$
Light haze	$2 \times 10^{-4}$
Haze	$6 \times 10^{-4}$ to $4 \times 10^{-4}$
Thin fog	$8 \times 10^{-4}$
Light fog	$2 \times 10^{-3}$ to $1 \times 10^{-3}$
Moderate fog	$6 \times 10^{-3}$ to $2 \times 10^{-3}$
Thick fog	$1 \times 10^{-2}$ to $8 \times 10^{-3}$

It can be seen that, for a very clear day, Beta is about 10 times greater than that for pure air and about 100 times greater for a clear day than that for pure air. Beta becomes very large for haze and fog conditions.

Information about the relation between the impurities in the air and altitude is limited. Tousey (33,35) indicates that attenuation at 10,000 feet on a very clear day was 35 percent greater than for pure air. While this is admittedly only a clue, it is the only evidence available to the present authors. Therefore, the following choice of values for Beta to characterize atmospheric attenuation at various altitudes has been made in a very conservative fashion.

Essentially pure air will be assumed for altitudes above 30,000 feet, and this air may be described by Beta equal to  $5 \times 10^{-6}$  per foot (33,35). In the above tabulation it will be seen that this is a value between that of pure air and that for a very clear day on the surface of the earth and much nearer the former. The limit for a clear day,  $1 \times 10^{-4}$ , has been chosen to represent sea level, while a third value, 7.5 times greater than that for pure air, is assumed for 10,000 feet. A smooth curve drawn through these three points yields the following estimates for the variation of Beta with altitude:

<u>Altitude (Feet)</u>	<u>Beta, Per Foot</u>
30,000 - above	$5 \times 10^{-6}$
20,000 - 30,000	$8 \times 10^{-6}$
10,000 - 20,000	$1 \times 10^{-5}$
5,000 - 10,000	$5 \times 10^{-5}$
0 - 5,000	$1 \times 10^{-4}$

The above values describe the effect of atmospheric attenuation in reducing contrast, as expressed in formula (4) above. This formula relates the apparent contrast of a distant object seen against a background of horizon sky to its inherent contrast at zero distance when a horizontal line close to the earth is considered. It is possible to derive (or assume) a value of Beta which will represent a "single" layer of the atmosphere through which the line of sight passes. This value of Beta would not hold for a slanting line of sight because sky brightness would vary and there would be a change in density of the atmosphere with altitude.

When a target is seen against a background with a brightness contrast differing from that of the horizon sky, the apparent contrast along slant paths is related to its inherent contrast by the relation (41)

$$C_R = \frac{C_0}{1 + \frac{B_{H'}}{B_0} (e^{\beta \bar{R}} - 1)} \quad (5)$$

where  $B_{H'}$  is the brightness of the horizon sky in the direction of the target,  $B_0$  is the brightness of the earth, and  $\bar{R}$  is the optical slant range in feet of a line of sight which would give the same contrast reduction as along a path of length  $R$  within a standard atmosphere. The formula for the optical slant range,  $\bar{R}$ , is

$$\bar{R} = \frac{21700}{\sin \theta} \left( 1 - e^{-R \sin \theta / 21700} \right) \quad (6)$$

where  $R$  equals distance in feet from the target and  $\theta$  is the angle which the line of sight makes with the horizontal (41).

The relationship between the brightness of the horizon sky and that of the earth is expressed in the formula by the ratio  $\frac{B_{H'}}{B_0}$ . Some typical sea level values for this ratio are given below:

<u>Sky Condition</u>	<u>Ground Condition</u>	<u>Sky-Ground Ratio</u>
Overcast	Fresh snow	1
Overcast	Desert	7
Overcast	Forest	25
Clear	Fresh snow	0.2
Clear	Desert	1.4
Clear	Forest	5

In the accompanying calculations, it has been assumed that this ratio will be 1.00, though it is likely that from high altitudes this ratio will be less than 1.00 because the sky will be dark. The effect is to place the calculations on the conservative side, i.e., the estimates of the distances finally computed will be slightly lowered.

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There are two limitations in the use of the formula for  $C_R$  to compute visibility at extreme distances. The formula provides for only one Beta coefficient to describe the condition of the atmosphere. While this may be a fairly good approximation when dealing with visibility for one or even two miles, it is not an adequate approximation for lines of vision which cut through many different "layers" of the atmosphere. In using this formula, therefore, separate calculations have been made for sections of the atmosphere in each of which it is reasonable to assume a constant Beta coefficient, and these have been summated to yield the final results. As has been shown, five such atmospheric bands have been assumed (see page 28).

The other limitation comes from the assumption in the derivation of this formula that the surface of the earth is flat. For short distances this introduces negligible error, but appreciable error may be expected where large distances are involved. The magnitude of error is so appreciable for the conditions under discussion that adjustments were made to reduce its influence upon the calculations. The angle of the tangent line of sight with the horizontal was calculated for 7 different altitudes, as follows:

200,000 feet	3° 57'
100,000	2° 48'
50,000	1° 59'
30,000	1° 32'
20,000	1° 15'
10,000	0° 53'
5,000	0° 37'

and the intermediate findings were summated for the final result. This does not altogether eliminate the errors due to the continuously varying tangency with altitude; but, as indicated, the influence is largely compensated. The Appendix illustrates some of the calculations which were made

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on the basis of these modifications of the basic formulas. It may also be indicated that any possible effects due to a non-homogeneous atmosphere and non-uniform illumination are not taken into account in these calculations. Obviously, the formula has been used in an approximate manner; but it is believed that, with the corrections for altitude, the convenience of calculation outweighs the disadvantage of the method.

## 2. Attenuation of brightness contrast by the atmosphere

Graphs will be presented in this section to demonstrate the manner in which brightness contrast is reduced with the passage of light through the atmosphere in four directions of view for four selected altitudes. The directions of view are described in angles with respect to the surface of the earth:

- a. 90 degrees
- b. 60 "
- c. 30 "
- d. 0 " (tangent)

The altitudes are:

- a. 200,000 feet
- b. 100,000 "
- c. 50,000 "
- d. 30,000 "

As may be expected, the attenuation of brightness contrast, expressed as a percent of the original contrast, is increased as the slant path passes through greater distances in the lower atmosphere. In all the figures which demonstrate the effect of atmospheric attenuation (Figures 4-7), the greatest loss of brightness contrast for a given distance occurs for the vertical line of sight, i.e., the one to make an angle of  $90^\circ$  with the surface of the earth. (Calculations were not made for the horizontal path close to the surface of the earth.) The smallest loss per unit distance occurs, naturally, for the line of sight tangent to the earth's surface, for altitudes above

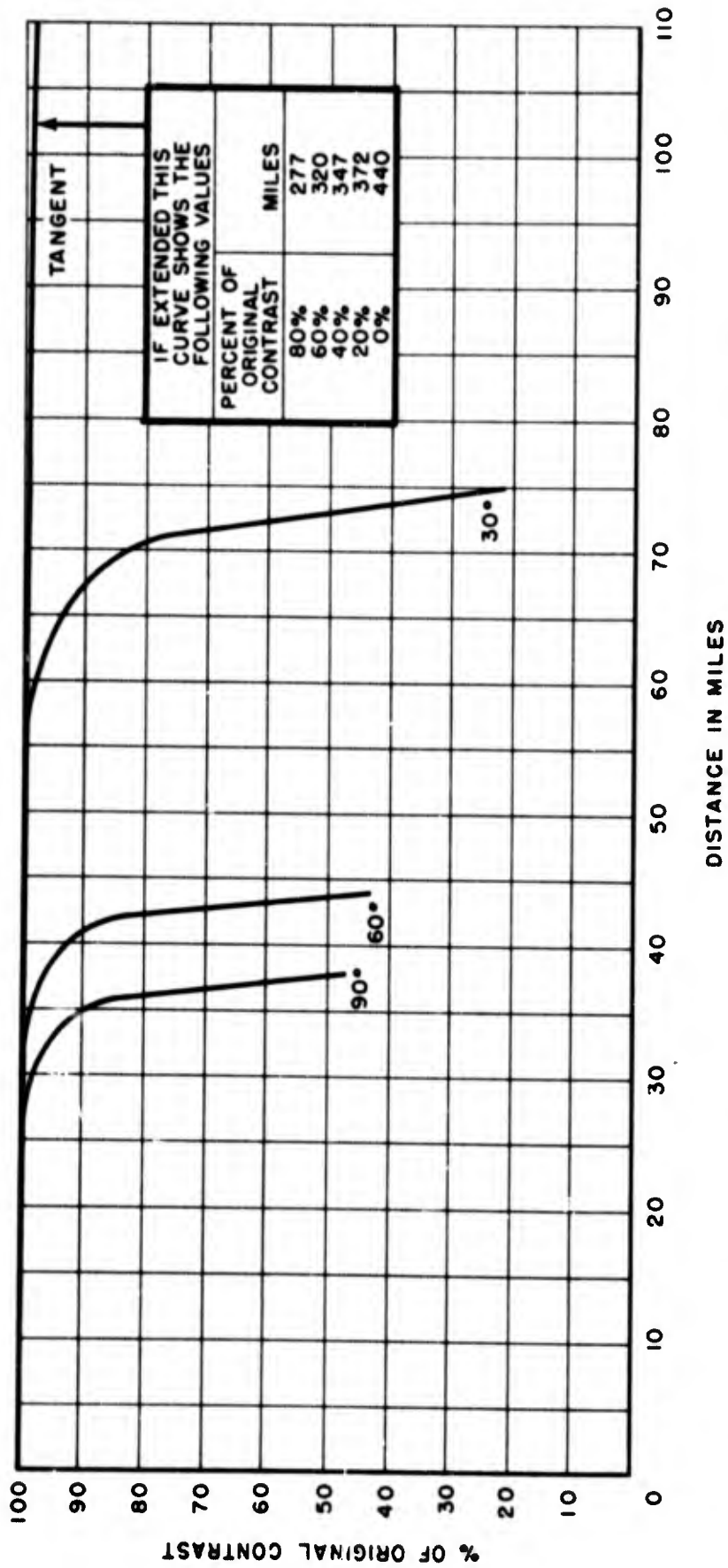


FIGURE 4: THE ATTENUATION OF CONTRAST BY THE ATMOSPHERE ALONG VARIOUS LINES OF SIGHT. THE OBSERVER IS AT 200,000 FEET ALTITUDE AND THE LINES OF SIGHT ARE GIVEN WITH THE EARTH AS A BASE.

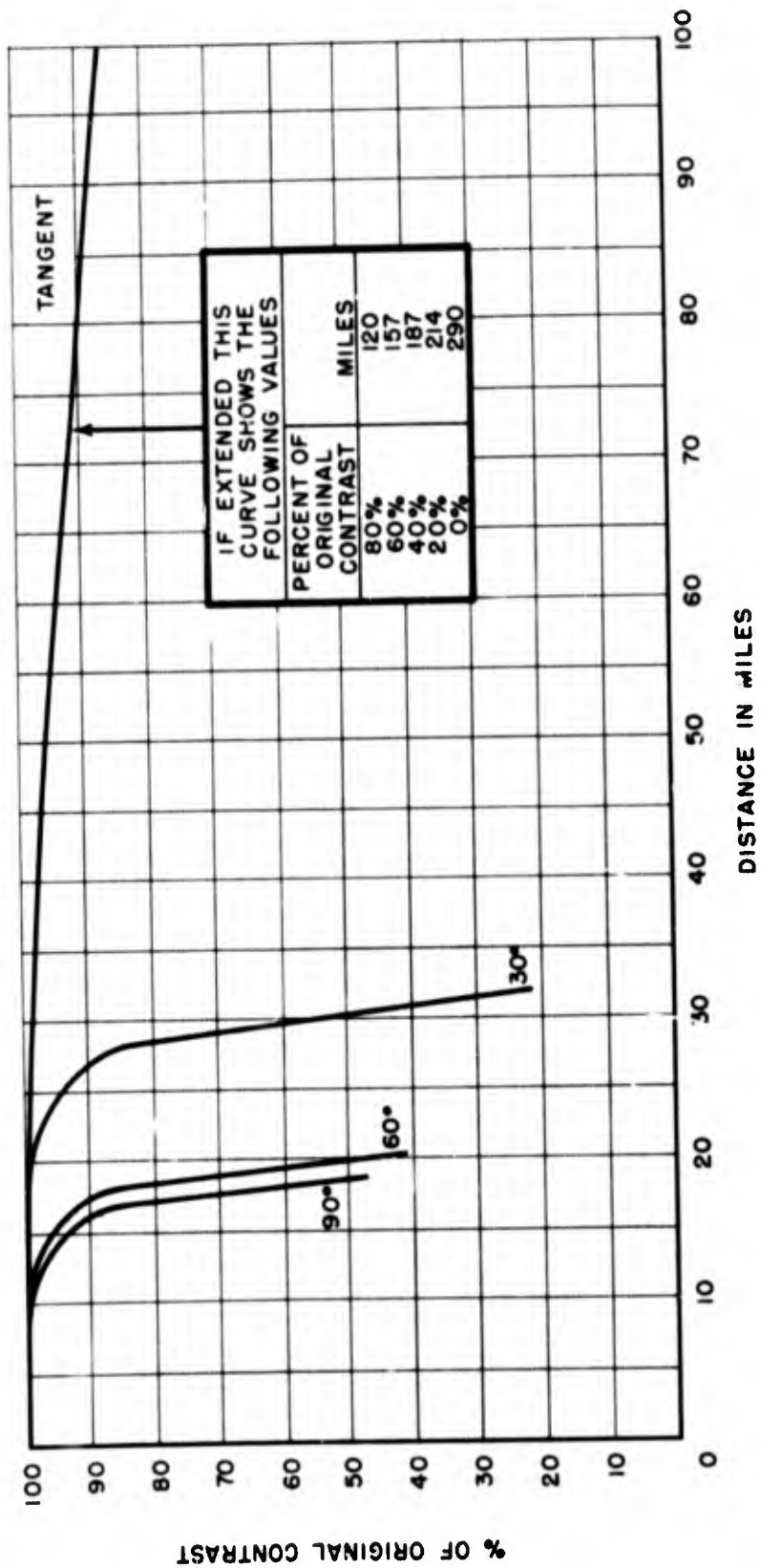


FIGURE 5: THE ATTENUATION OF CONTRAST BY THE ATMOSPHERE ALONG VARIOUS LINES OF SIGHT. THE OBSERVER IS AT 100,000 FEET ALTITUDE AND THE LINES OF SIGHT ARE GIVEN WITH THE EARTH AS A BASE.

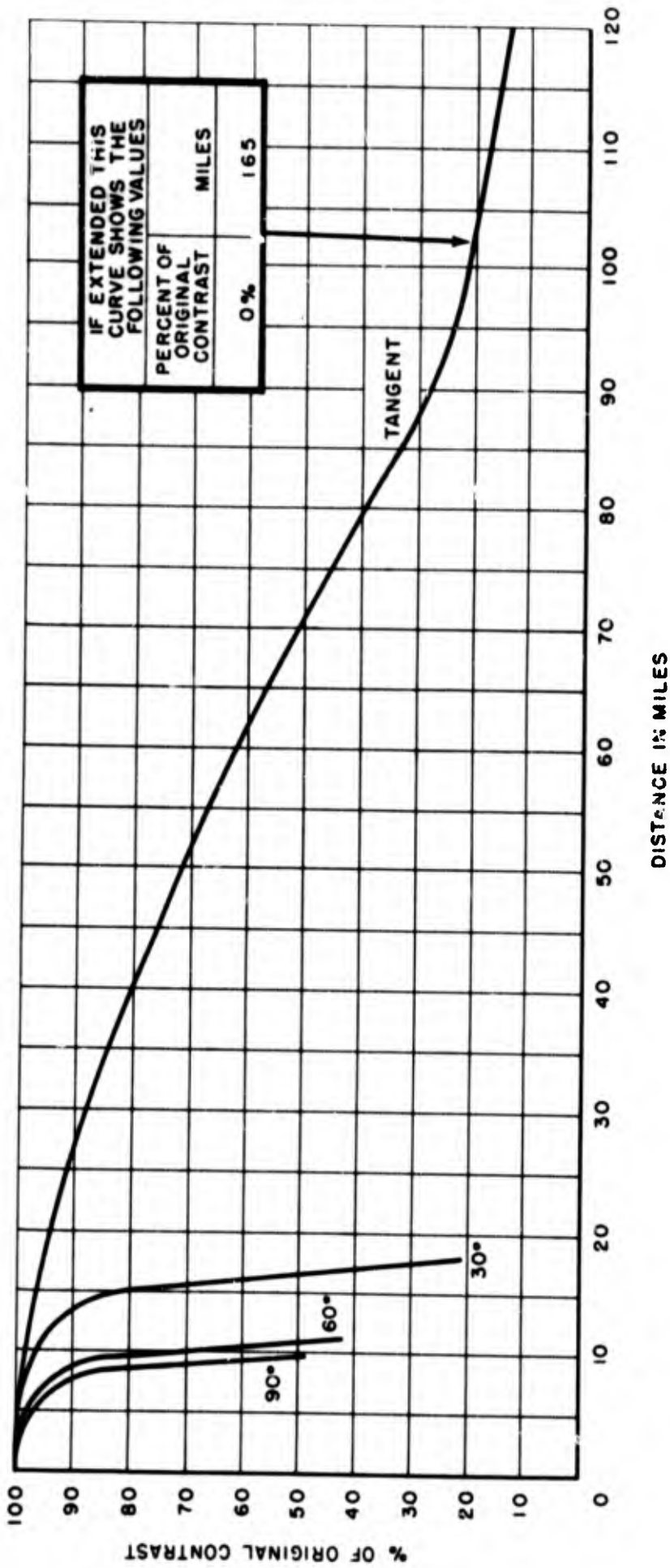


FIGURE 6: THE ATTENUATION OF CONTRAST BY THE ATMOSPHERE ALONG VARIOUS LINES OF SIGHT. THE OBSERVER IS AT 50,000 FEET ALTITUDE AND THE LINES OF SIGHT ARE GIVEN WITH THE EARTH AS A BASE.

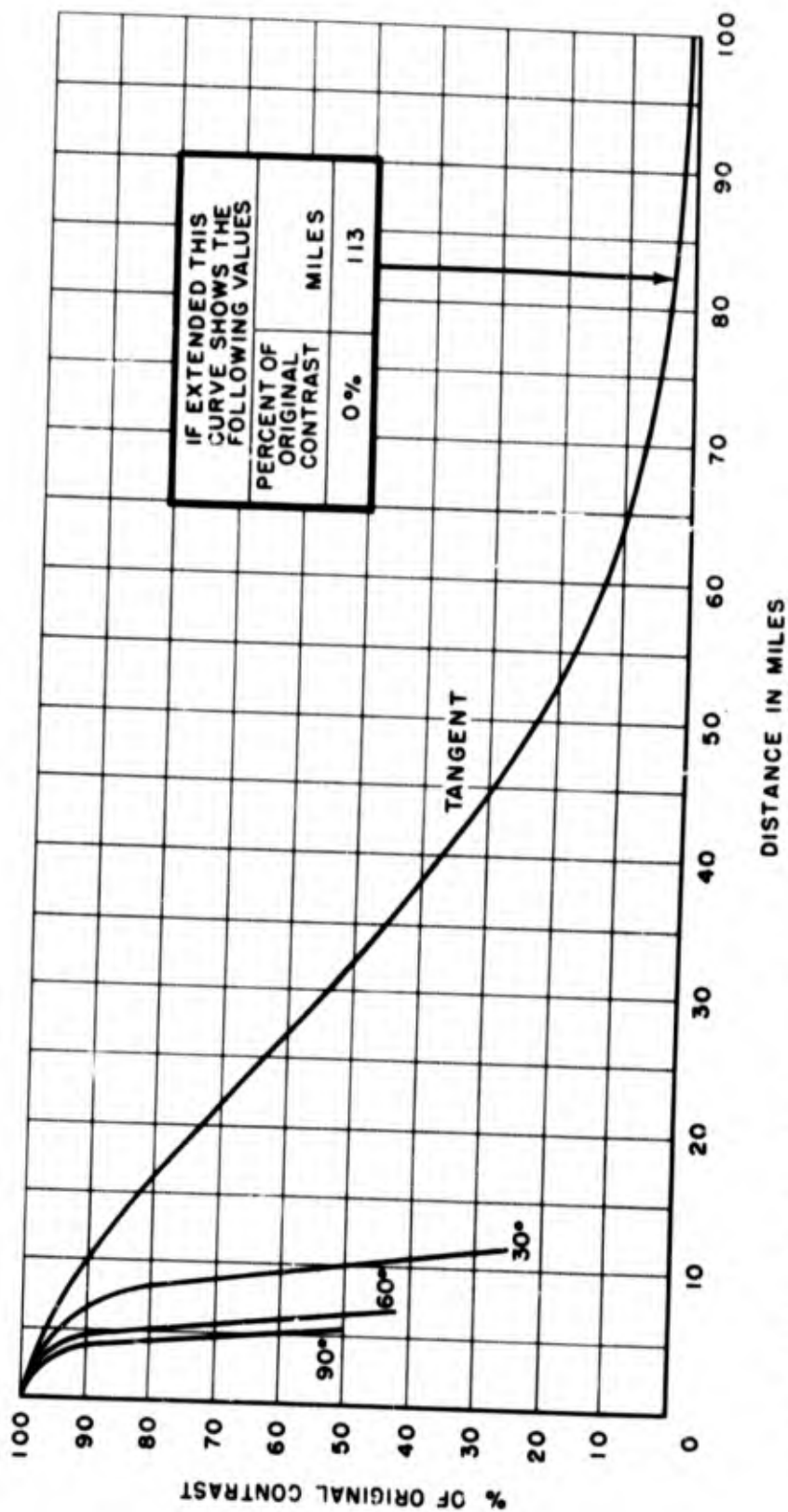


FIGURE 7: THE ATTENUATION OF CONTRAST BY THE ATMOSPHERE ALONG VARIOUS LINES OF SIGHT. THE OBSERVER IS AT 30,000 FEET ALTITUDE AND THE LINES OF SIGHT ARE GIVEN WITH THE EARTH AS A BASE.

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50,000 feet.

D. Sunlight and sky brightness

Sunlight illumination increases and sky brightness decreases with increase of altitude. Representative values which may be applied to the calculation of visibility will now be considered.

Maximum solar illumination is of the order of 12,000 footcandles, according to measurements reported by Teele on the flight of the Explorer II balloon (32). This value agrees with data reported by Christensen on two flights to 40,000 feet in a B-17 (9). Jones and Condit (21), who use data reported by Moon and Kimball, show a value of about 11,500 footcandles (123,400 lumens/sq meter) as the direct solar illumination just outside the earth's atmosphere. Tousey and Hulbert (34) use Kimball's data to calculate a value of 13,600 footcandles for maximum solar illumination, i.e., the illumination outside of the atmosphere. The latter authors also calculate values of 11,300 footcandles based on Abbott's data and 12,300 footcandles based on Teele's data for maximum solar illumination. They consider the value of 11,300 to be based on insufficient data and that of 12,300 to be low. On the basis of their own data (collected on 11 airplane flights to 10,000 feet and one to 20,000 feet), Tousey and Hulbert conclude that 13,600 footcandles is a good approximation for solar illumination outside the atmosphere.

Since solar illumination may vary, a conservative value of 12,000 footcandles is used in the present calculations to represent the maximum solar illumination. The scattered light, which at sea level approximates 20 percent of the value of direct sunlight, decreases with altitude, and has been disregarded as a factor at high altitude.

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The brightness of the sky is one of the determinants of the brightness contrast of an object seen against it. Sky brightness also determines the adaptation brightness or sensitivity level of the observer's eyes. The sky appears bright to an observer on the earth because sunlight is scattered and absorbed by water vapor and dust particles in the air. Since the atmosphere becomes freer of particles as altitude increases, it is to be expected that scattering decreases and that the sky will appear darker than it does at the surface. This is borne out by all the evidence that is presently available.

Of course, the sky does not have a uniform brightness. The brightest portions of the sky occur at the horizon and in the area immediately surrounding the sun, while the darkest portions lie in a region 90 to 180 degrees azimuth from the sun. The sky always has a variegated brightness pattern which alters during the course of the day and with the change of the seasons. The average brightness of the clear north sky, measured at sea level, varies from about 700 to 2000 footlamberts according to time of day and season of the year (20). Jones and Condit (21) give 400 to 1400 footlamberts as minimum and maximum average brightness values in a perfectly clear sky; the sun's brightness is about 500,000,000 footlamberts under these conditions. The brightness of the sky increases when the sky is clear (range 650 to 6000 footlamberts) and when there is haze (1800 to 100,000 footlamberts), but decreases from these levels when there are light clouds (1000 to 4000 footlamberts) or heavy clouds (400 to 1200 footlamberts); the brightness of the sun for the observer on the earth decreases with the increase of haze and clouds.

All observers agree that the sky becomes progressively darker as altitude increases. The following description of the sky at various altitudes

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is based upon the report of the two Explorer balloon flights (40):

<u>Altitude (Feet)</u>	<u>Appearance of the Sky</u>
14,500	hazy
15,000	hazy
16,000	horizon hazy
40,000	sky dark blue
57,000	sky very dark blue
60,000	sky blue-black
73,000	up: pitch black
	50° above horizon: very dark, almost black
	30° above horizon: ordinary sky blue
	20° above horizon: light blue
	horizon: band of white haze

---

A report that the sky appeared "purple" and that "the stars came out" has been made by the pilot who flew the X-1 airplane to some unannounced high altitude (37). Data on the variation of sky brightness with altitude were collected on the second Explorer flight and these have been reported by Teele (32). The sky brightness was measured by a group of light sensitive cells mounted about 38 degrees above the equator of the gondola. These swept the sky as the gondola rotated, thus including a portion of the sky near the sun. Two minimum brightness values occur on each sweep at the two points 90 degrees azimuth from the sun. These minima are used as reference values. There is a direct proportional relationship between sky brightness in percent and altitude in barometric pressure. Teele presents a graph which shows a straight line between 100 percent sky brightness at 760 mm Hg (sea level) and 5 percent sky brightness at 30 mm Hg (72,000 ft). Miley and McClellan (27) confirm this report with their finding, based upon measurements made with rocket-borne equipment, that sky brightness at 82,000 feet is 3 to 7 percent of that measured near the ground for the respective directions chosen. Neither Teele nor Miley and McClellan give absolute brightness values with which to evaluate their percent brightness

figures. This type of report is made, no doubt, because of the somewhat haphazard rotation during the ascent of the gondola and the rocket. In any case, the high altitude values are a percent of the sky brightness values at low altitude on the day of the flight.

Some measurements of sky brightness have been made on airplane flights, in one case to an altitude of 40,000 feet. Thus, Christensen (9) shows that the brightness of the sky, 30 degrees above the horizon, decreases with altitude from about 1250 footlamberts at 10,000 feet to about 500 footlamberts at 40,000 feet. At 60 degrees above the horizon, brightness decreases from 600 to 200 footlamberts for the same increase in altitude. The horizon was brightest in the presence of clouds and its brightness increased with altitude. The horizon brightness was 2600 footlamberts at 10,000 feet and 3000 footlamberts at 40,000 feet.

These values, together with some from other sources, have been plotted in Figure 8. Attention may be directed to the brightness of the sky as observed from the surface of the earth. Values are given for the brightness range of the horizon, a point 45 degrees above the horizon and the zenith. These do not represent the extreme brightness values which may occur. Rather, they are the average brightness of 31 selected points in the clear sky measured repeatedly over long periods of time. Due to variation in solar altitude and in azimuth distance from the sun, a point on the horizon may range in average brightness from 72 to 7000 footlamberts; a point 45 degrees above the horizon may range from 43 to 3290 footlamberts; while the zenith of the sky may range from 32 to 1790 footlamberts. When any of these values (except for a thin line at the horizon itself) are taken as a reference equal to 100 percent, their brightness decreases toward zero percent regularly with altitude in the manner which has already been described. The other values on the graph represent absolute values of sky brightness

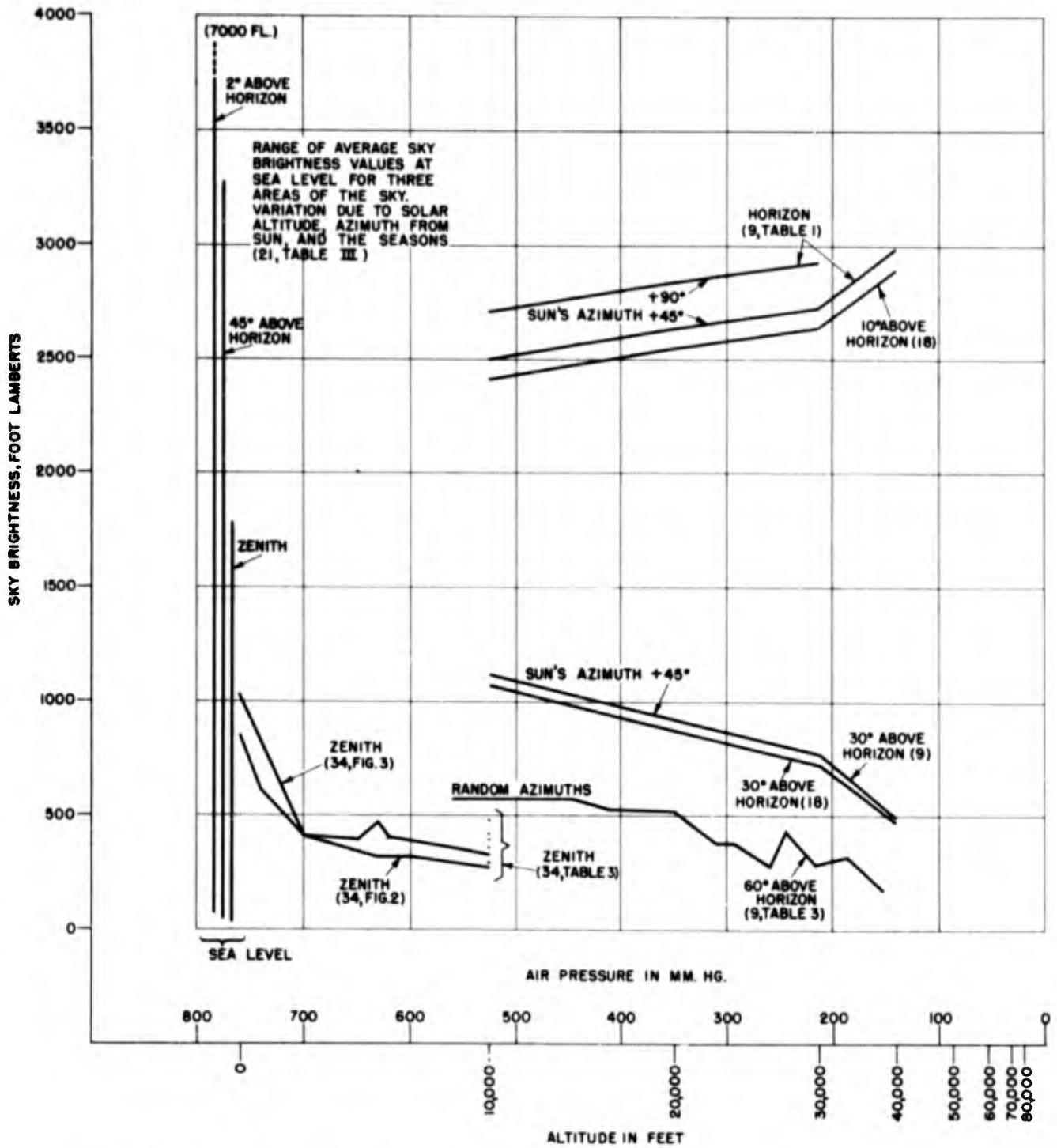


FIGURE 8: RELATION BETWEEN SKY BRIGHTNESS AND ALTITUDE, FOR SEVERAL POSITIONS IN THE SKY. THE NUMBERS IN PARENTHESES IDENTIFY THE STUDIES AS LISTED IN THE REFERENCES AT THE END OF THIS PAPER.

as observed in certain portions of the sky at various altitudes on the day of the flight. Their significance should be seen as showing the tendency of sky brightness, except for that of the horizon, to decrease with altitude. The absolute values, however, cannot be taken to represent some constant value for sky brightness at that point.

Since this paper is concerned with very high altitudes, a range of values must be selected to represent the probable sky brightness that will be encountered there. Shifting for a moment to a logarithmic brightness scale, in which form most visual acuity data are presented, the assumption is made that sky brightness varies from log 0 to log 1.5 footlamberts (1 to 31.6 footlamberts). While this range may be exceeded in some instances (the zenith sky at very high altitudes may be less than 1 footlambert while the horizon at low altitudes is brighter than 32 footlamberts), it is a fair estimate for the various conditions at the entire range of altitudes considered in this paper. One reason for preferring calculations based on a narrow range of sky brightness is that they provide a more precise range of visibility for a given level of target contrast than would be the case if a wider range of sky brightness is admitted. Reference to Figure 1 will show that threshold values do not change much at adaptation brightnesses above log 2 footlamberts, i.e., 100 footlamberts. Therefore, log 1.5 footlamberts was chosen as a reasonable estimate of high brightness background conditions. This does not forfeit much accuracy if the actual background is brighter because the contrast threshold is relatively constant at these and higher adaptation brightnesses. The value of log 0 footlambert as the lower level of background brightness for daylight appears reasonable for all conditions except possibly for that part of the sky which is directly overhead.

### III. Estimates of Visibility

The preceding discussion may be summarized by applying the several findings to the calculation of the visibility of a specific target. To do so, it will first be necessary to establish reasonable values for the size and contrast ratios of some target that might be encountered.

The dimensions of two advanced type aircraft as they would appear from various approaches are presented below (1):

	<u>Bell XS-1</u>	<u>Douglas XD-558</u>
Length	31 ft	35 ft
Wing span	28 ft	25 ft
Wing area	130 sq ft	150 sq ft
Thickness of fuselage	4.5-5.5 ft approx.	4 ft
Estimated side view area	100 sq ft	160 sq ft
Estimated top view area	130 sq ft	280 sq ft
Estimated head on view area	65 sq ft	65 sq ft

The portion of the target which will appear visible to an observer will depend upon the angle at which the sun's rays strike it. A circular object with a diameter of 10 feet (area of 78.5 square feet) has been chosen to represent the target in these computations. If the actual target area which is illuminated is larger than the area of this circle, visibility would be better than the calculations predict.

Maximum illumination, as shown above, may be taken as 12,000 footcandles.

The reflectivity of an airplane surface would probably not be greater than 80 or less than 3 percent. The larger value is about equal to that of white matte paper and greater than that of a polished aluminum surface, which has a reported reflectivity of 60-70 percent, whereas the reflectivity of dull black paint is given as 3-5 percent. The brightness range, then, of such objects under 12,000 footcandles illumination may extend from 360 to 9600 footlamberts. Consider, for a moment, that the background brightness might range from 1 to 100 footlamberts. Under these conditions, contrast for the dark target (360 footlamberts) ranges from 359 to 2.6, and for the bright target (9600 footlamberts), from 9599 to 95.

The contrast of a very bright target against a very dark background yields a large contrast ratio, but this extreme combination may not actually occur. The very dark background presupposes that the target is well over the head of the observer, while the maximum target brightness (with solar illumination) requires that the target be at a level with or below the observer. The calculations which follow are based on what appears to be a reasonable compromise in which the contrast ratios have been assumed to range between 1 and 100.

The final results of the calculations, which incorporate the several facts and assumptions previously discussed, are shown in Figures 9, 10, 11, and 12. Viewing positions at altitudes of 200,000, 100,000, 50,000, and 0 feet have been selected for presentation. The figures have been drawn to a scale of 0.29 cm to the mile for both axes so that distance may be read in any direction with the aid of a ruler.

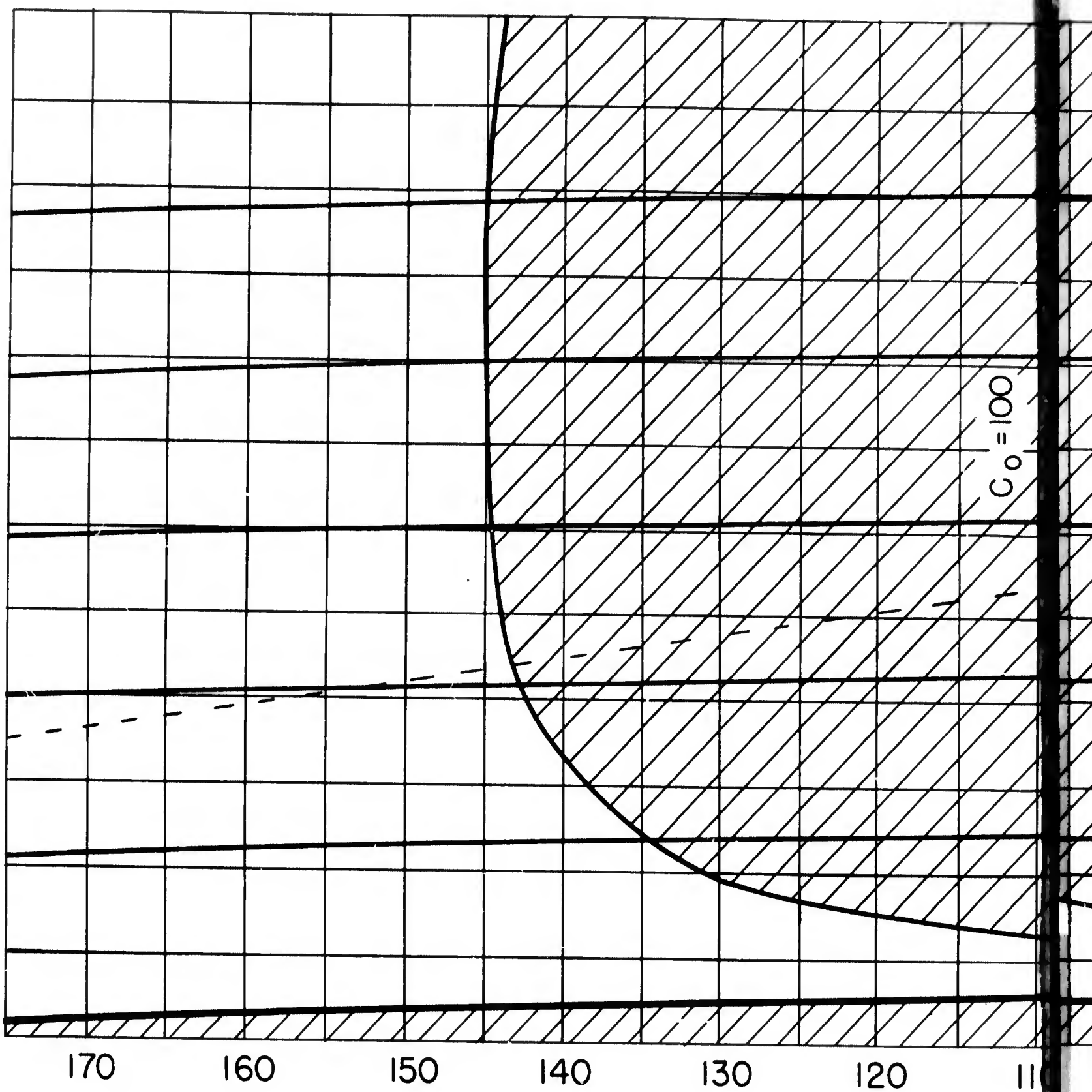
The curved line at the bottom of the figures represents the curvature of the earth's surface. It has been assumed that the earth is a perfect sphere whose radius is 3958.89 miles. Visibility, as previously noted, is

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Figures 9, 10, 11, and 12, which follow, show visibility in all directions when the observer is at one of the indicated altitudes. The target is a circular object with a diameter of 10 feet and visibility is shown when target contrast is 1, 5, 10, and 100. Certain lines of sight, which are indicated by dotted lines, are shown; these are lines from the observer (a)  $0^\circ$  (tangent), (b)  $30^\circ$ , and (c)  $60^\circ$  to the earth's surface. The adaptation brightness is given in logarithmic units:  $\log 1.5$  equals 31.6 foot-lamberts and  $\log 0.0$  equals 1 footlambert. Each unit on the horizontal and vertical scales equals 5 miles or 26,400 feet (cm x 3.4 equals miles).

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———— LOG ADAPTATION  
BRIGHTNESS = 1.5

----- LOG ADAPTATION  
BRIGHTNESS = 0.0

FIGURE 9. VISIBILITY RE

A

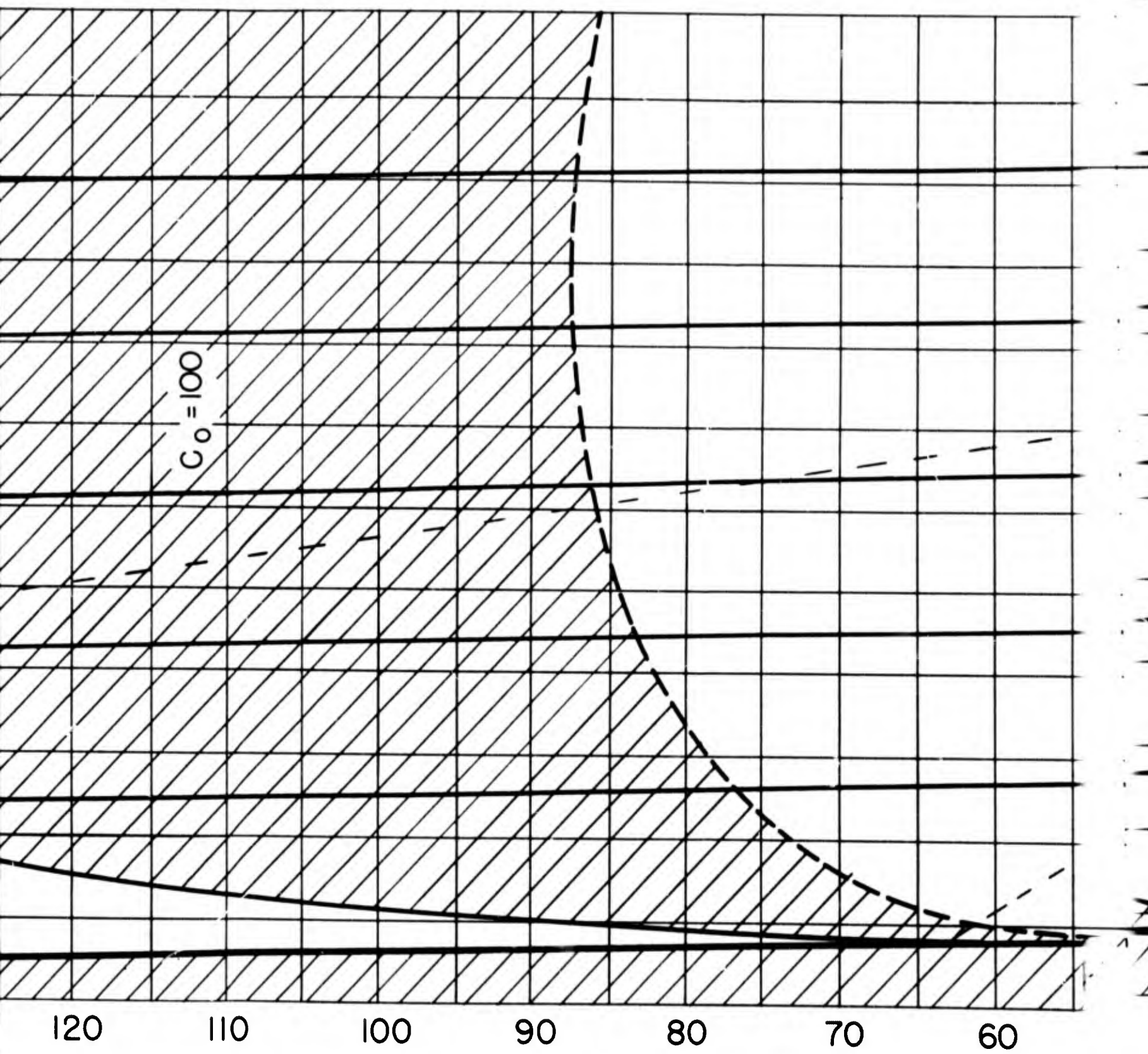
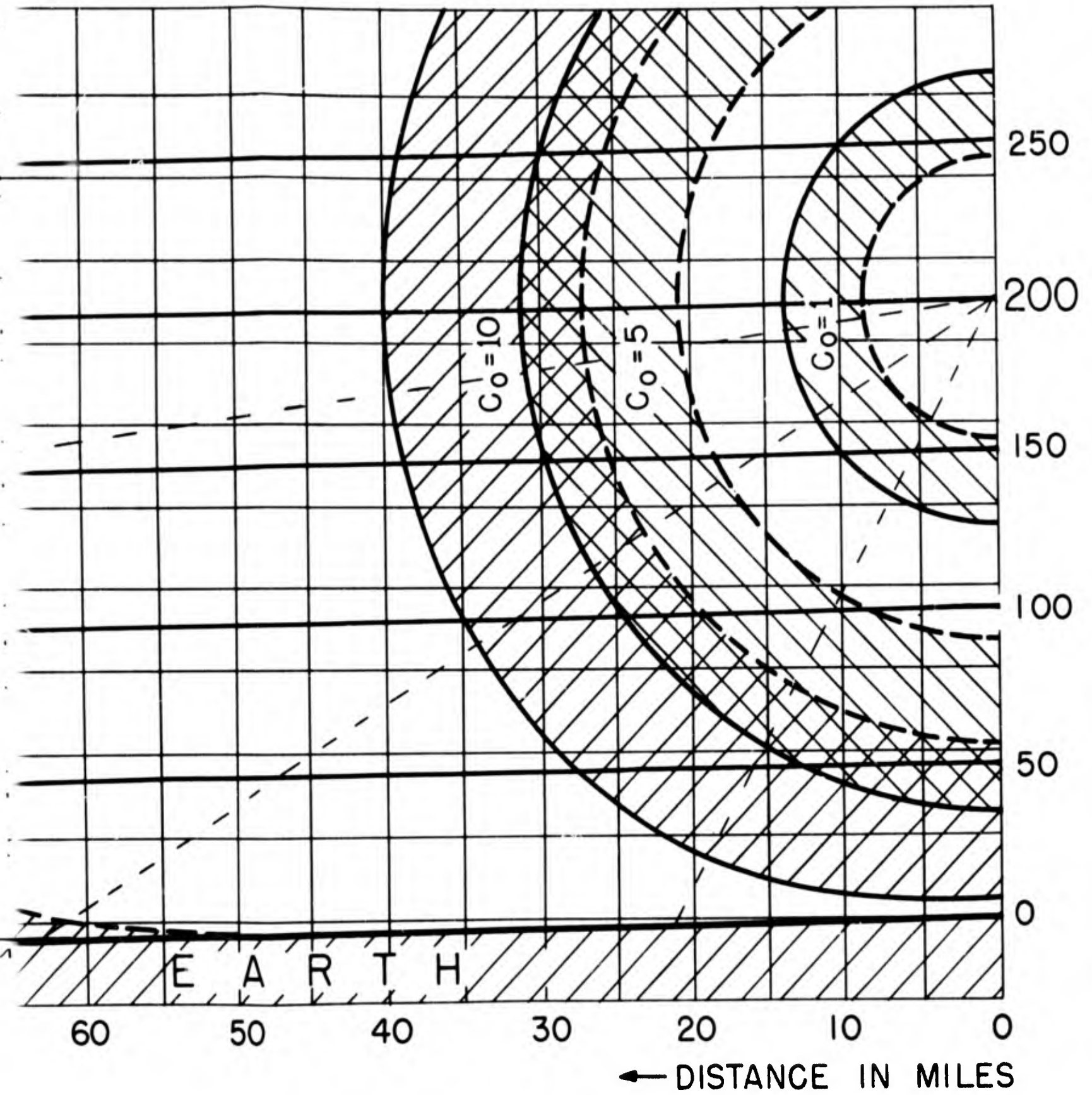


FIGURE 9, VISIBILITY IN ALL DIRECTIONS FROM 200,000 FEET

B

ALTITUDE IN  
THOUSANDS  
OF FEET

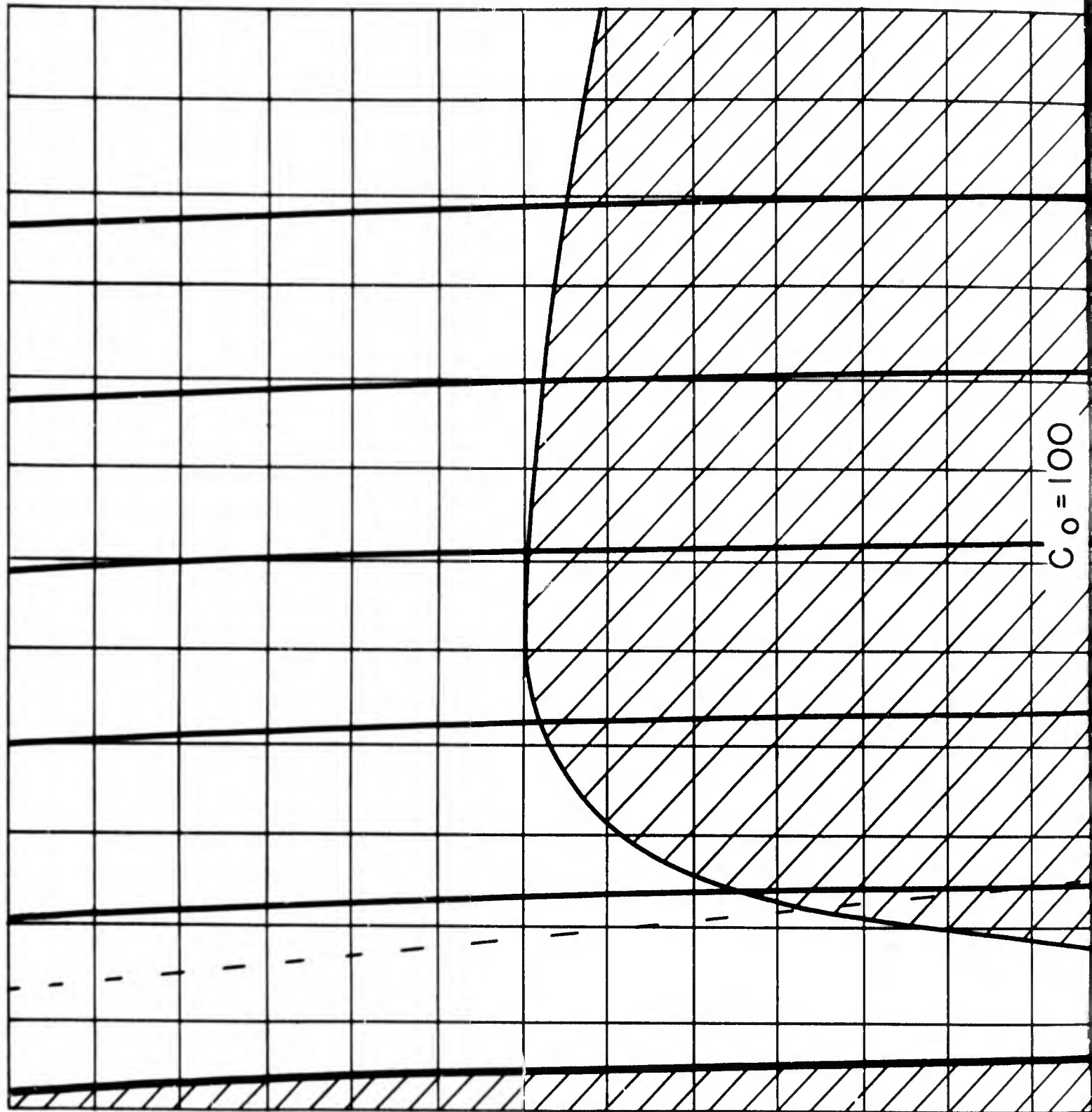


000 FEET

C

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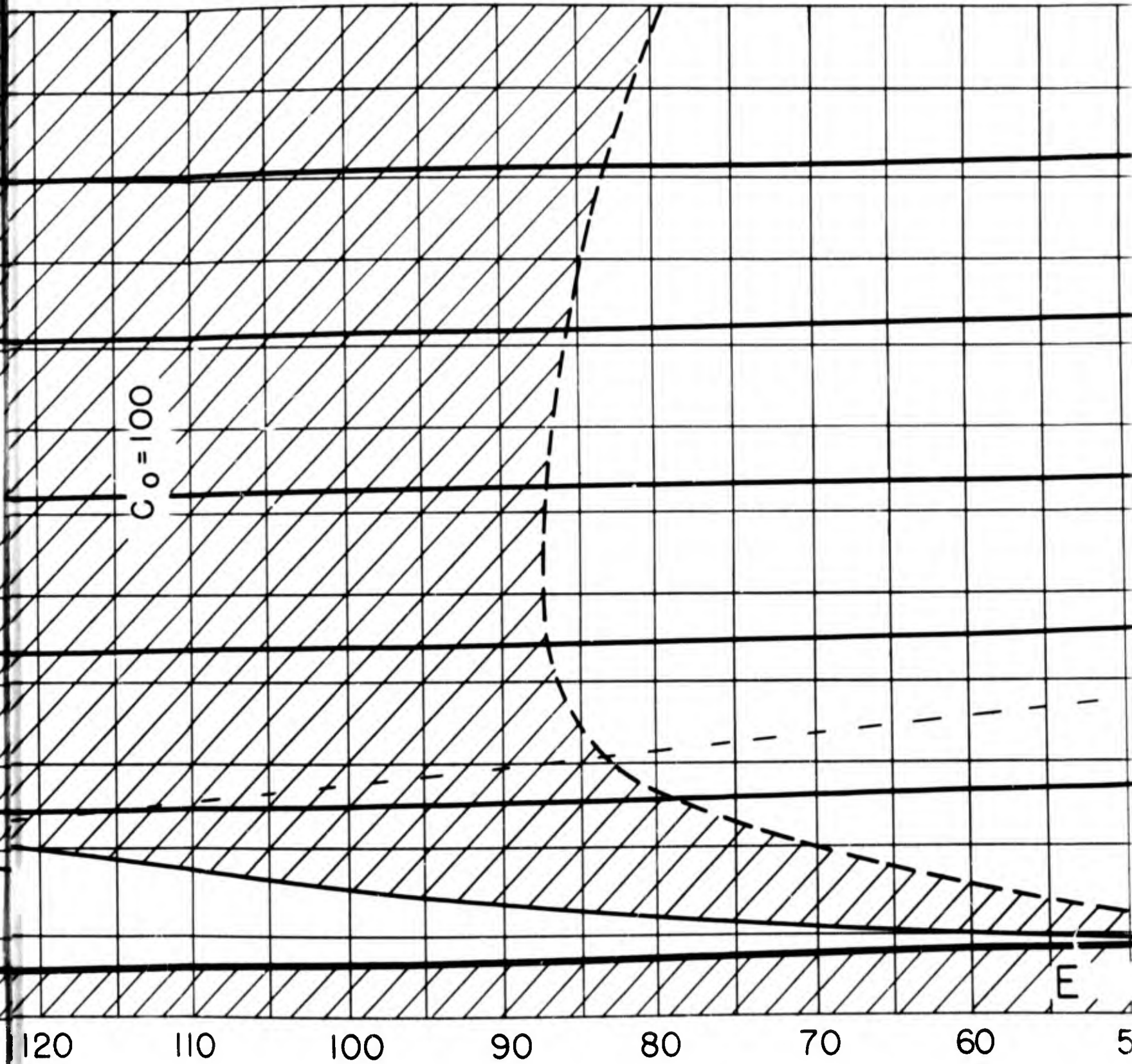
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- LOG ADAPTATION  
BRIGHTNESS = 1.5
- - - LOG ADAPTATION  
BRIGHTNESS = 0.0

FIGURE 10. VISI

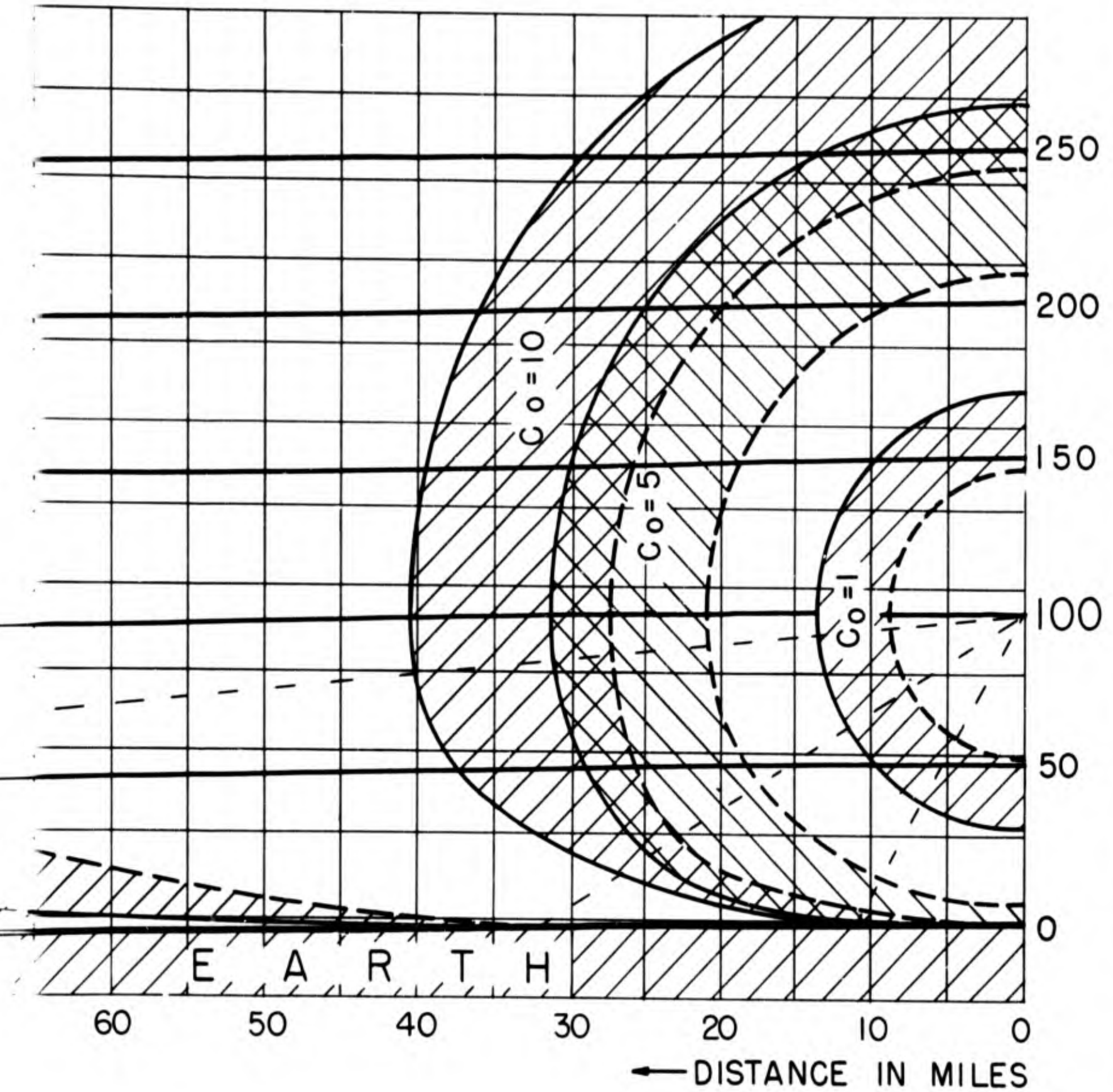
A



10. VISIBILITY IN ALL DIRECTIONS FROM 100,000 FEET

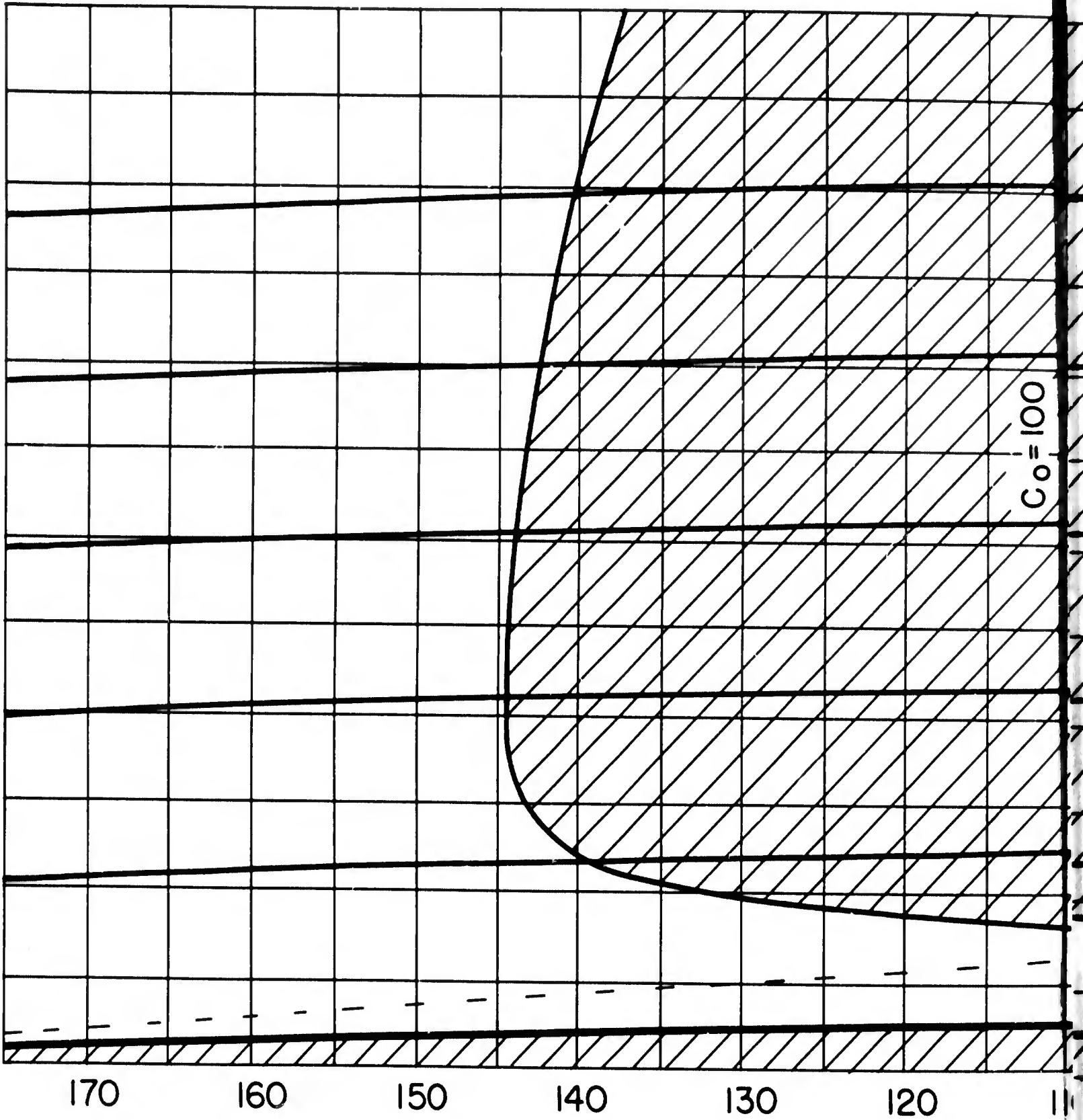
B

ALTITUDE IN  
THOUSANDS  
OF FEET



,000 FEET

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——— LOG ADAPTATION  
 BRIGHTNESS = 1.5  
 - - - LOG ADAPTATION  
 BRIGHTNESS = 0.0

FIGURE 11. VISIBILITY

A

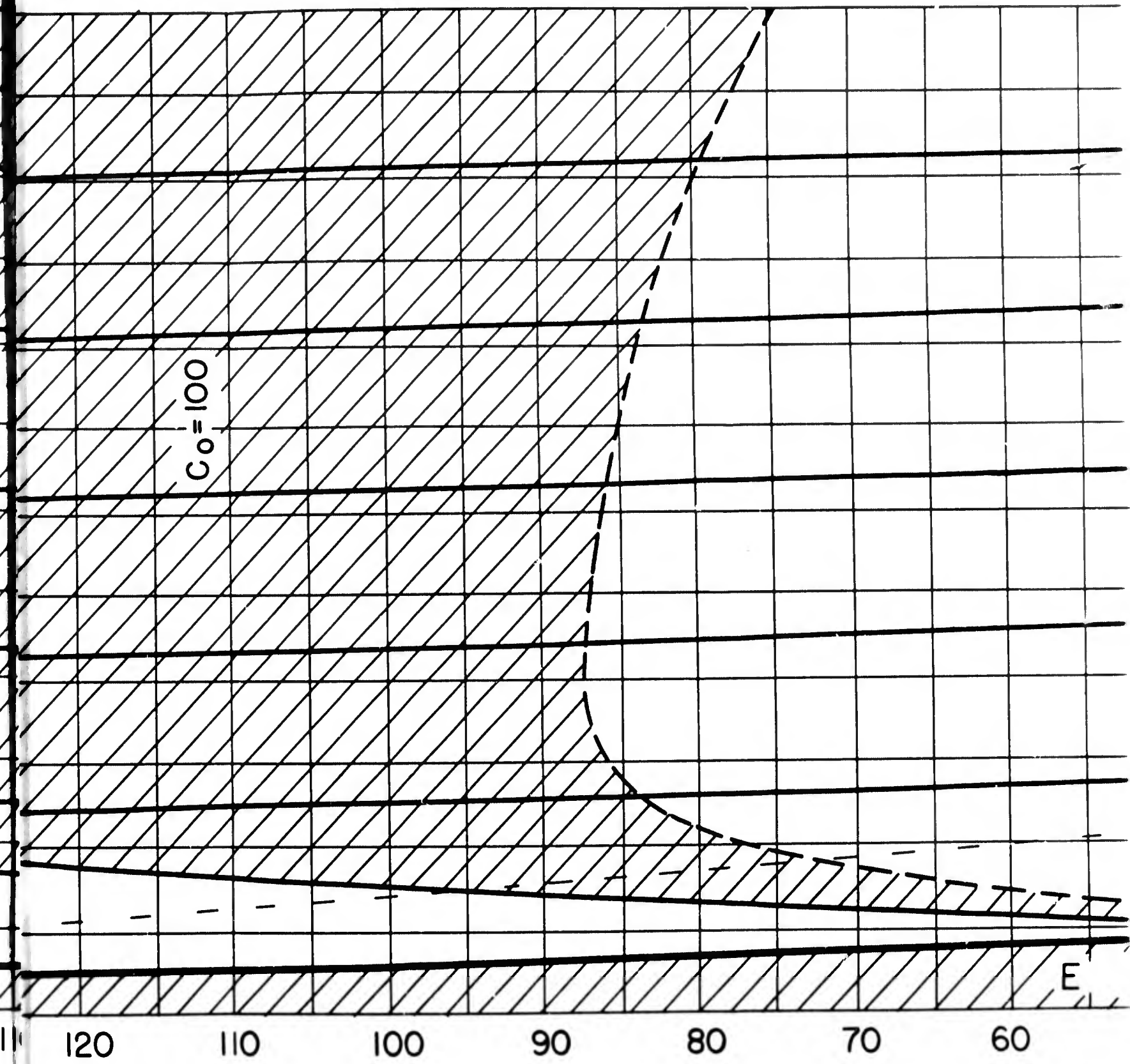
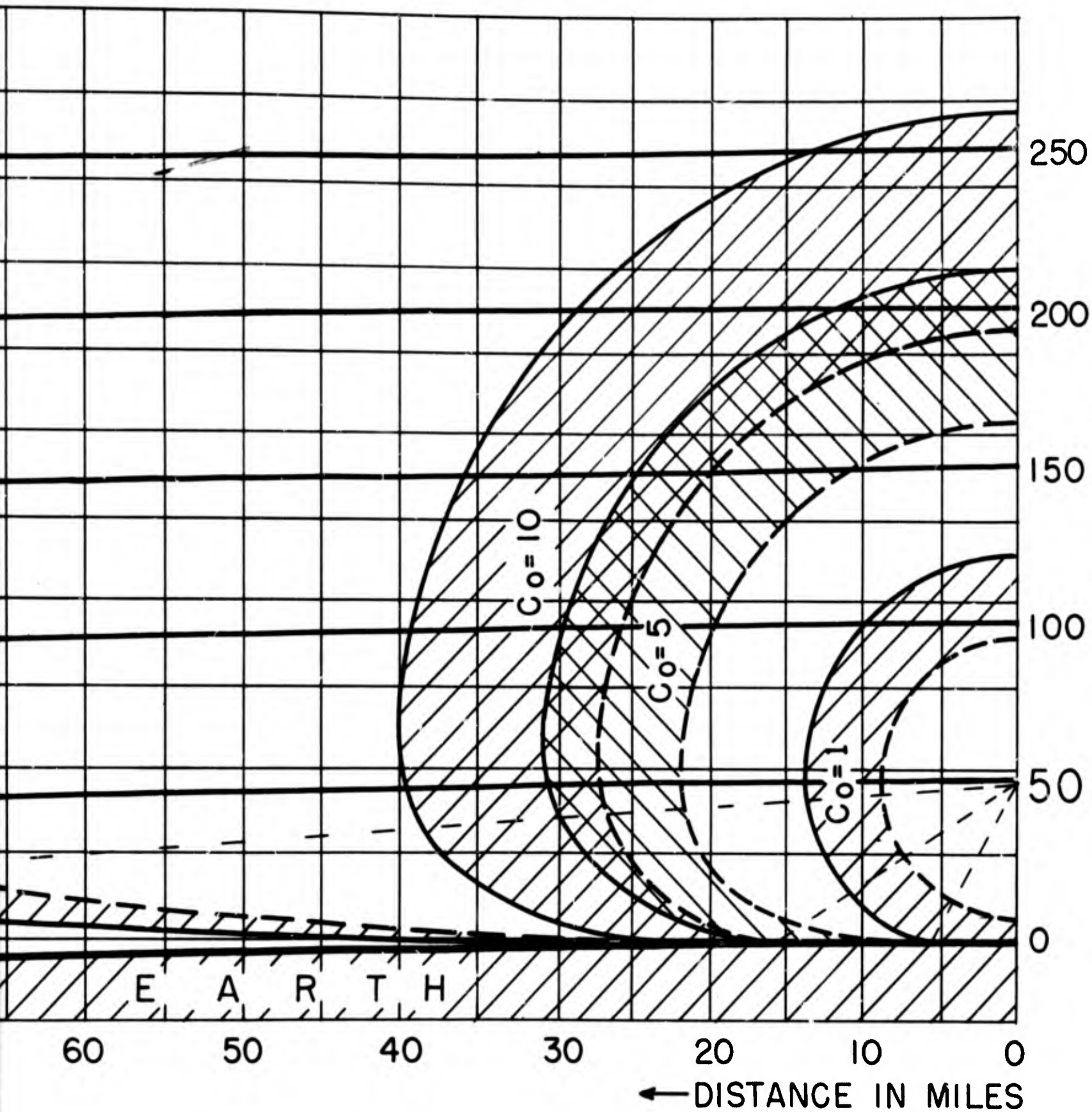


FIGURE 11. VISIBILITY IN ALL DIRECTIONS FROM 50,000 FEET

B

ALTITUDE IN  
THOUSANDS  
OF FEET



,000 FEET

C

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ALTITUDE IN  
THOUSANDS  
OF FEET

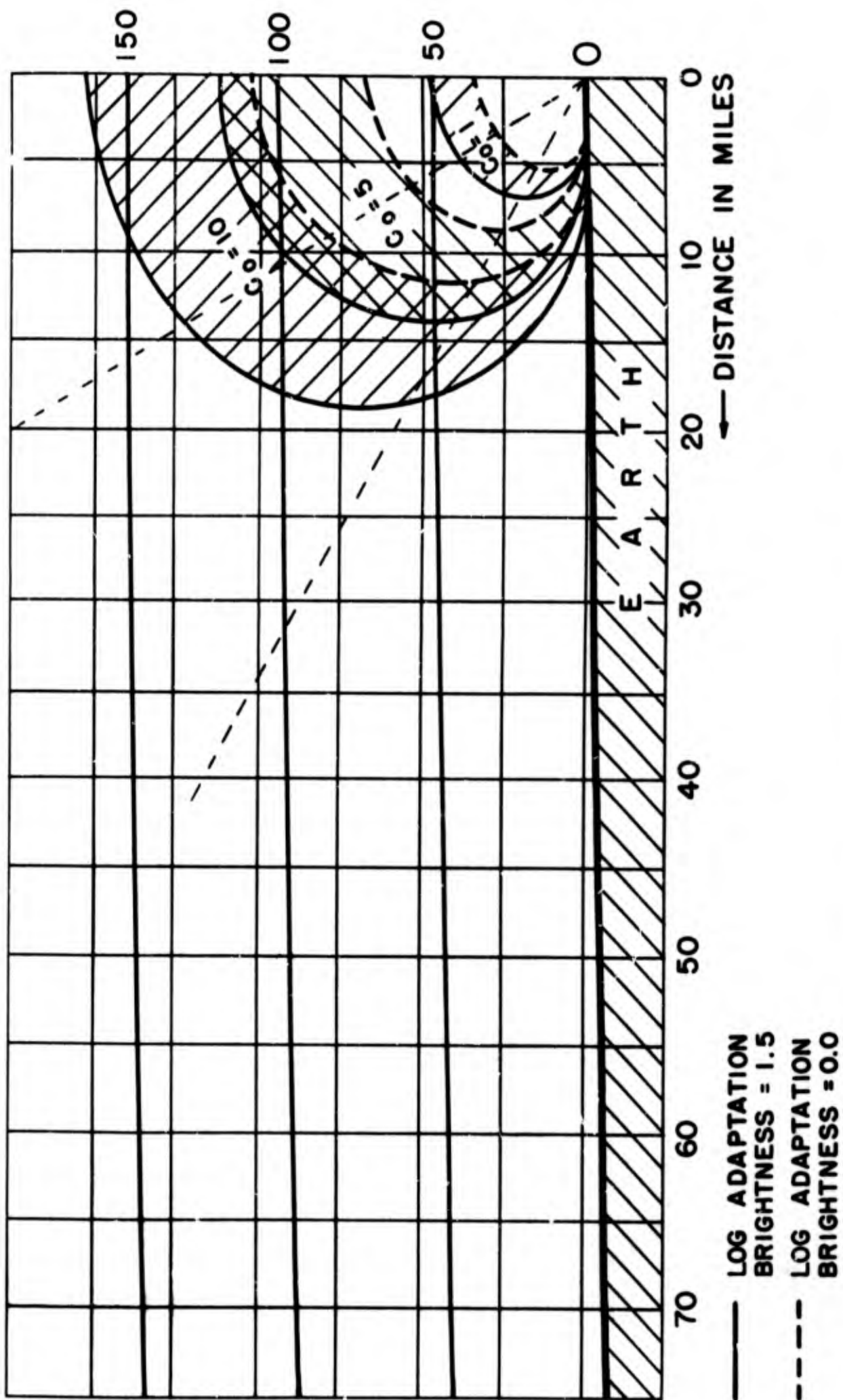


FIGURE 12. VISIBILITY IN ALL DIRECTIONS FROM THE EARTH

estimated for a circular target with a diameter of 10 feet. Separate computations have been made when this target exhibits inherent contrast values of 1, 5, 10, and 100. Visibility is shown for each of these contrast values when the adaptation brightness is log 1.5 and log 0 footlamberts.

The figures have been drawn in this form even though the contrast ratio of the target against its background will not be constant for all directions of the compass. The brightness of the background actually varies and so will the brightness of the target because the angle of incidence of the sun's rays on the target will change. Thus, the visibility threshold for any given flight path may cut across several of the brightness contrast curves shown in Figures 9, 10, 11, and 12.

Comparison of these figures shows that visibility improves as altitude increases. An increase occurs because the effect of atmospheric attenuation for a given distance along a particular line of sight is less when the observer is at a higher altitude. There are, however, two factors which are not incorporated in these graphs and which may improve visibility at high altitudes even more than the graphs suggest. These are the changes in contrast ratio as the altitude increases and as the target appears closer to an overhead position in the dome of the sky. The sky is known to become darker with an increase in altitude and thus, generally, the contrast ratios must become greater. The exact effect of these factors cannot be determined until there is more complete knowledge of illumination conditions at high altitudes.

The illumination conditions for an observer at high altitudes are very different from those at sea level. At sea level the adaptation brightness, which is determined by the brightness of the sky, is generally above 1000 footlamberts. Since the source of light is from above, a target seen against

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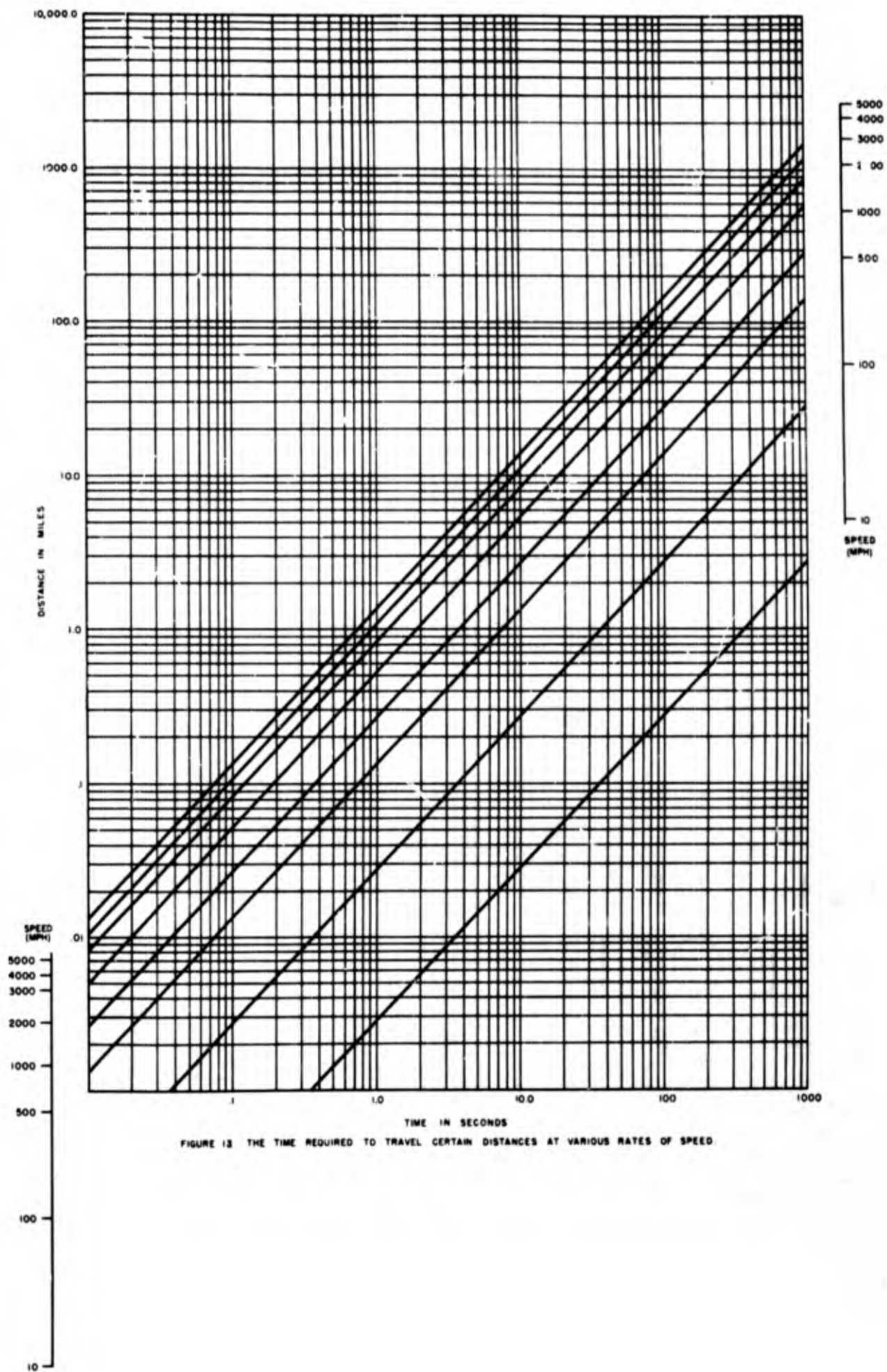
the sky will be darker than its background. Such contrast ratios will consequently be less than 1, and contrast ratios as high as 15 will rarely be found. Since a contrast ratio of 100 is virtually impossible for an observer on the ground, a curve for this ratio is not included. Visibility from sea level generally falls inside the curve for contrast ratios equal to 1.

Another important difference between the visibility conditions for observers at low altitudes and those at high altitudes should be noted. For an observer on the ground, the line of sight that encounters the least total atmospheric attenuation is one that makes a 90 degree angle with the surface of the earth. However, for an observer at a high altitude, say, 100,000 feet, the downward line of sight encounters the greatest amount of atmospheric attenuation per unit distance. Thus the most advantageous direction in which to look, i.e., the maximum distance at which a target may be seen, is related to the altitude of the observer.

The following examples will illustrate information which Figures 9-12 provide. Distances may be obtained directly from a ruler placed on the graphs, with each centimeter representing 3.4 miles. When the contrast ratio equals 1 and the sky brightness is log 1.5 footlamberts, the target (10 feet diameter) is visible at a distance of 3.7 miles when an observer looks along a horizontal line and 9.5 miles when he looks along a vertical line from the surface of the earth. The limit of visibility is greater at higher altitudes, varying within the limits of 11.6 to 13.6 miles according to altitude and direction of view. When the contrast ratio is 10, visibility ranges from 7.1 to 30.3 miles from the surface of the earth and 21.4 to 39.4 miles at the higher altitudes. It is obvious that two major factors, altitude and contrast, determine these distances: visibility is greater

at higher altitudes because less atmospheric attenuation occurs, and visibility is greater with higher degrees of contrast because visual sensitivity increases with greater contrast. For example, the target is visible in the horizontal direction at 200,000 feet at ranges of 13.6, 30.9, 39.8, and 141.4 miles when the contrast ratios are 1, 5, 10, and 100 respectively.

Although these distances are large as compared to those which are found at the surface of the earth, the significance of such distances is related to the speed at which the pilot may be travelling. How much time is available after detection occurs at the extreme range of visibility? A direct answer to this question depends upon the relative course and speed of the plane and the target, the instant at which the target is sighted, and the time taken to initiate appropriate action. Figure 13 is offered to facilitate the conversion of distance into time available for action at several speeds. Suppose, for example, an observer at 50,000 feet sights another target at extreme range and at the same altitude. A contrast ratio of 10 and sky brightness of log 1.5 footlamberts is assumed. Figure 12 shows that the limit of visibility for these conditions is about 38.8 miles. Suppose, further, that the target is a missile travelling directly toward the observer at 1000 miles per hour and that the observer's plane is moving toward the target at 1000 miles per hour. The rate of closing is, then, 2000 miles per hour. Reference to Figure 13 shows that about 71 seconds are required to cover 39 miles at a rate of 2000 miles per hour. This is the longest time that would be available for a collision course at these speeds because it has been assumed that the target is seen by the observer as soon as the limit of visibility has been reached. Of course, seeing the target at extreme range will depend upon alertness in the direction of the target equal to the alertness under which the laboratory data were collected.



Therefore, 71 seconds must be considered the maximum time. When adjustments are made for the visual search procedure used by the pilot, his degree of alertness in the sector of the target, and his unwillingness to respond to a 'faint hunch' in lieu of a clearly visible target, it is likely that 71 seconds will no longer remain.

This is only an example to show the application of Figure 13. Even higher speeds may be encountered than those considered here, in which case, the time available to the pilot decreases further from the values given in the example. No allowance has been made for the possible requirement that the pilot maneuver his plane to an attacking (or defending) position after another object has been sighted. Such maneuvers take time and also introduce another group of factors, such as the flight paths which are permissible within human and mechanical limits at such speeds. It must be noted, in conclusion, that little time appears to be available between the time when another object may be sighted and when it will either be over-run or lost from view. Thus, despite the relatively long range visibility which may be possible at high altitudes, very short times are available for dealing with the visual objects appearing in this field. This fact must, of necessity, place considerable limitation upon the usefulness of vision for objects beyond the pilot's own craft.

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Appendix

**Example:**

The calculation of brightness contrast reduction due to the atmosphere along a line of sight tangent to the earth's surface with the observer at an altitude of 200,000 feet.

**Formulas:\***

$$\bar{R} = \frac{21700}{\sin \theta} \left( 1 - e^{-\frac{R \sin \theta}{21700}} \right)$$

$$CR = \frac{C_0}{1 + \frac{B_{H'}}{B_0} (e^{\beta \bar{R}} - 1)}$$

$$\text{If } \frac{B_{H'}}{B_0} = 1.00,$$

$$\text{Then } CR = C_0 e^{-\beta \bar{R}}$$

\*See page 29 for explanation of formulas.

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Appendix

Calculation of R and  $C_R/C_0$  for line tangent to earth's surface:

Altitude (in feet)	R (in feet) (1)	sin $\theta$ (2)	$\bar{R}$ (in feet) (3)	B (4)	$e^{\bar{B}R}$ (5)	$C_R/C_0$ (6)
200,000	$2.898 \times 10^6$	.0690	$.003 \times 10^6$	$5 \times 10^{-6}$	0.0	1.00
100,000	$2.047 \times 10^6$	.0488	$.040 \times 10^6$	$5 \times 10^{-6}$	1.02	.98
50,000	$1.447 \times 10^6$	.0346	$.095 \times 10^6$	$5 \times 10^{-6}$	1.24	.81
30,000	$1.120 \times 10^6$	.0268	$.119 \times 10^6$	$8 \times 10^{-6}$	2.00	.50
20,000	$.915 \times 10^6$	.0219	$.231 \times 10^6$	$1 \times 10^{-5}$	5.17	.19
10,000	$.647 \times 10^6$	.0154	$.230 \times 10^6$	$5 \times 10^{-5}$	51.94	.019
5,000	$.457 \times 10^6$	.0109	$.409 \times 10^6$	$1 \times 10^{-4}$		
0	0	0				

(1)  $R = \sqrt{h(h + 7917.78)}$

(2)  $\sin \theta = h/R$  as defined in the derivation of the formula (11).

(3) Calculated by subtracting  $\bar{R}$  for 100,000 feet.  
(with  $\sin \theta = .0488$ ) from R for 200,000 feet.  
(with  $\sin \theta = .0690$ ) and so on.

(4) See page 28.

(5) This column gives cumulative values from 200,000 feet down to the indicated altitude.

(6) Multiplied by 100, these values indicate the percent of the original contrast ratio which still exists.

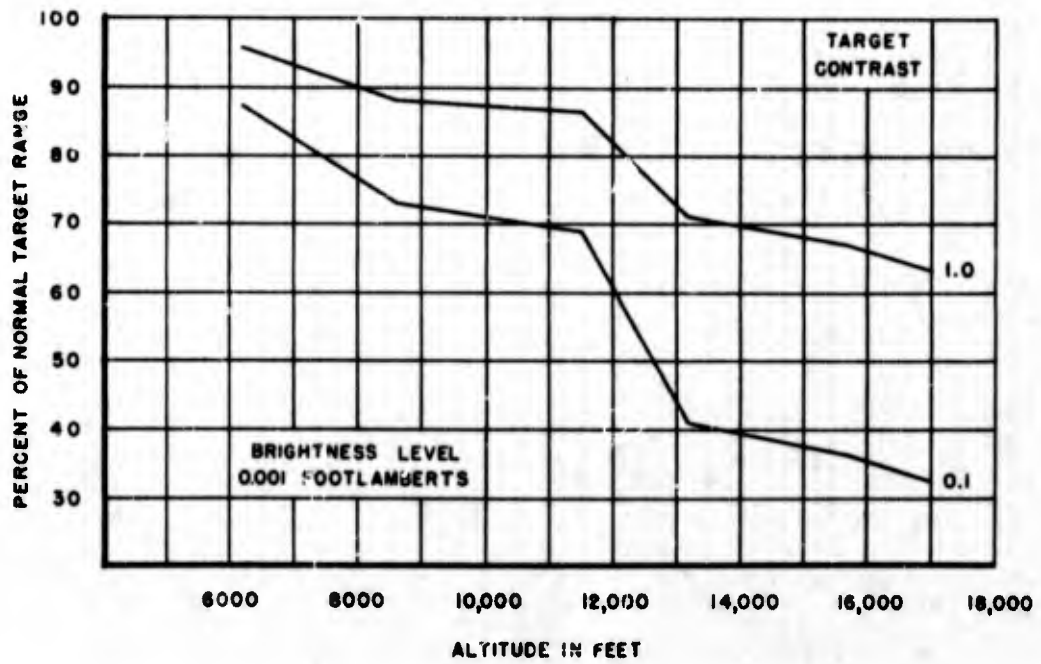
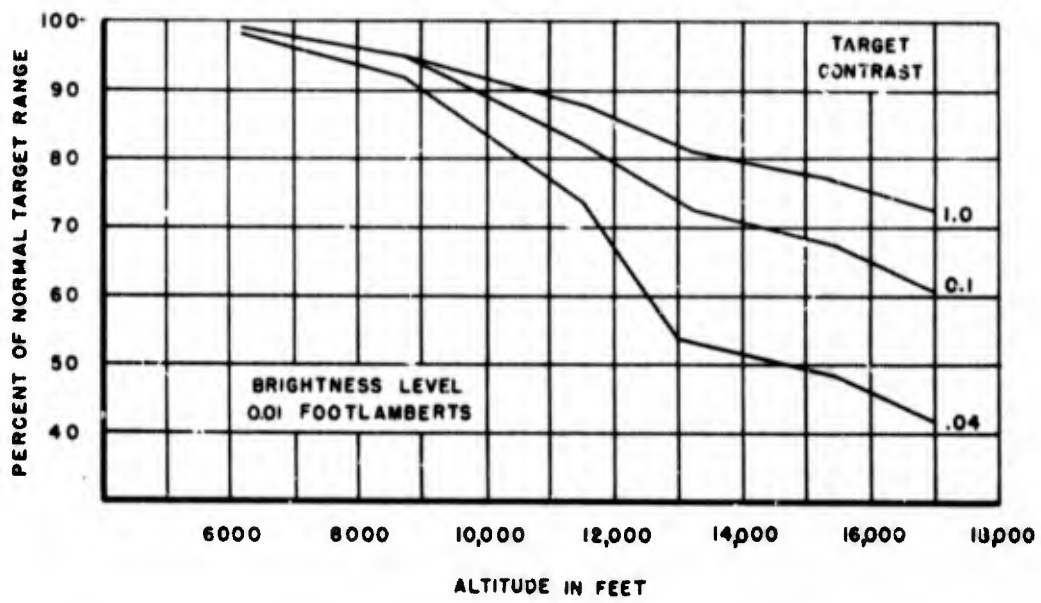
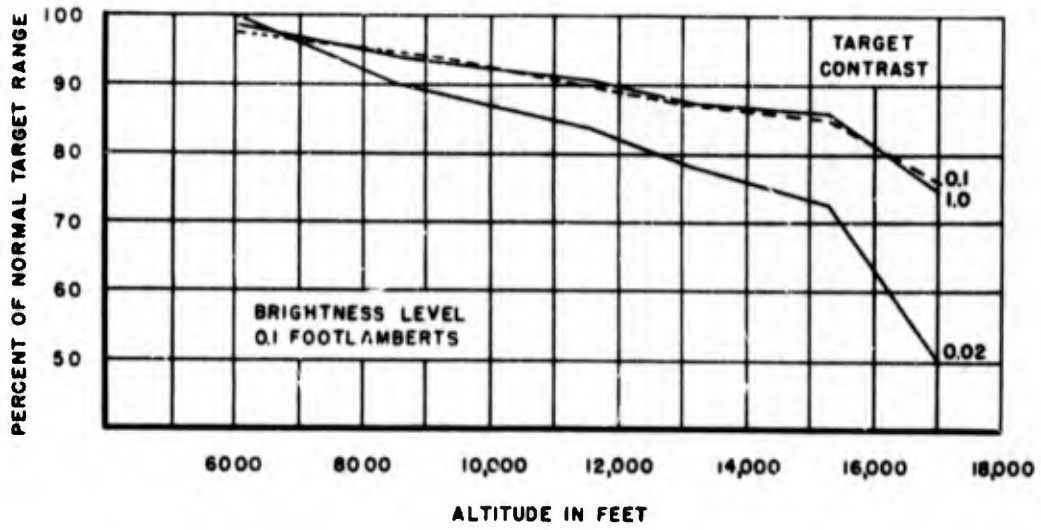


FIGURE 14: REDUCTION OF TARGET RANGE DUE TO ANOXIA FOR VARIOUS DEGREES OF TARGET CONTRAST WHEN THE VISIBILITY IS UNLIMITED, SHOWN FOR THREE LEVELS OF ADAPATATION BRIGHTNESS. DRAWN FROM DATA BY BLACKWELL (7).

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