AD-A017 599

A MODEL FOR VISUAL DETECTION OF AIRCRAFT BY GROUND OBSERVERS

Arthur C. Poe, III

Army Missile Research, Development and Engineering Laboratory
Redstone Arsenal, Alabama

October 1974

Technical Report RD-75-30

A MODEL FOR VISUAL DETECTION OF AIRCRAFT BY GROUND OBSERVERS

Arthur C. Poe III
Aeroballistics Directorate
US Army Missile Research, Development and Engineering Laboratory
US Army Missile Command
Redstone Arsenal, Alabama 35809

October 1974

Approved for public release; distribution unlimited.

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RD-75-30	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A MODEL FOR VISUAL DETECTION OF AIRCRAFT BY GROUND OBSERVERS		5. TYPE OF REPORT & PERIOD COVERED Technical
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Arthur C. Poe III		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander, US Army Missile Command Attn: AMSMI-RD Redstone Arsenal, Alabama 35809		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Proj. No. 1H32215369704 AMCMS Code: N/A
11. CONTROLLING OFFICE NAME AND ADDRESS Commander, US Army Missile Command Attn: AMSMI-RPR Redstone Arsenal, Alabama 35809		12. REPORT DATE October 1974
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Visual detection
Psychophysical experimentation
Contrast and threshold contrast
Calculation of glimpse probability

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A model is presented for predicting the time cumulative probabilities of visual detection of a single aircraft by a ground observer searching an unstructured background. The important elements of the model are supported by appropriate references to psychophysical experimentation. The model is registered on a small amount of field testing at present; the author intends to broaden the scope of the model and continue registration on field tests in the future.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DISPOSITION INSTRUCTIONS

DESTROY THIS REPORT WHEN IT IS NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

DISCLAIMER

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

TRADE NAMES

USE OF TRADE NAMES OR MANUFACTURERS IN THIS REPORT DOES NOT CONSTITUTE AN OFFICIAL INDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL HARDWARE OR SOFTWARE

CONTENTS

1. BACKGROUND

A model of the following situation is discussed. A large number of young men have been trained in the unaided visual search for and detection of aircraft in flight. Now they will spend a short time searching at a small site in open terrain. Every now and then a single aircraft will fly an arbitrary path passing near the site. Shortly before each aircraft's appearance the group is assigned a certain azimuth sector of sky to search and a time to begin searching. Each man searches independently of the others. Wherever a man detects an aircraft he presses a button to record a detection time. After each aircraft has passed, a record remains of the cumulative frequency of detection times for that sortie. The cumulative frequency function associates each time with a number between 0 and 1 which may be thought of as the probability that a man selected randomly from the group has detected the target by that time (see Fig. 1). The model is to duplicate each recorded cumulative frequency function when given:

1) the size and location of the search sector

2) the time at which search is begun

3) the aircraft's dimensions and flight path, and

4) the local meteorological visibility.

More importantly, the model is to predict cumulative frequency functions accurately for untested combinations of the above parameters.

There is a certain amount of visual theory and laboratory data on which to base such a model and a certain amount of actual field detection test data on which to register the model. But as yet, the theory is loose, the number of collateral considerations (such as local sun position and brightness, ground and target reflectivities, cueing due to smoke trails, sound, or glint, etc.) is large, the field test data is sparse in relation to the parameter space, and the consequent lack of success in building accurate predictive models is notorious. This author feels that improvement lies in the direction of more careful modeling of the actual search process and available laboratory data on threshold contrasts, and in the adoption of a framework which predicts detection frequencies for a single well-defined set of parameters rather than skipping directly to models which predict results for average or randomly selected sets of parameters (a physical rather than a statistical model). Herein we shall attempt to construct a new model, reviewing pertinent findings of other researchers at critical points, and to compare ex-post model predictions with field test results.

2. THE SEARCH PROCESS

Consider a ground observer searching for an aircraft suspected of being in the area, but with an unknown flight path. His searching behavior will be influenced by:

Preceding page blank

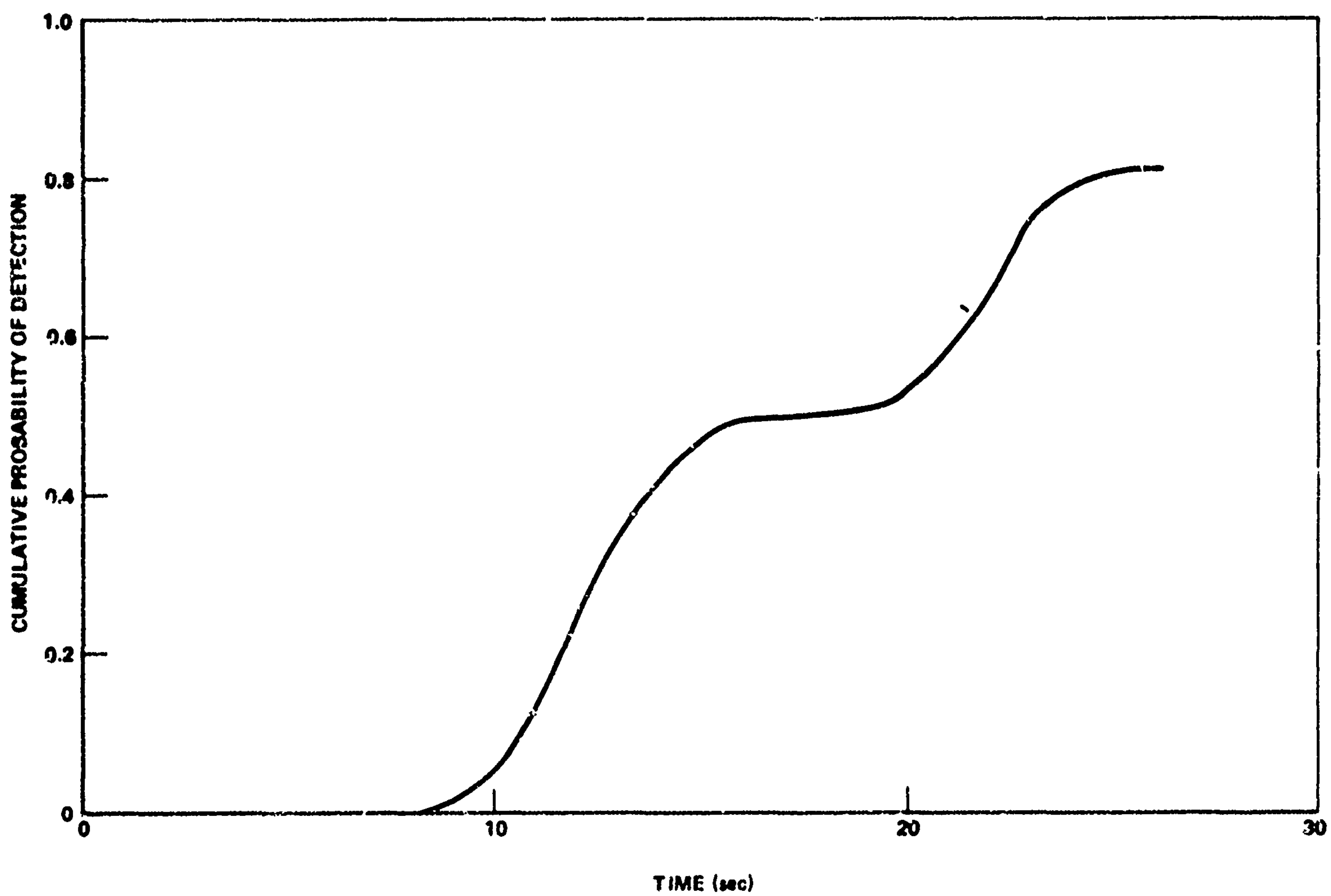


Figure 1. Sample probability of detection curve.

1) the extent of the sector

2) his mental picture of what he is looking for and where he expects to find it, and

3) other elements in the sector which might be confused with the target - or more generally, the background "structure."

In the situation modeled, the observer has been told to search an azimuth extent between two identifiable points probably on the horizon and an elevation extent large enough to include most appearing targets. If the surrounding terrain is flat, the observer will probably choose the horizon as a lower boundary, but if the terrain is rugged and/or the observer is stationed high, he may feel he should spend considerable time searching below the horizon. If the day is quite clear and high-flying aircraft are not of interest, the observer may search only the lowest 10° above the horizon and not expect to miss important targets. On the other hand, if the visibility is poor or high targets are important, the upper boundary should be raised.

At present the model provides only for "rectangular" search sectors of extent 10° in elevation and between 20° and 180° azimuth. The center of the sector should not be more than 25° above or below the horizon. The reason for the present restriction to sectors only 10° tall is simplicity in modeling-it is natural to scan such a sector in linear sweeps back and forth; sectors taller than 10° would involve a more complicated two-dimensional scan pattern. More will be said about this later in this report.

The flight path of the target past the observer may be straight and level or may involve maneuvers. The straight and level path is characterized by its altitude and offset (horizontal range at closest approach). Maneuvers are simple climbs, dives, horizontal turns or combinations of these. In the model, the aircraft is moved along its path and banked as specified by input cards. The model does not assume that the aircraft is in the search sector. Indeed, with maneuvers as well as some straight and level flights, the target may spend most of the time outside the search sector, yet still be visible with peripheral vision.

Structure in the background consists operationally of anything that causes the observer to alter his scanning path or rate from that natural in a featureless field. Some typical structures are:

1) The horizon itself, on which the observer finds it useful to focus now and then and which provides a reference line for efficient scanning of larger horizontal sectors.

2) Sharply delineated boundaries to the sector, such as the edge of a projection screen, which generally do not occur in the modeled situation.

3) Flora, which, with its constant pattern of varying colors, shades, and textures, tends to hide the target, causing the natural scan rate to decrease.

4) Cloud banks which are articulated enough to cause scan rate to decrease.

On the other hand, the open sky, uniform cloud covering, and distant terrain can appear featureless. In a highly structured background field, the observer may not be aware of the target's presence except when viewing it foveally (direction of target and gaze coinciding). But as the background becomes more nearly featureless, the importance of peripheral vision in detection increases. A smoke trail, glint (specular reflection of the sun), or even the target itself may catch the observer's attention when located as much as 80° off the foveal axis. Immediately after gaining such a peripheral cue, the observer will shift his glance toward the cue to confirm his suspicion. In a structured rectangle the observer's pattern of glimpses will be broken by many apparently random departures from the straightforward back and forth pattern, unless the structure forces an extremely low scan rate (as in the case of the printed page). However, even an unstructured rectangle is not searched perfectly back and forth, mainly for physiological reasons over which the observer has no control.

In the model, the background is assumed unstructured; the scan pattern is perfectly systematic and the scan rate is chosen appropriate to natural levels in unstructured fields. More will be said about this later. For these reasons, applicability of the model to cases where the background is structured or the scan pattern or rate is not natural to the observer is minimal.

It is widely believed that the observer's normal ocular activity consists of a series of fixation periods and the short intervals or jumps between them. Of interest at this point are:

1) The duration of a fixation

2) The relative duration of the inter-fixation periods

3) The nature of the pattern traced out by a series of fixations

4) The angular distance between successive fixations.

A number of investigations into these phenomena have been reported in the literature; the results vary with the nature of the visual task being performed and conditions of observation. Cobb and Moss[1] found that the distribution of minimum duration of a fixational pause was adequately described as Gaussian with a range of 0.071 to 0.25 sec and a mean of 0.15 sec. Their procedure involved estimating the time spent in a pause midway during a shift of gaze from point A to point B. Leibowitz and Bourne[2] reported a skewed distribution of durations with a mode of 0.30 sec and a mean of 0.48 sec although it is not clear that their measurement involved only one fixation, rather it was the time spent viewing a test object while making a shape judgment about it. Ford, White, and Lichtenstein[3] report results of a study of visual activity in searching an empty 30° diameter screen. The mean fixation duration was 0.23 sec (with a range of 0.04 to 0.60 sec). The typical pattern of search was roughly circular concentrating in an annulus about midway from center to periphery. The mean distance between fixations was 8.6° (range: 1° to 30°). About 15% of the search time was spent jumping between fixations. White and Ford[4] were interested in visual search of 1[illegible] and 30° diameter circular radar plan position indicators. Such a field is structured with a radial scan line rotating with one end fixed in the center of the screen. The spoke made a complete revolution every 10 sec. They found a slightly skewed distribution of fixation durations with mean 0.37 sec, median 0.36 sec, and range 0.11 to 0.79 sec, independent of size of screen. They found also that the typical pattern of fixations followed the scan line around the screen, at an average radius of one-half the screen's radius, with 6 or 7 very brief excursions per revolution toward center and edge. This yields no clue to the pattern of successive fixations expected in the search of an empty narrow horizontal rectangle, but indicates how strongly the natural search pattern can be influenced by structure. Finally, they mentioned that very similar results were obtained by Baker[5] in an independent investigation. White and Ford[6] summarize briefly the results reported in references (3) and (4). White[7] restates the above findings and implies that for sectors larger than those studied, the angular distance between fixations would be larger than 8.6° although the fixation duration would not change much. Enoch[8] studied the average fixation durations and inter-fixation distances involved in searching maps of various sizes. The results are shown in Table 1.

TABLE 1. OCULAR BEHAVIOR DURING MAP READING

Map Diameter (deg)	Average Duration of Fixation (sec)	Average Inter-Fixation Distance (deg)
3	0.578	0.87
6	0.468	1.82
9	0.384	2.13
18	0.361	3.72
24	0.355	4.33
51°,18'	0.307	6.30

It must be remembered that a map is highly structured and so the inter-fixation distances are probably smaller than those natural to a featureless field. Sugarman, Hammill, and Deutschman[9] measured detection rates during search for several types of targets including circles of various uniform contrasts and sizes superimposed on a large unstructured rectangular screen. At the end of the experiment they measured eye movements of one particular observer. They found that the observer shifted his gaze 171 times in 57 seconds, giving an effective average glimpse time of 0.33 sec. They report also that the first four full-field scans took a total of 4.5 sec, the next several 3 to 4 sec each, then followed one of 14 sec. After the 14 sec scan, the pattern of 1 sec scans slowing to 4 sec scans was repeated.

The present author, in a very rough attempt to determine typical scan rates, looked recently at videotape recordings of the Marine Corps' LADS-1 or AMTOC-1 visual acquisition and tracking field tests conducted near Yuma, Arizona in 1970. In these tests ground observers searched preassigned sectors of desert sky for aircraft purported to be flying by (just as in our situation to be modeled). The preassigned search sectors were of 30°, 60°, and 120° extent in azimuth and all consisted roughly of the 10° in elevation just above the horizon. The observers carried portable tracking devices, some of which were equipped with a videotape recorder aligned with the crosshairs of the tracking device. The observer turned on his recorder, started search, and finally informed his partner that detection had occurred. The recordings indicate that some of the observers kept their trackers pointed toward the ground until detection occurred, then swiftly aimed them at the target. During the search phase (prior to detection) the tracker traced out a pattern on the ground that was presumably highly correlated with the upper body motion of the searcher. The typical search pattern that emerged was a series of moderately rapid full field scans, right to left to right, etc., broken now and then by excursions presumably to investigate suspect areas. Generally there were only several full field scans recorded prior to detection. In the few cases that involved as many as ten, there was no clear cut evidence of the slowing down, then speeding up, effect noted by Sugarman, et al. A stopwatch was used to determine the duration of these full field scans. Assuming a glimpse rate of 3 per second, an estimate was made of the average distance between adjacent glimpses. The results are tabled below and plotted in Fig. 2.

TABLE 2. OCULAR ACTIVITY DURING SEARCH OF THE SKY

Azimuth extent of sector	30°	60°	120°
Total No. of full field scans	96.5	94.2	72
Range of durations	1.75-4.50 sec	2.00-4.75 sec	2.50-6.00 sec
Total duration	262 sec	282 sec	284 sec
Average Duration	2.72 sec	2.99 sec	3.94 sec
Average No. of glimpses per scan	8.16	8.97	11.82
Average distance between adjacent glimpses	3.68°	6.69°	10.15°

In order to plot these results with other interfixation distances, an assumption had to be made as to the vertical extent of the AMTOC search sectors. In Fig. 2, it was assumed that the vertical extent was 8° in order that the White and Ford point (W) lay right on the curve. The Enoch

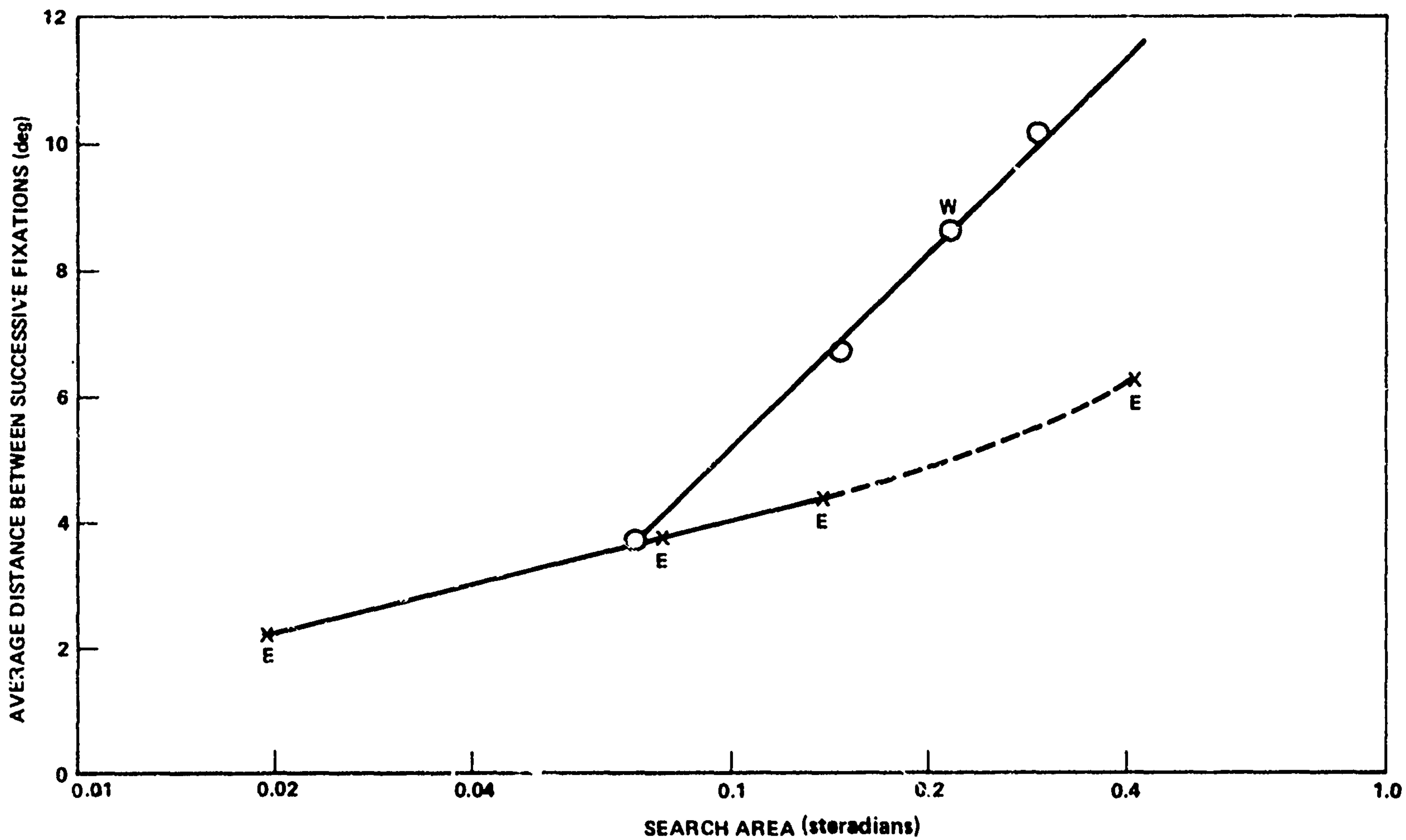


Figure 2. Average interfixation distances.

findings for reading maps are shown for comparison and labeled E. In view of the Enoch findings, it would be unwise to extrapolate the unstructured search results to sectors of extent below 0.07 sr or much above 0.4 sr.

In summary, then a certain amount of experimental evidence supports the following conclusions regarding natural free search in an unstructured field:

1) Average glimpse rate is in the neighborhood of 3/sec.

2) Perhaps 85% of the search time is spent actually glimpsing, the rest in jumps between fixations. Actual average glimpse times are on the order of 0.28 sec.

3) The shape of the field has an effect on the natural search pattern, circular fields are searched with roughly circular scan patterns and long low horizontal rectangles are searched with a back and forth motion.

4) There is a definite tendency to scan larger areas with larger inter-fixation distances than smaller areas, but not so rapidly as to cover the larger area in the same time as the smaller. Fig. 2 may serve as a tentative guide to this effect.

In the model, the search process is handled as follows: The sector is assumed to be a rectangle of azimuth extent between 30° and 180° and running in elevation from the horizon to 10° above the horizon. An observer scans toward the right edge on a line 2½° above the horizon, then back toward the left edge on a line 7½° high, then repeats the process. The simulation frame time is 1/3 sec. Each 1/3 sec the scan position is advanced a fixed angular distance depending on the sector size as shown in Fig. 2. The 5° jump between lines is made instantaneously. It remains to discuss the initial position.

Consider an aircraft approaching the observer radially along the left sector boundary. If the observer is looking near the left edge he will detect much more rapidly than if he were looking near the right edge. It is desired that the result represent the frequency function of an observer whose initial scan position is chosen at random. Therefore the model averages results for a number of observers. For purposes of initial position only, the search sector is partitioned into 5° squares (a 90° x 10° sector contains 36) and an observer is started in the center of each square. The number of observers comprising the average is thus also the number of 5° squares into which the sector can be partitioned.

Every 1/3 sec the model calculates a glimpse probability, Pg, for each observer. This glimpse probability is cumulated for each observer according to the formula $PCUM_t = PCUM_{t-1} + (1 - PCUM_{t-1})\ Pg$. The result is then $\overline{PCUM_t}$ averaged over the observers. Before discussing glimpse probabilities further, let us go into contrasts.

3. CONTRAST AND THRESHOLD CONTRAST

The signature of the target in the visual spectrum consists of its presented area and its brightness contrast against the background. The visual angle (apparent diameter) of the targets in the region of most detection action is small, say one to 20 minutes of arc, so that color contrast can reasonably be ignored. What is detected is generally a dark point against a lighter background or vice versa. Middleton's delightful book[16] gives an excellent introduction to the topic of contrast and its transmission through the atmosphere. Here we shall give only a brief summary. Intrinsic brightness contrast is defined as

$$C_o = \left| \frac{B_t - B_b}{B_b} \right| ,$$

the absolute value of the difference between target and background luminance divided by background luminance. Luminance is the photometric analogue of the radiometric term radiance and is measured in lumens/ $(Sr - m^2)$ or foot-Lamberts.

An aircraft in the daytime sky is illuminated by three sources: direct sunlight, air light from the rest of the sky, and reflected light from the ground. During most types of flight (except directly toward or away from the observer, or circular horizontal turns with observer at center) the portion of the aircraft's surface visible to the observer is constantly changing. Moreover, the luminance at any particular point on the aircraft is changing constantly as it receives differing quantities of sunlight, airlight, and reflected ground light. Furthermore, the background brightness is subject to certain variations from point to point in the sky. Consequently, substantial variations in contrast over a flight path lasting 20 sec are common. Common levels of aircraft intrinsic contrasts are between 0.05 and 0.75.

There is very little systematic knowledge of the way in which actual contrasts vary in flight. One may measure material reflectances and lighting distributions and calculate contrasts that should occur, but generally, the agreement is poor. Alternately one may remotely measure contrasts in flight, to see how they behave and attempt to build models which predict the observed behavior. Again, this author's personal experience has been unsatisfying. The topic remains an area for future research.

The weakest point in the model at present is that intrinsic contrast must be specified as an input (changes during a flight are allowed) but the analyst has little information on which to base his choice. The parameter is significant in that results can vary widely depending on the choice made.

Atmospheric haze is the dominant cause of alteration of the contrast in the visible spectrum. The apparent contrast of a target whose intrinsic contrast is C_o and which is positioned at range R is

$$C = C_o \exp\left[-\frac{kR}{V_m}\right]$$

where V_m is the meteorological visibility and k is a dimensionless constant such as 3.912 or 3.44, depending on the criterion used in determining the visibility. This calculation of apparent contrast holds exactly for horizontal lines of sight and is a good approximation for nearly horizontal paths. The formula is firmly based in theory and agreed on by most researchers.[10,11,12]

The calculation of glimpse probability P_g depends on the ratio of apparent contrast to threshold contrast. Calculation of threshold contrast C_t is neither firmly based in theory nor agreed on by independent researchers. Let us define threshold contrast as that level at which a normal pair of eyes, chosen at random, has a 50% probability of seeing the target. Threshold contrast is a function of four major parameters:

1) Size of target, α, in minutes of arc subtended.

2) Peripheral angle, λ, in degrees from the target to the foveal or fixation direction.

3) Level of brightness to which the eyes have been adapted.

4) Duration of target exposure.

The minor variables include: shape of target, whether vision is monocular or binocular, and whether target is brighter or darker than background (of positive or negative contrast). Contrast thresholds are measured empirically, generally in viewing rooms, and generally using a small number of observers[13-20]. Differences in test procedures and data reduction methods strongly influence the results.

The number of variables influencing contrast thresholds has been a deterrent to complete mapping of the space. Various investigators have fixed one or two of the major parameters and attempted to map out subspaces. The present author has used references 17-20 to put together a map of threshold contrast versus target size, α, and peripheral angle, λ, at the constant values of adaptation brightness level 75 to 100 ft-L and exposure duration 1/3 sec. The process of putting this map together has required months of data smoothing, cross-plotting, correcting what appear to be measurement errors, comparing results with other mappers (notably Seyb[21] and Davies[22,23]), making sure that the result is consistent with Ricco's Law: as target size diminishes, $C_t \rightarrow k/\alpha^2$ for foveal vision, and many months of trying out results on the AMTOC detection data.

A comparison of Taylor's[19] data with Blackwell and Moldauer's[18] data suggests that Taylor had trouble controlling the accuracy of his peripheral angle measurement under 5°. So the present model uses foveal data from Blackwell and McCready[17], near periphery data from Taylor[19]

(λ = 5 to 12½°) and trends in the far periphery (λ = 15 to 90) from Sloan[20]. Sloan's trends, rather than actual data, are used since her adaptation brightness level (3.2 ft-L) and exposure duration (1 sec) are rather far removed from the present selections and since her viewing was monocular.

The formulas used for threshold contrast, C_t, are as follows:

TABLE 3. FORMULAS FOR THRESHOLD CONTRAST

$$C_{t_o}(\alpha) = \frac{a_o}{\alpha^{(b_o)}}$$

a_o	b_o	for
0.240	2.0	$0 < \alpha \leq 1'$
0.240	1.982	$1' < \alpha \leq 2.5'$
0.155	1.507	$2.5' < \alpha \leq 3.5'$
0.108	1.220	$3.5' < \alpha \leq 4.5'$
0.0524	0.736	$4.5' < \alpha \leq 6'$
0.0327	0.473	$6' < \alpha \leq 10'$
0.0214	0.289	$10' < \alpha \leq 20'$
0.0128	0.117	$20' < \alpha$

$$C_{t_1}(\alpha) = \frac{a_1}{\alpha^{(b_1)}}$$

a_1	b_1	for
0.525	2.0	$0 < \alpha \leq 1'$
0.525	2.106	$1' < \alpha \leq 2'$
0.431	1.821	$2' < \alpha \leq 4'$
0.301	1.561	$4' < \alpha \leq 8'$
0.164	1.269	$8' < \alpha \leq 16'$
0.0728	0.977	$16' < \alpha \leq 40'$
0.0506	0.878	$40' < \alpha$

$$C_t = \begin{cases} C_{t_o}(\alpha) & \text{for } 0 \leq \lambda \leq 0.6° \\ C_{t_o}(\alpha) + (\lambda - 0.6)\, C_{t_1}(\alpha) & \text{for } 0.6° < \lambda \leq 15° \\ \left[C_{t_o}(\alpha) + 14.4\, C_{t_1}(\alpha)\right] \ell^{[0.000643(\lambda^2-225)]} & \text{for } \lambda > 15°,\ \alpha \leq 9.1' \\ \left[C_{t_o}(\alpha) + 14.4\, C_{t_1}(\alpha)\right]\left(\frac{690}{\alpha}\right)^{[0.0001486(\lambda^2-225)]} & \text{for } \lambda > 15°,\ \alpha > 9.1' \end{cases}$$

These formulas should be good for the ranges $0 < \alpha \leq 120'$, $0 \leq \lambda \leq 90°$, as long as λ is measured in the horizontal meridian. Sloan's data provides for a further modification if λ is in the vertical or on an oblique meridian, but this provision has not yet been incorporated into the model. It is to be noted that C_t is linear in λ for $\lambda \leq 15°$. Figures 3 and 4 show $C_{t_o}(\alpha)$, $C_{t_1}(\alpha)$, and the factor exp $[0.000643(\lambda^2 - 225)]$.

The reader may well question the use of extreme accuracy in handling threshold contrasts when their originators (e.g., John Taylor in a telephone conversation) claim an accuracy only to a factor of 3 (½ log unit).

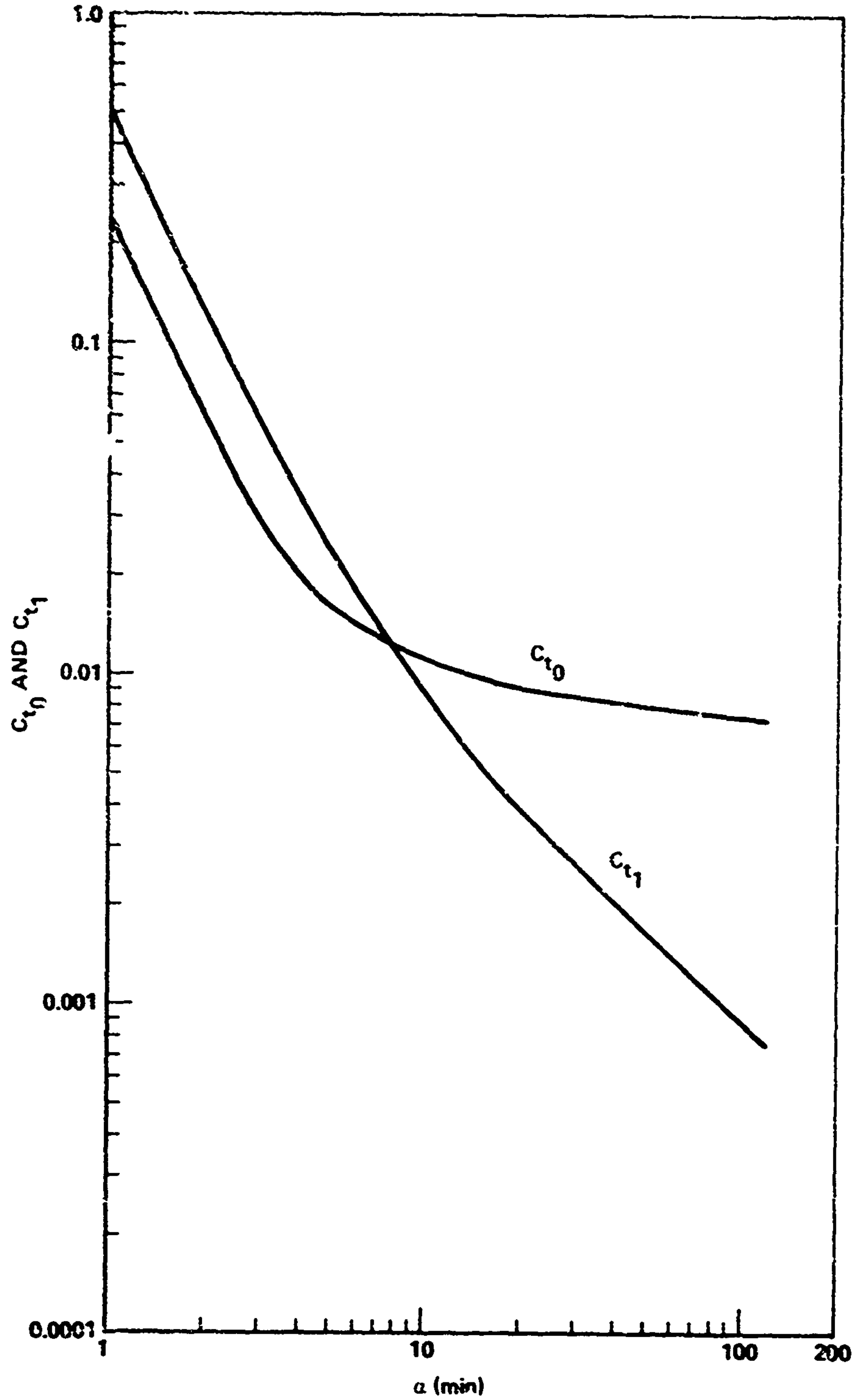


Figure 3. Foveal contrast threshold and slope in the near periphery.

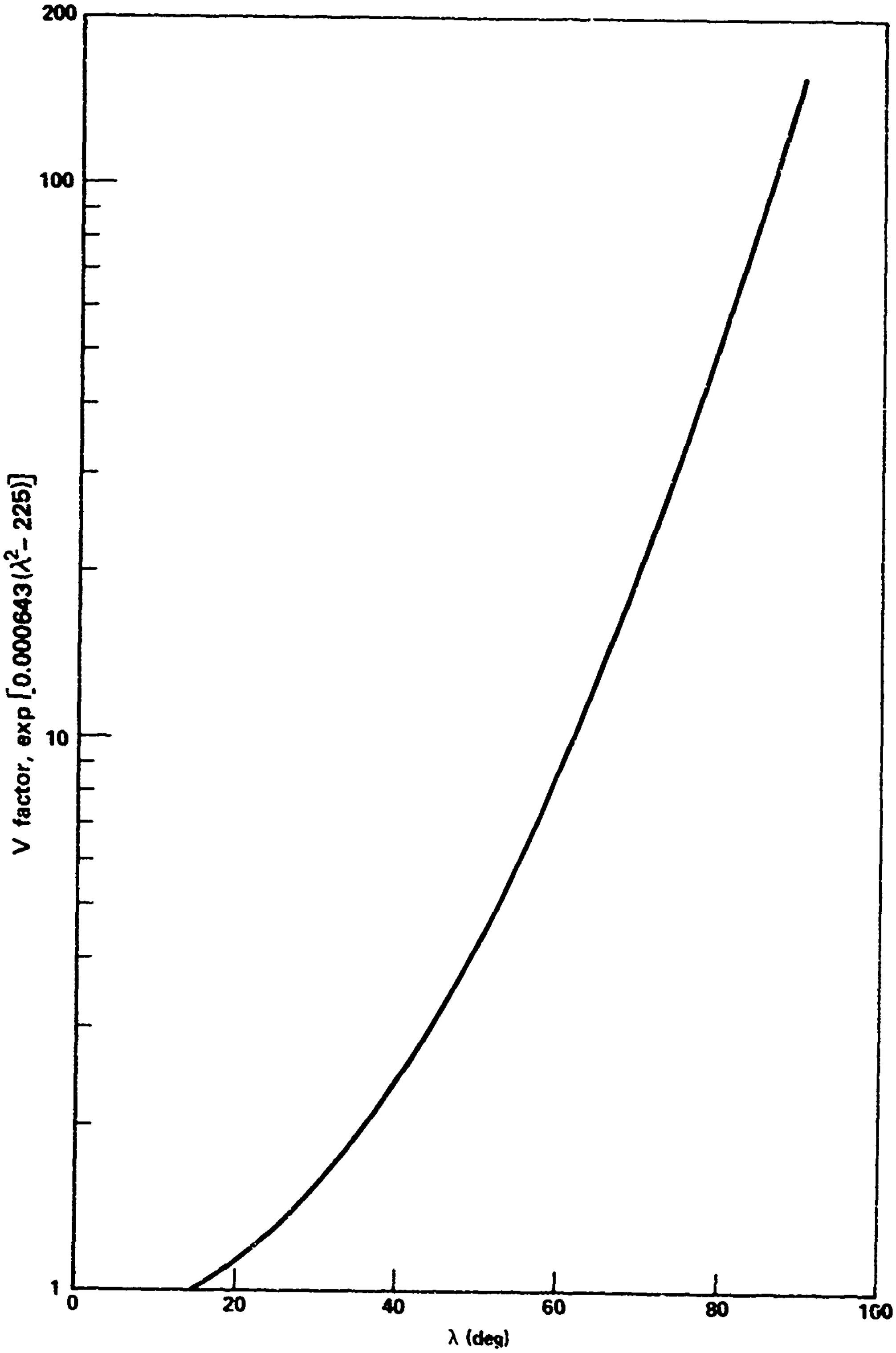


Figure 4. Correction factor for targets in far periphery ($\alpha < 9.1'$).

Further, they will find plausible excuses (e.g., forced choice versus yes-no responses by the subjects in the experiment) to explain their inability to duplicate the data of others. Yet this author feels the accuracy is much better than claimed and, moreover, it is significant: a 20% reduction in threshold contrast in only a small portion of the sample space can cause a five second reduction in detection time predictions.

4. CALCULATION OF GLIMPSE PROBABILITY

Fully as important to the model as the threshold contrast is the procedure for transformation of C/C_t into glimpse probability. Blackwell[24] has extensively investigated this matter, summarizing data on more than one million observations by 36 observers in 11 different studies. He concludes that contrast ratio at detection (contrast at detection divided by threshold contrast) may be represented as a random variable whose distribution is normal with mean (necessarily) unity and standard deviation σ (in Blackwell's notation, $\sigma/.$). He further argues that σ is quite constant, that is, fairly independent of the level of the parameters mentioned in Section 3. Let us briefly examine his data.

In each of the 11 studies one or more of the above-mentioned parameters was varied, others remaining constant. In reference 24, for each study, a σ for each level of the parameter(s) varied and a "grand mean" σ was reported. The following table shows the minimum and maximum σ and the grand mean for each study.

TABLE 4. BLACKWELL'S REPORTED σ'S

Study	Minimum σ	Maximum σ	Grand Mean σ
1	0.363	0.672	0.479
2	0.311	0.402	0.354
3	0.433	0.539	0.471
4	0.324	0.456	0.419
5	0.333	0.467	0.390
6	0.284	0.354	0.337
7	0.285	0.345	0.302
8	0.484	0.547	0.519
9	0.412	0.544	0.483
10	0.373	0.620	0.455
11	0.340	0.365	0.352

A typical σ in Table 4 was found in the following manner: The parameter levels were specified and a range of contrasts suspected to bracket the threshold value was identified. At various contrast levels in this range the observations were carried out and resulted in proportions of correct responses. On at least some of the data, χ^2 tests indicated that the hypothesis that the distribution of contrasts at detection was normal could not be rejected. Therefore, on the assumption of normality, probit analysis was applied to the responses to estimate mean and standard deviation of the distribution. The tabled value is the estimated standard deviation divided by the estimated mean.

Now, consider the random variable contrast at detection divided by threshold contrast. It has mean unity and an absolute lower bound of zero. A distribution of such a variable can be regarded as approximately Gaussian for most practical purposes only as long as its standard deviation is less than about 0.4. At higher σ's, the tails get severely distorted. The standard deviation of the triangular distribution on the range zero to two is 0.408. A standard deviation greater than 0.55 is significantly non-Gaussian. The standard deviation of the uniform distribution on the range zero to two is 0.577. Certain skewed distributions with the same σ's as the above two examples can be constructed which look a little more Gaussian, but not much. Consequently, the assumption of normality and also the argument for constancy of σ are questionable. After all, what is the range of possible standard deviations for a distribution with mean unity and lower bound of zero? Nevertheless, the frame work of the present model requires specification of the distribution of contrast ratio at detection.

In Figure 5 sample Gaussian distributions with means unity and standard deviations 0.3, 0.4, 0.5, and 0.6 are shown. At a C/C_t ratio of 0.2, Pg is 0.0045 when $\sigma = 0.3$, but Pg is 0.09 when $\sigma = 0.6$. After 30 glimpses (10 sec.) in such a way that C/C_t remains constantly 0.2, cumulative probability has risen to 0.13 in the first case and 0.94 in the second case. If one case represented field detection data and the other a model prediction, the match would be unacceptable. It turns out that the preponderance of detections in the AMTOC tests and in our situation to be modeled occur in the region where $0.005 < Pg < 0.10$. In the absence of a moderately accurate specification of σ for the parameter levels of interest here, the author has experimented with several constant σ's and several ways of varying σ for different target sizes and peripheral angles. At present, the best model predictions have resulted when $\sigma = 0.32$ (constant). During a discussion with Blackwell, he indicated a preference for a higher σ and suggested that the left tail be skewed (as for example the dotted line in Figure 5) so that low Pg's could be reached with positive C/C_t's. This has not yet been tried.

Neither Taylor[19] nor Sloan[20] reported σ's for their experiments. Both these investigators used yes-no testing rather than Blackwell's forced-choice method; reliable estimation of σ in the former instance is difficult.

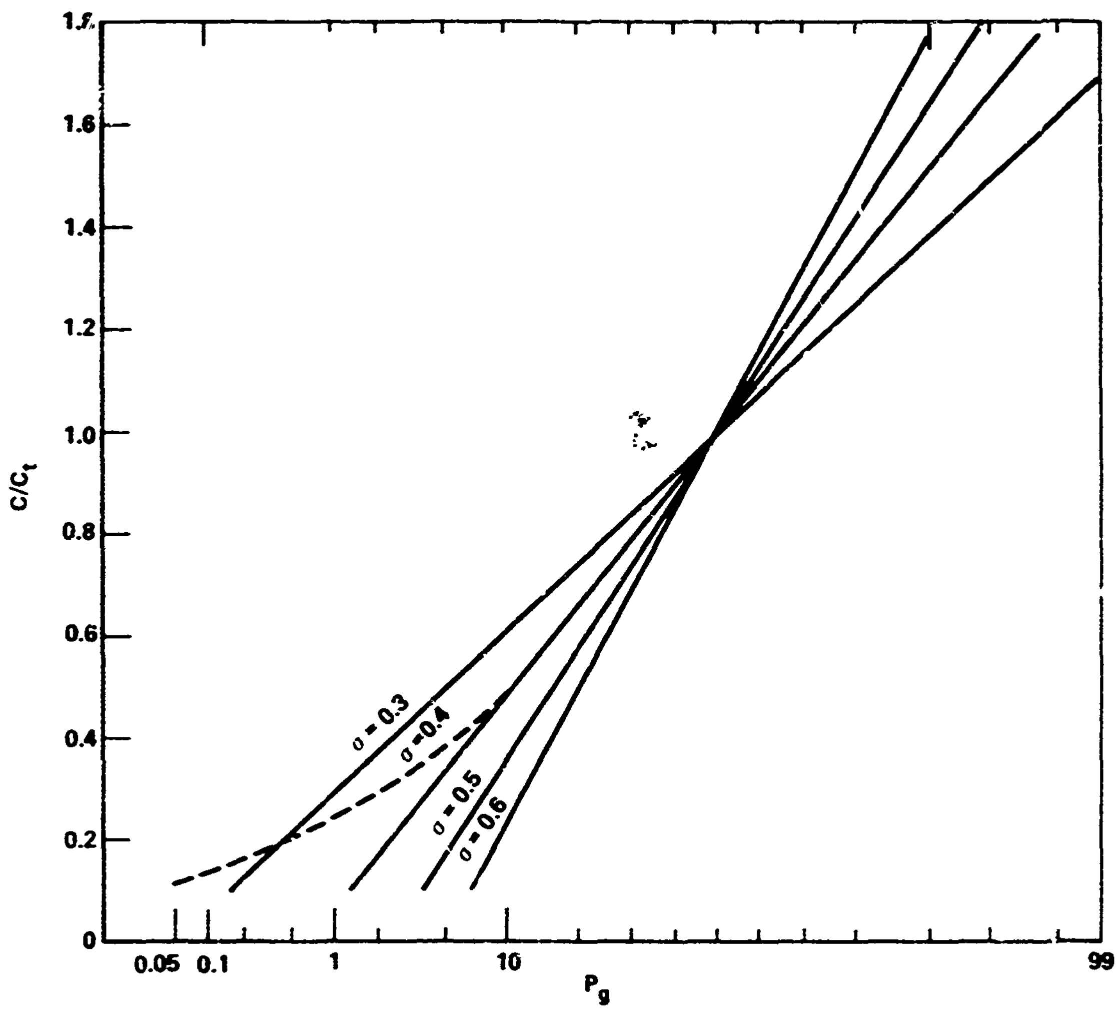


Figure 5. Alternative choices of P_g versus C/C_t.

Summarizing the model, then, at each instant the aircraft is positioned on its path at range R(km), presenting the desired aspect to the viewers. The presented area A_p (m^2) is converted to visual angle $\alpha = 3.88\sqrt{A_p}/R$ (minutes of arc). The input intrinsic contrast is converted to apparent contrast based on the range R and the input meteorological visibility. Then, for each observer, threshold contrast C_t is calculated as in Section 3 using the visual angle α and that observer's peripheral angle λ. It is assumed that $(C/C_t - 1)/\sigma$ is a standard normal deviate and that $\sigma = 0.32$. P_g for that observer is taken as the integral up to that deviate under the standard normal curve. Finally, as explained in Section 2, P_g is cumulated over time for each observer and the cumulative probabilities are averaged over the field of observers.

5. COLLATERAL TOPICS

In this section will be discussed briefly a number of topics which have some bearing on the detection of aircraft.

a. Terrain Backgrounds

On some occasions terrain backgrounds may be considered unstructured - e.g., distant mountains, expanses of flat sand or dirt, near terrain whose structure is obscured by haze. Such cases are handled in the model merely by a change of contrast. Writing $C_o = B_t/B_b - 1$ without the absolute value sign and noting that targets and terrain backgrounds are generally darker than the sky, it is seen that a switch from sky to terrain background means that C_o generally rises closer to zero (negative) or becomes slightly positive. Generally $|C_o|$ is reduced and the target is more difficult to see. If the terrain is structured, both the mode of search and the ability of the brain to pick the target out of the structure will be altered and the model is no longer applicable.

b. Smoke Trails

If the aircraft is emitting a smoke trail, the latter becomes a cue to the aircraft's presence. In fact it is not unreasonable to assume that the target has been detected as soon as the smoke has been observed. The smoke trail has a certain size (as seen by the observer) and a certain contrast against the background; only after reasonable assumptions can be made concerning these quantities, treatment of the smoke becomes straightforward. Each distinct aircraft type may be considered to have a smoke trail characterized by its (visible) length, breadth (under various wind conditions), color, and opacity. In the AMTOC field tests on the F8 aircraft (a light smoker) it is the opinion of the present author that smoke aided detection only when the aircraft's direction of motion was within 10° or so of directly toward the observer. However, observers at other field tests on other aircraft insist that smoke trails are more visible when the target is crossing at 90° than when it is approaching head on.

c. Sun Contrast Model

It is possible to construct a model of intrinsic contrast under the assumptions that the target is a Lambertian reflecting sphere, that the ground is a horizontal Lambertian reflecting plane, that the sky is of uniform brightness (except for a small sun), and that the sun is shining with a given brightness (possibly reduced by thin haze or clouds). Let the reflectances of target and ground be ρ_t and ρ_g, respectively. Let the sun and sky brightnesses be B_s and B_o, and assume the sun is of solid angular size ω_s. Let ϕ_s and θ_s be sun elevation and azimuth (from a given reference direction) and let ϕ_t and θ_t be elevation and azimuth of the target from the observer. Then let K be the ratio of illuminances due to sun and sky received on a plane normal to the sun's rays: $K = \omega_s B_s/\pi B_o$. Let G be the ratio of luminance reflected from the ground to sky luminance: $G = \rho_g(1 + K \operatorname{Sin} \phi_s)$. Let β be the angle between sun and observer as measured at the target:

$$\beta = \cos^{-1}\left[- \sin \phi_s \sin \phi_t - \cos \phi_s \cos \phi_t \cos (\theta_t - \theta_s)\right].$$

Then

$$C_o = \frac{\rho_t}{2} (1 + G) - \frac{\rho_t}{3} (1 - G) \sin \phi_t$$

$$+ \frac{2\sigma_t}{3} \frac{(K)}{\pi} \left[\sin \beta + (\pi - \beta) \cos \beta\right] - 1.$$

Simple modifications can be made to the model under the assumptions that the background is :

1) A sky of varying brightness

2) A distant terrain plane at an inclination to the horizontal.

The author has experimented with this model on the AMTOC data but, due mainly to the non-availability of B_s, results are poor. Often, the contrast model predicts changes in contrast in apparently the wrong direction.

d. Glint

Glint is specular reflection of the sun on a portion of the surface of the target. It consists of a small region of extremely high contrast which is a definite aid to detection when it occurs. The main difficulty in predicting glint is failure to account for the complex shape of the aircraft's fuselage and wings.

e. The Two-Dimensional Nature of Peripheral Angle

Data on the behavior of threshold contrast with vertical peripheral angle are available. The author hopes to include this effect in the model shortly. For one thing, the eyebrows limit the upper periphery to 55° or so, depending on depth of eye socket, etc.

f. Target Angular Motion

In the opinion of the present author, angular motion does not aid target detectability against an unstructured background (especially when the observer is scanning a search sector) until the motion exceeds several degrees per second. A target crossing at a speed of 250 m/sec at a range of 5000m has an angular velocity of less than 3°/sec; such high angular rates are not common in the case of ground search. This opinion is based largely on the negative results of regression of residual detection in the AMTOC tests on the known angular velocities. Now, in a structured field, even with so simple a structure as a horizon within a degree of the target, there is reason to suspect that detectability increases. Consider the snake in the grass that is almost invisible until it moves slightly. This effect should be modeled but the author is unaware of any empirical investigations into the question.

g. Several Aircraft in Formation

There is no question that the presence of more than one aircraft in a small solid angle increases the probability of detection of at least one. Again, there is a certain amount of laboratory and field detection test data available that should help to quantify the effect. The author has not yet considered the problem.

h. Variation in C_t With Adaptation Brightness Level

Daylight brightnesses can vary from 10 to 10,000 ft-L, and there are available moderately accurate estimates of the variability of threshold contrast with this parameter. But there are several reasons for not including this effect in the model. The main reason is that the model user is reluctant either to specify the parameter or to add this as an extra variable to a study. The second reason is that contrast threshold levels do not change much over the wide range of daylight brightnesses. The present author is of the opinion that as long as the model's use is limited to daylight of unspecified brightness, the threshhold contrasts for the 75-100 ft-L level should be adequate.

i. Search in Two Dimensional Sectors

Laboratory data on the pattern of successive glimpses in searching square and circular sectors are available but have not yet been included in the model. It appears that, under conditions of natural search behavior, it is generally true that edges and center of sector are visited less frequently than a region midway between the two. The author hopes to incorporate this extension to the model but has not yet done so. If it appears that results of such a refinement are no different than the results of the assumption of random walk, the latter will be adopted.

j. Multiple Searchers

When the observer is part of a crew of several and the interest is in the first detection or probability that at least one detects the target, two questions arise.

1) On the assumption that all observers search the same sector, do they perform independently in a statistical sense? The author knows of no clear cut data which support either answer.

2) On the assumption that searchers do perform independently, should the searchers all take the entire field, or divide it up? The author has used the model to answer this question. The aircraft were of two sizes and flew a wide variety of straight and level paths.

Search involved two observers, both searching the same 120° x 10° sector in one case, and dividing the sector into two adjacent 60° x 10° sectors in the other. The cumulative probability over time that at least one detection occurs is almost the same using either technique.

6. MODEL REGISTRATION ON THE AMTOC-1 DATA

During June 1970, the US Marine Corps, the US Army Missile Command, and Braddock, Dunn and McDonald, Inc. participated in a field detection and tracking test of the Redeye air defense weapon against the F8 aircraft at Yuma, Arizona. This author is of the opinion that the test plan was very well conceived and executed. Most of the data needed for a detection model registration is available and apparently accurate. The key item missing is in-flight measurement of contrast; consequently that parameter has been free in the present study. All the necessary information is contained in references 25-29.

In all there were about 250 test runs. Each run lasted several minutes and involved 20-30 observers operating independently for the most part. The sequence of pertinent events is as described in Section 1. The four main test variables were:

1) Maneuver type (including straight and level at 500 and 1000 ft, dive @ 5 km, dive @ 10 km, climb @ 5 km, climb @ 10 km, and climb/dive combinations).

2) Offset range (nominally 0, 1.5, and 3 km)

3) Unmask range (5, 10, and 15 km), and

4) Search sector size (30°, 60°, and 120° in azimuth by roughly 10° in elevation).

Approaches were from a variety of compass points, not known in advance by the observers, but usually within the sector. On occasion, the pilot erred in approach azimuth or the test director erred in assigning search sector, with the result that the aircraft flew largely out of the assigned sector, providing valuable data on detections in the far periphery.

In selecting a registration set, the author limited himself to straight and level runs (in order to simplify inputs) and ruled out all runs for which :

1) Either the detailed a/c path or the individual detection time data for each observer was absent,

2) The questionnaire data indicated that too many observers were cued by sound, glint, or smoke trail.

The result is a set of 42 runs. Of the 42, ten are selected for presentation here. The inputs for the selected runs are shown in Table 5. The underlined contrasts in Table 5 represent time periods when the aircraft was verified to be viewed below the horizon against distant mountains.

TABLE 5. MODEL REGISTRATION INPUTS

Run No.	Search Sector Azimuth Extent (°)	Unmask Range (km)	Altitude (M)	Speed (M/sec)	Visibility (km)	Initial Contrast C_o and Changes (Sec After Unmask)
109	30	4.8	200	275	68.4	0.325
225	30	5.6	200	294	46.7	0.20, 0.39 @ 2.0
340	30	9.3	150	311	48.3	0.18, 0.13 @ 10, 0.25 @ 19
345	30	9.9	200	324	48.3	0.65, 0.45 @6, 0.43 @ 10
127	60	4.7	200	349	76.4	0.14, 0.12 @ 5.5, 0.10 @ 7.1
255	60	8.0	175	310	56.3	0.081, 0.183 @ 5, 0.10 @ 9, 0.117 @ 16, 0.20 @ 17.3
271	60	10.3	380	282	56.3	0.05, 0.195 @ 20, 0.18 @ 23.5, 0.30 @ 27
190	120	5.0	150	288	14.5	0.21, 0.30 @ 5.0
231	120	4.8	325	303	56.3	0.30, 0.11 @ 4.0
286	120	8.1	250	29[illegible]	56.3	0.075, 0.15 @ 5, 0.095 @ 10, 0.0[illegible] @ 16

In Figures 6 through 15 planview graphs of the search sector with aircraft path and direction superimposed are shown. The beginning of the path segment shown (opposite end from arrow) represents position at unmask. The end of the segment shown represents position at last detection. Below the planview is seen a comparison of actual detection frequencies versus time (solid line) and model predictions (dashed line).

In general the agreement is quite good, but it must be remembered that the author was free to select contrast values and changes thereto in order to fit the data best. The aircraft were painted mostly white with some black areas. Over the 42 runs in the registration set, the average of the intrinsic contrasts chosen to fit the data best was 0.22 during periods when the background was sky and 0.15 when the background was known to be terrain.

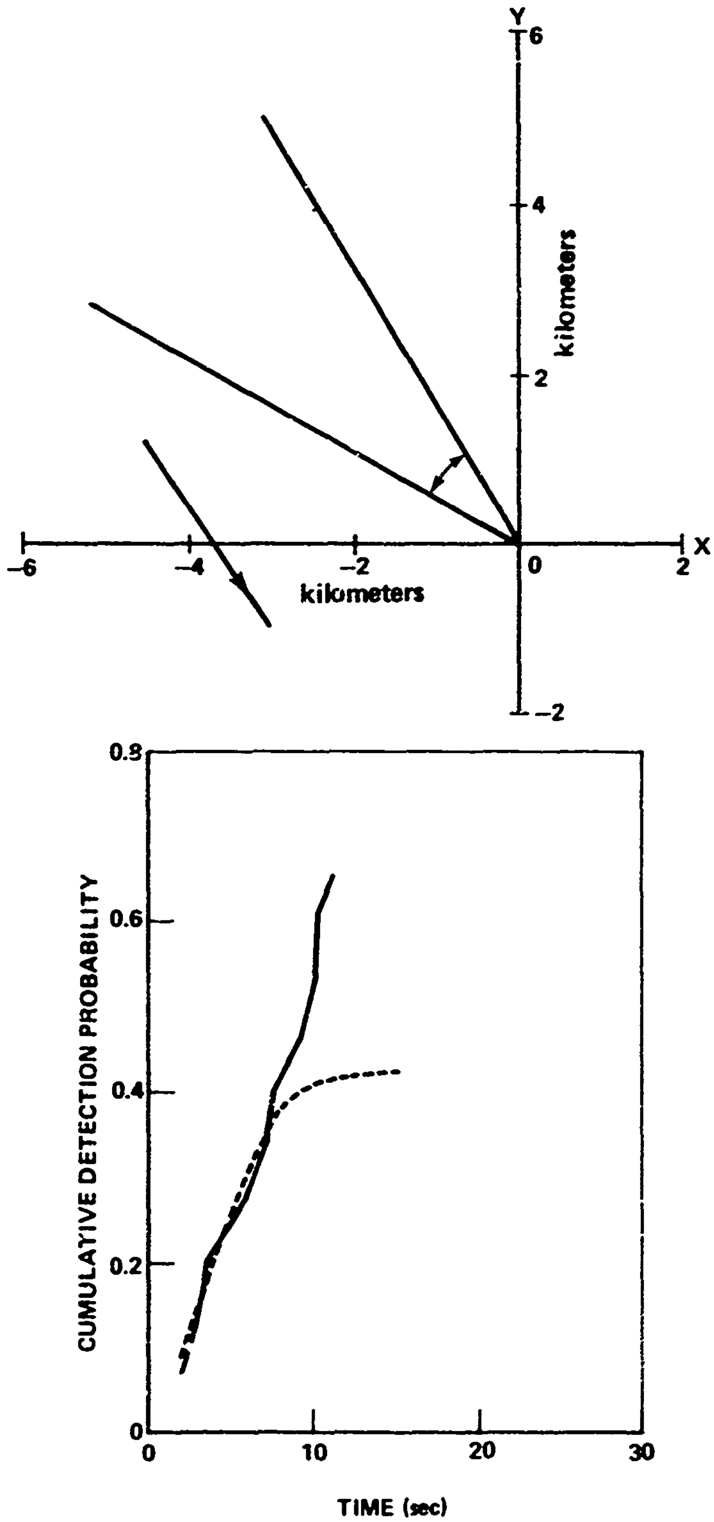


Figure 6. AMTOC Run 109.

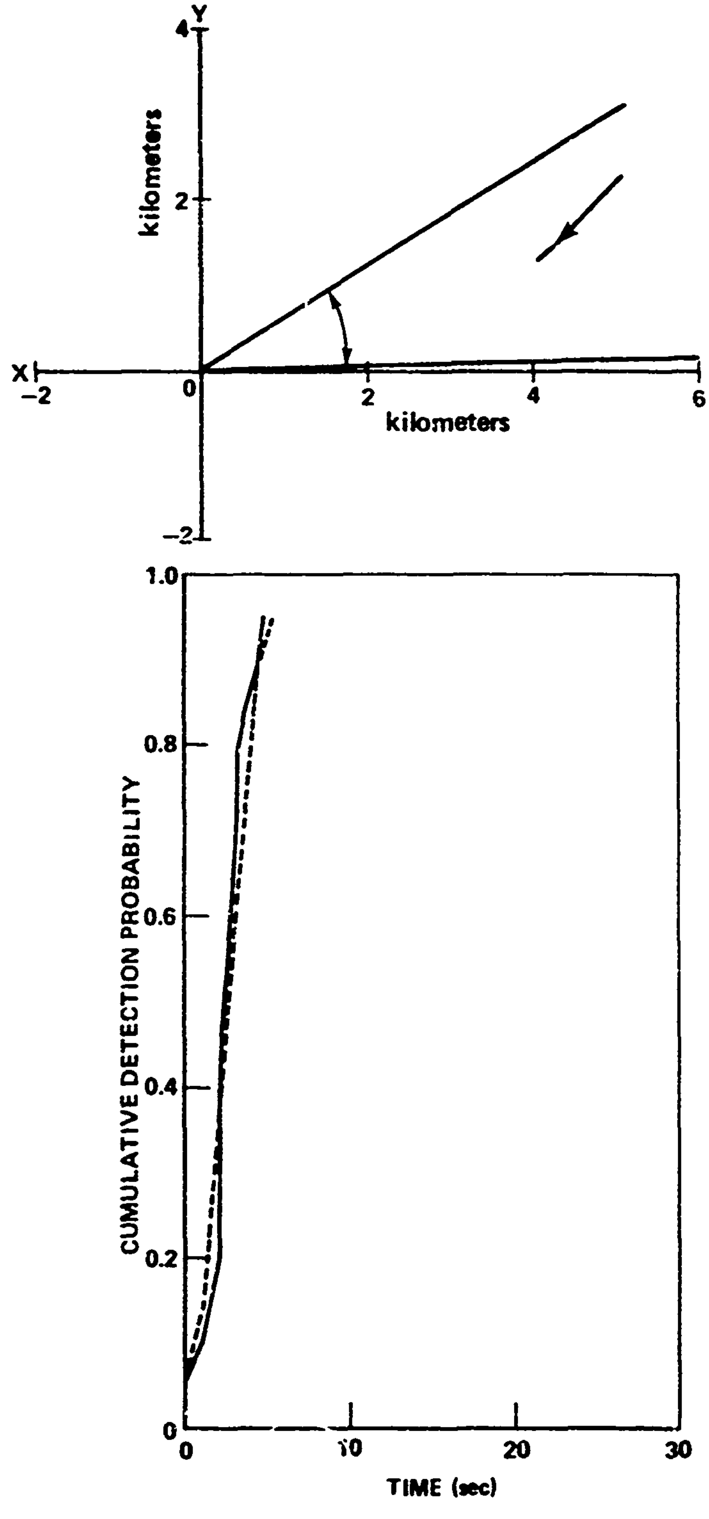


Figure 7. AMTOC Run 225.

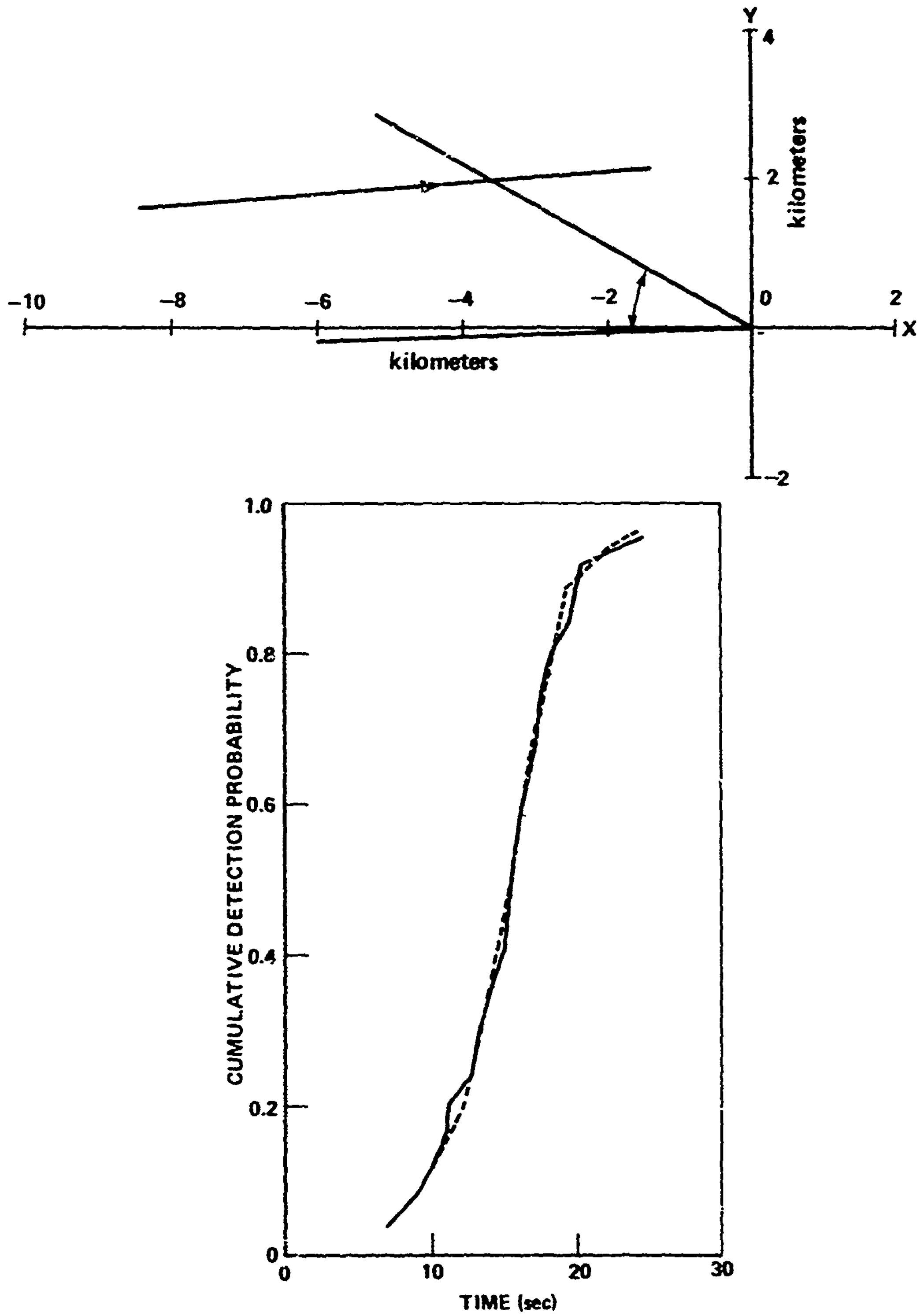


Figure 8. AMTOC Run 340.

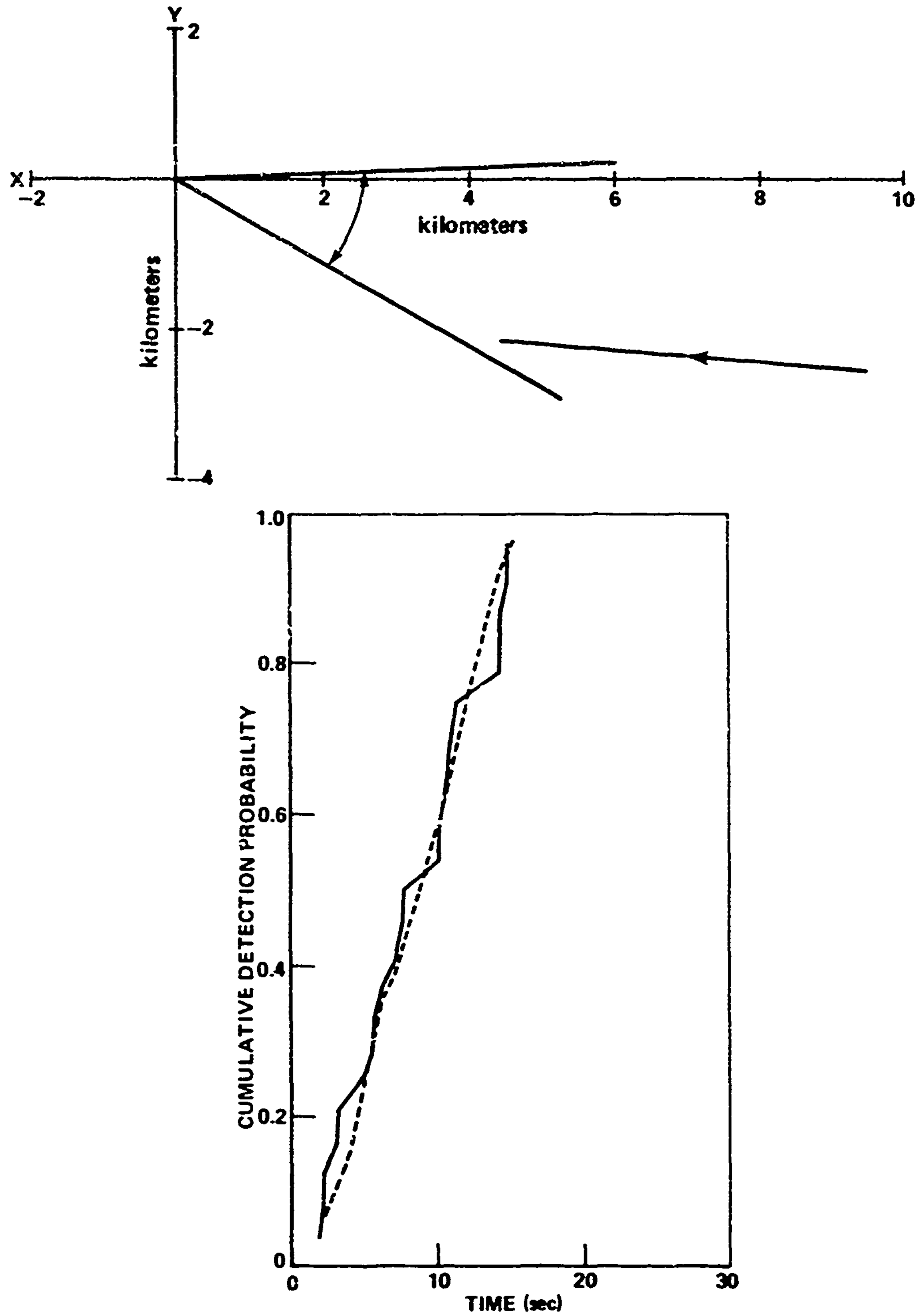


Figure 9. AMTOC Run 345.

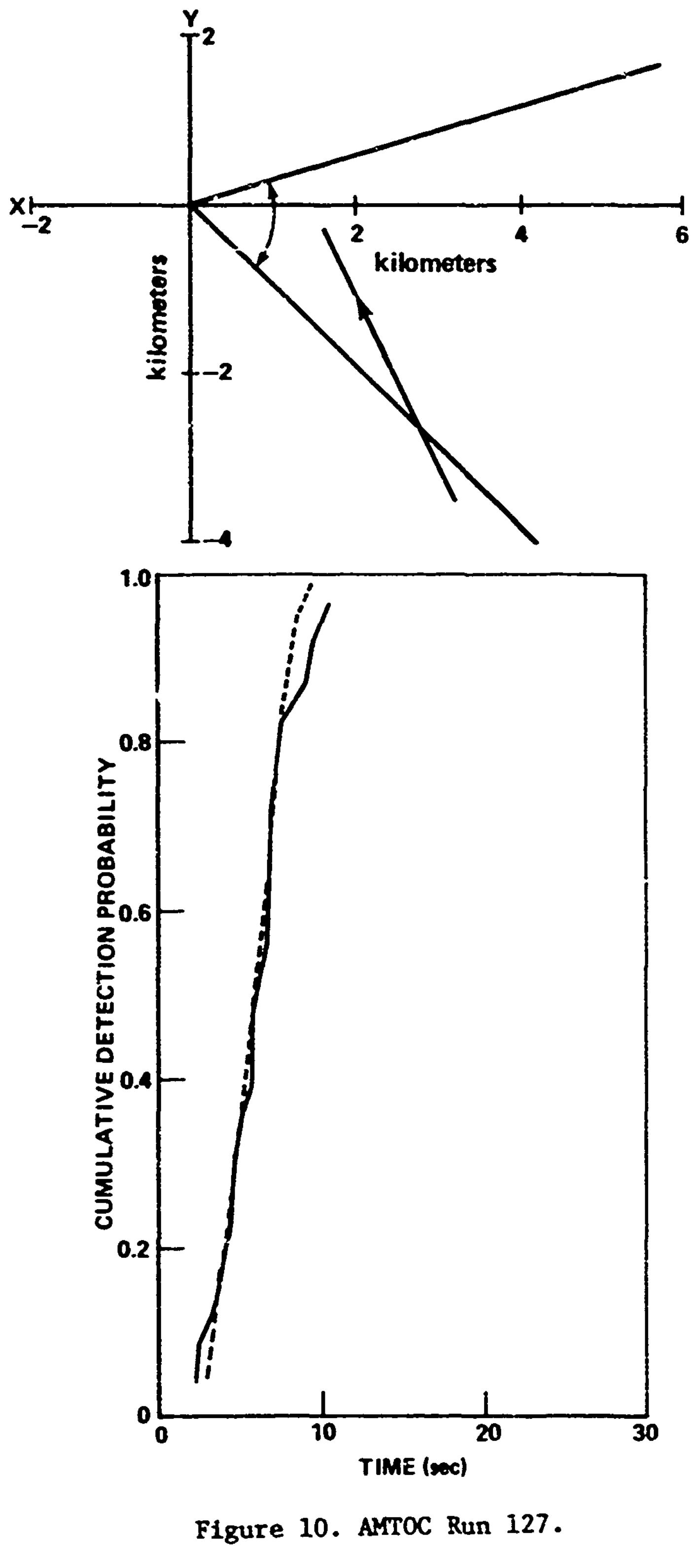


Figure 10. AMTOC Run 127.

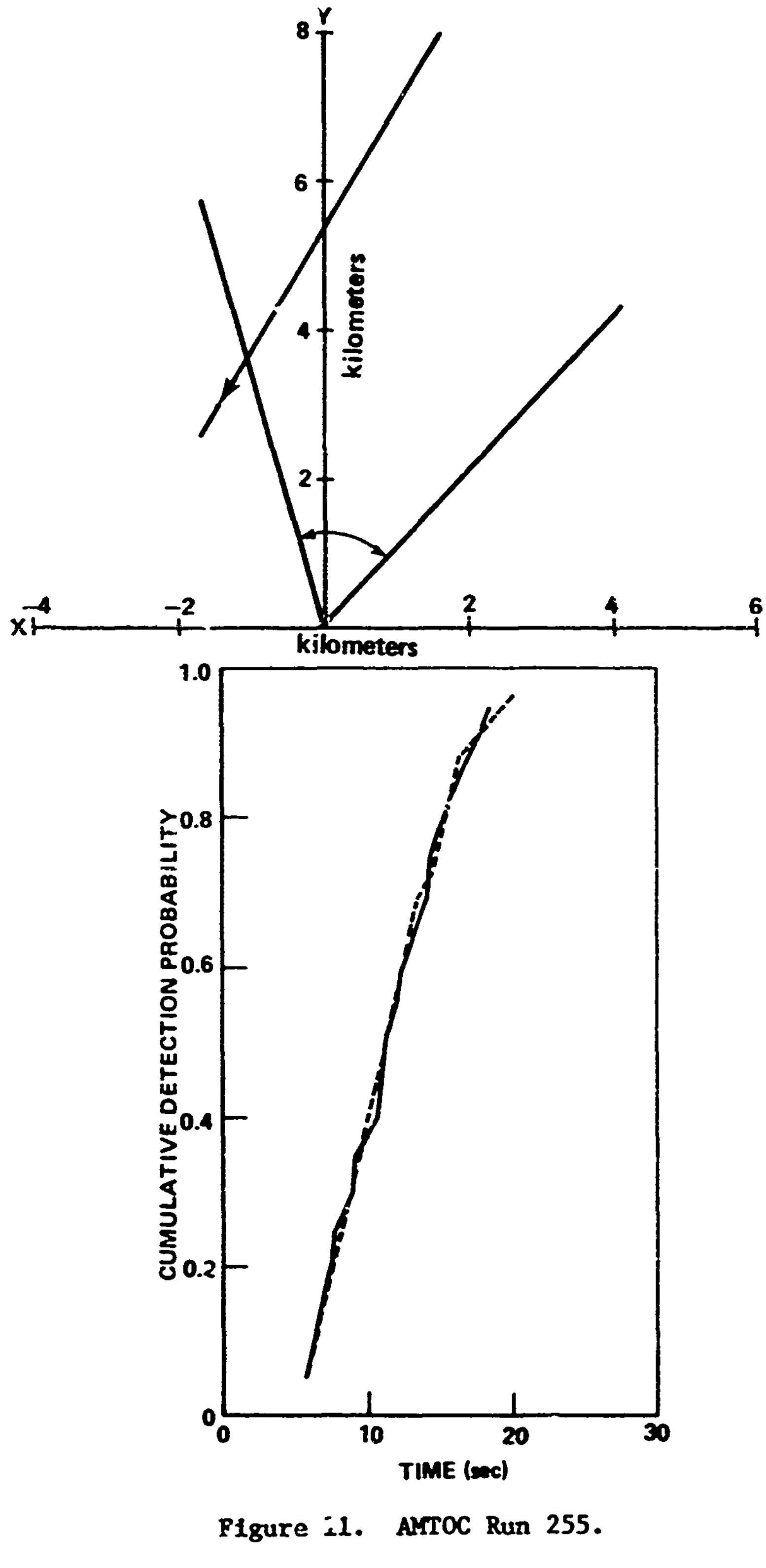
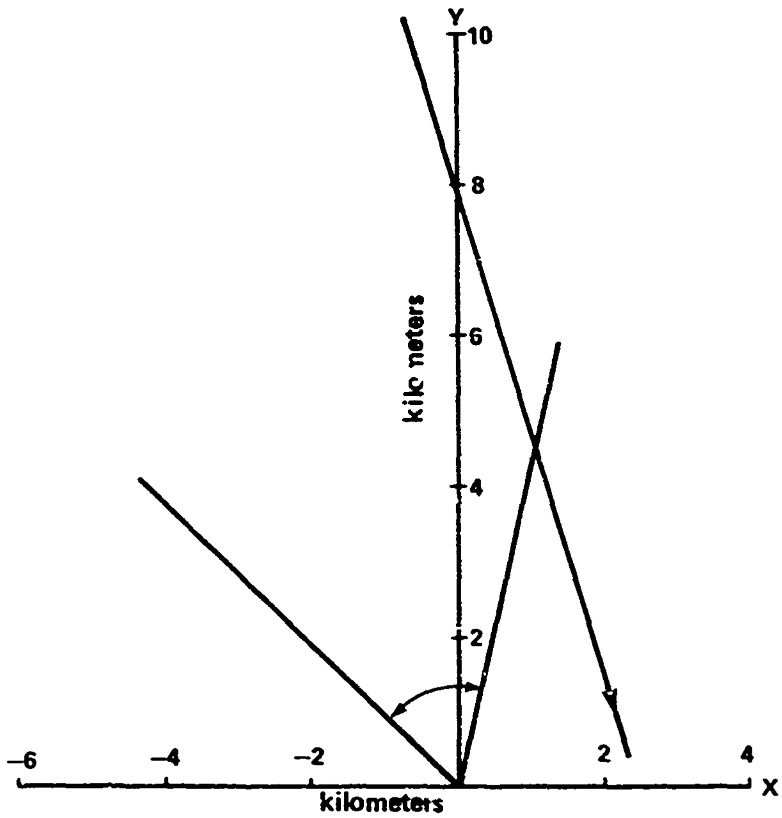


Figure 11. AMTOC Run 255.



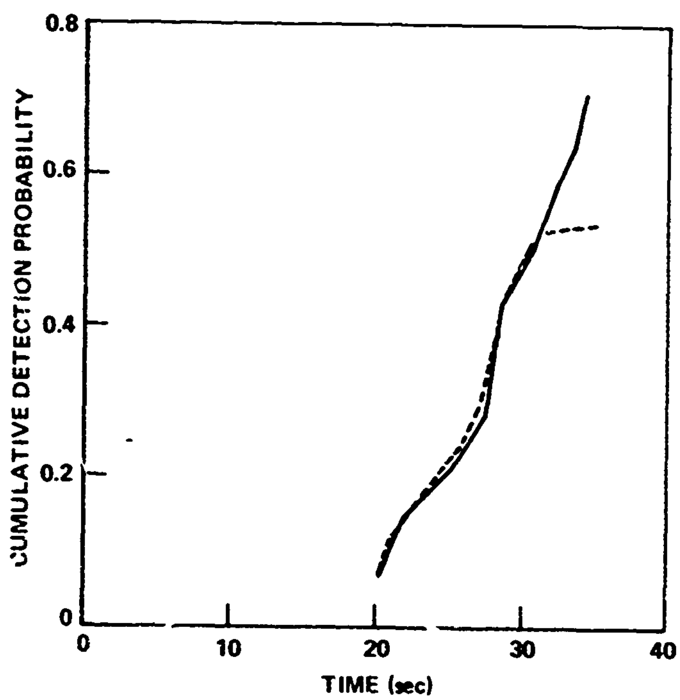


Figure 12. AMTOC Run 271.

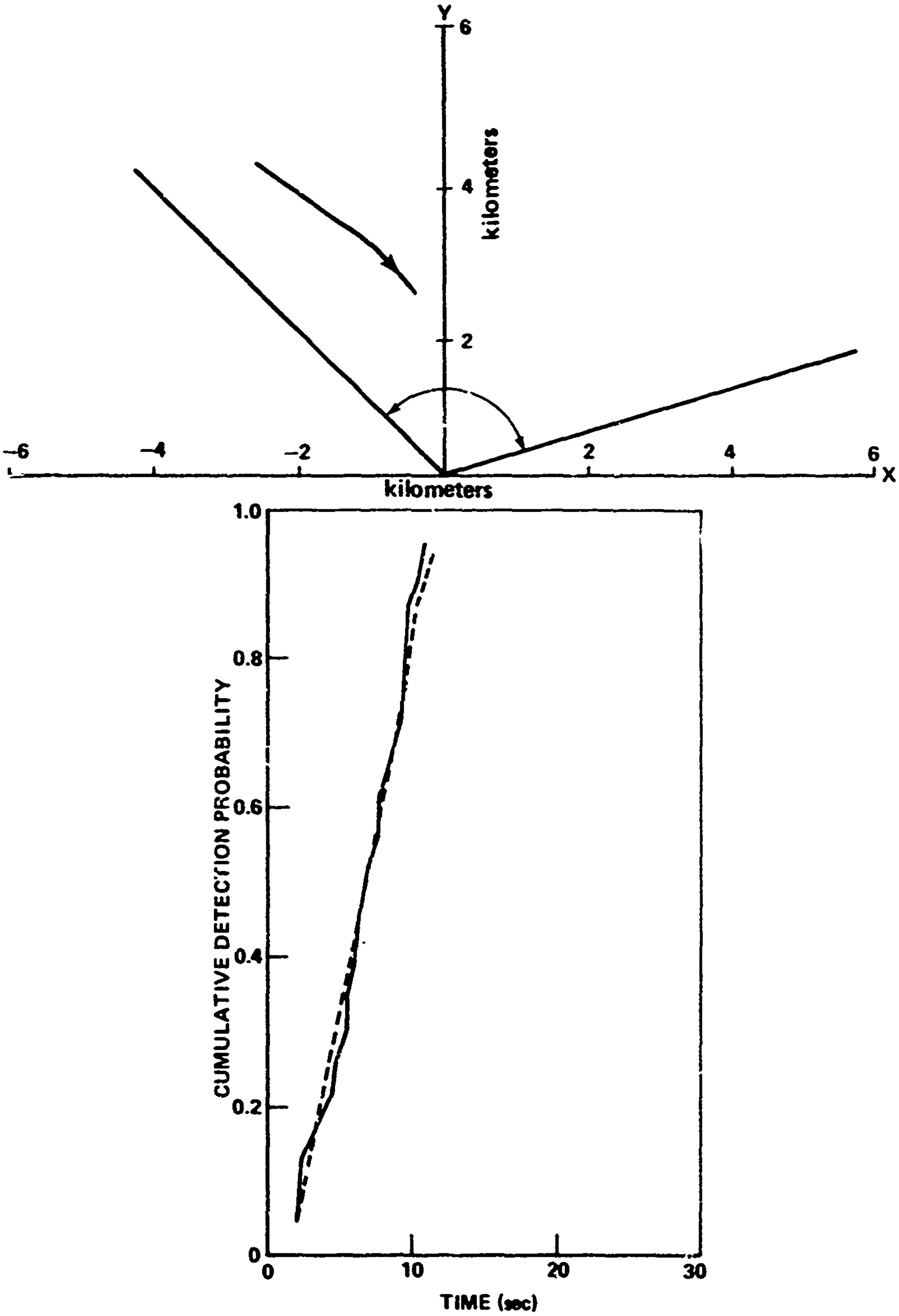


Figure 13. AMTOC Run 190.

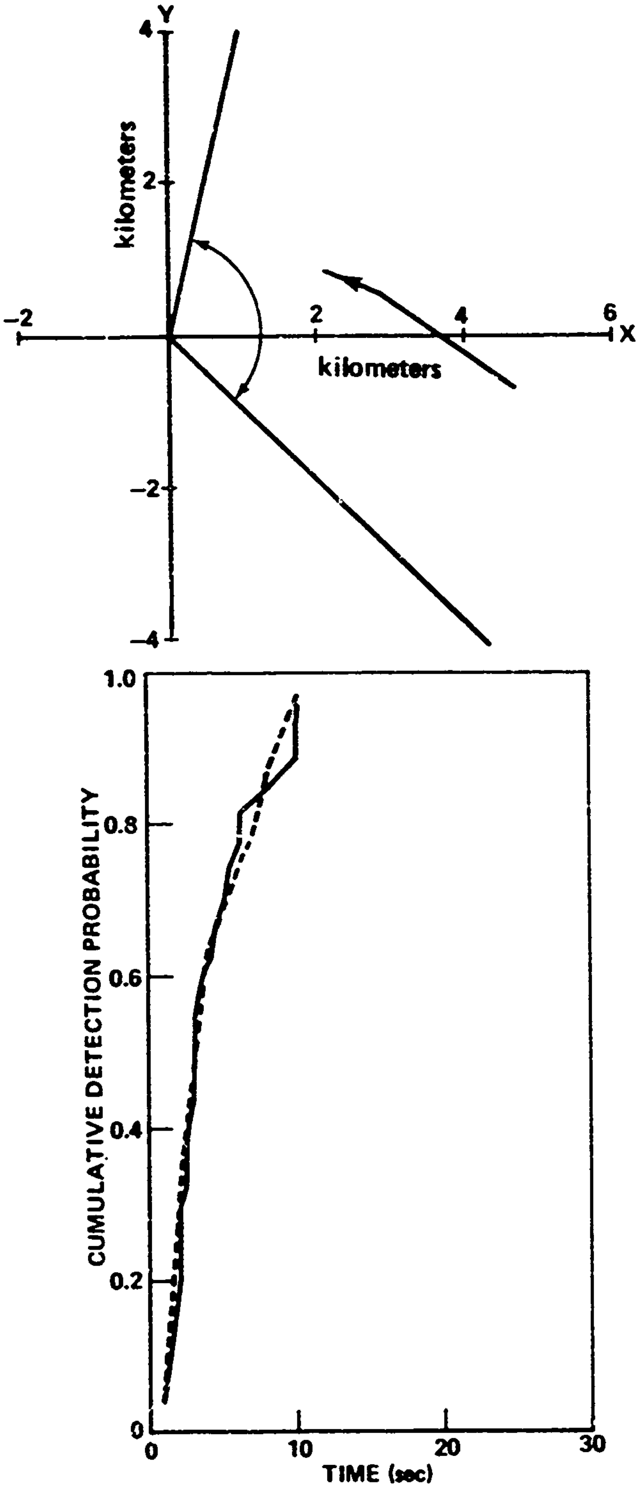


Figure 14. AMTOC Run 231.

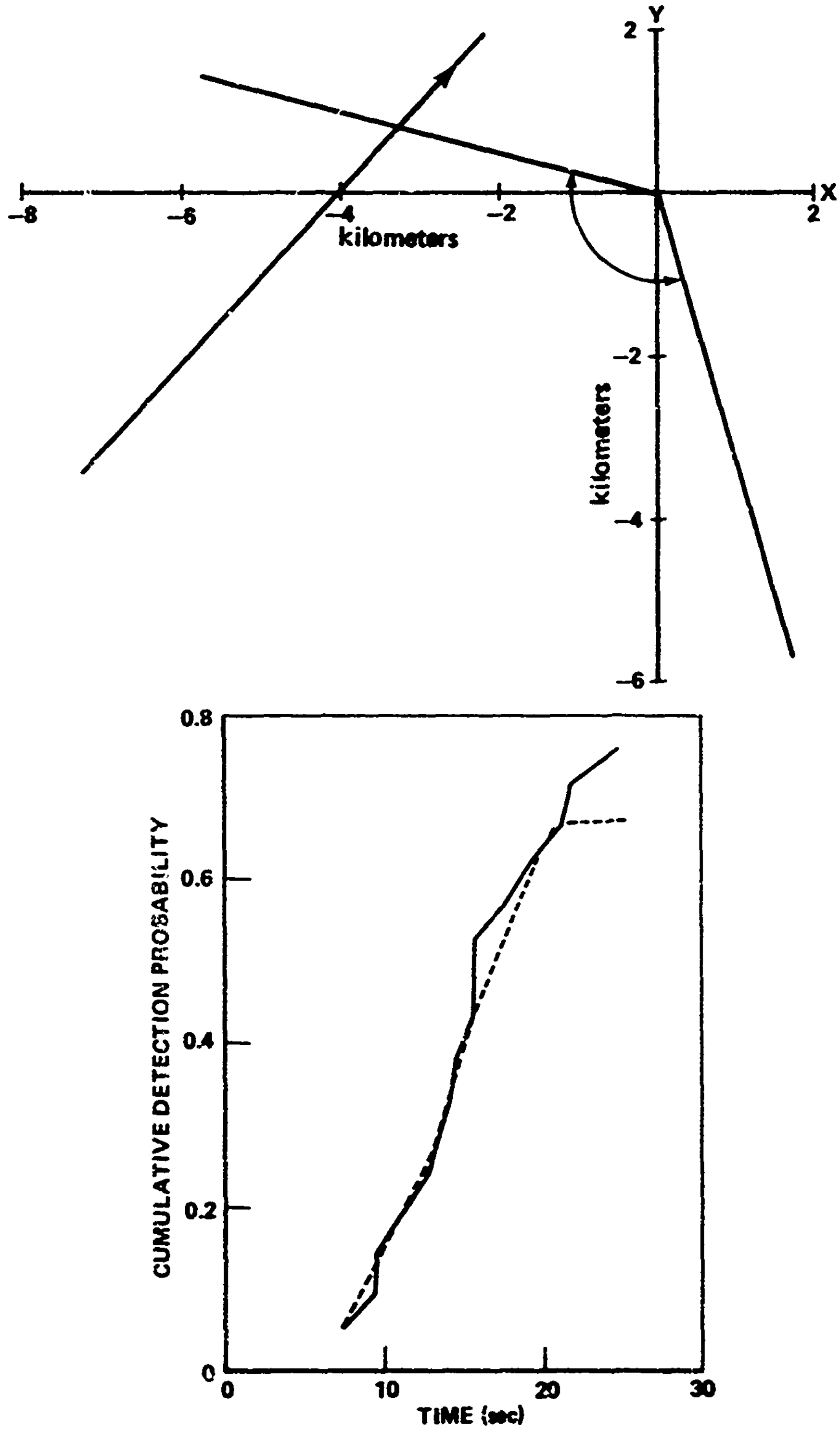


Figure 15. AMTOC Run 286.

REFERENCES

1. Cobb, P. W. and Moss, F. K., "The Fixational Pause of the Eyes," J. of Exper. Psychol., Vol IX, 1926, pp 359-67.

2. Leibowitz, H. and Bourne, L. E., Jr., "Time and Intensity as Determinants of Perceived Shape," J. of Exper. Psychol., Vol 51, 1956, pp 277-81.

3. Ford, A., White, C. T. and Lichenstein, M., "Analysis of Eve Movements During Free Search," J. Opt. Soc. Am., Vol 49, 1959, pp 287-92.

4. White, C. T. and Ford, A., "Eye Movements During Simulated Radar Search," J. Opt. Soc. Am., Vol 50, 1960, pp 909-13.

5. Baker, C. H., "Attention to Visual Displays During A Vigilance Task, I. Biasing Attention," British J. Psychol., Vol 49, 1958, pp 279-88.

6. White, C. T. and Ford, A., "Ocular Activity in Visual Search," in Visual Search Techniques, A. Morris and E. P. Horne, ed., NAS-MRC Publ 712, 1960.

7. White, C. T., "Ocular Behavior in Visual Search," in Visibility, S. Q. Duntley, Supplement to Applied Optics, Vol 3, No. 5, 1964.

8. Enoch, J. M., "Effect of the Size of a Complex Display Upon Visual Search," J. Opt Soc Am., Vol 49, 1959, pp 280-86.

9. Sugarman, R. C., Hammill, H. B. and Deutschman, J. N., "Simplifying Dynamic Visual Detection Simulations," Appendix A to Symposium Presentation at the Naval Training Devices Center, Calspan Corp., Orlando, Florida, 1971.

10. Middleton, W. E. K., Vision Through the Atmosphere, University of Toronto Press, 1952, 1958.

11. Duntley, S. Q., "Summary," in Visibility, S. Q. Duntley, Supplement to Applied Optics, Vol 3, No. 5, 1964, pp 551-56.

12. Lamar, E. S., "Visual Detection," Chapter 4, in Search and Screening, B. O. Koopman, Navy OEG Rpt. 56, 1946.

13. Cobb, P. W., and Moss, F. K., "The Four Variables of the Visual Threshold," J. Franklin Inst., Vol 205, 1928, pp 831-47.

14. Blackwell, H. R., "Contrast Thresholds of the Human Eye," J. Opt. Soc. Am., Vol 36, 1946, pp 624-43.

15. Lamar, E. S., et al, "Size, Shape and Contrast in Detection of Targets by Daylight Vision, I," J. Opt. Soc. Am., Vol 37, 1947, pp 531-45.

Preceding page blank

16. Lamar, E. S., et al, "Size, Shape and Contrast in Detection of Targets by Daylight Vision, II," J. Opt. Soc. Am., Vol 38, 1948, pp 741-55.

17. Blackwell, H. R. and McCready, D. W., "Foveal Contrast Thresholds for Various Durations of Single Pulses," U. of Michigan, Rpt ERI 2455-13-F, June 1958.

18. Blackwell, H. R. and Moldauer, A. B., "Detection Thresholds for Point Sources in the Near Periphery," University of Michigan, Rpt 2455-14-F, June 1958.

19. Taylor, J. H., "Contrast Thresholds as a Function of Retinal Position and Target Size for the Light-Adapted Eye: II, Data Supplement," Scripps Inst. Oceanog. SIO Ref. 63-3, Feb 1963.

20. Sloan, L. L., "Area and Luminance of Test Object as Variables in Examination of the Visual Field by Projection Perimetry," Vision Research J., Vol 1, 1961, pp 121-38.

21. Seyb, E. K., "A Mathematical Model for the Calculation of Visual Detection Range," SHAPE Technical Centre, TM-152, March 1967.

22. Davies, E. B., "Contrast Thresholds for Air-to-Ground Vision," British RAE-TR No 65089, April 1965.

23. Davies, E. B., "Visual Search Theory with Particular Reference to Air-to-Ground Vision," British RAE-TR No. 68055, March 1968.

24. Blackwell, H. R., "Neural Theories of Simple Visual Discrimination," J. Opt. Soc. Am., Vol 53, 1963, pp 129-60.

25. Braddock, Dunn and McDonald, "USMC LADS Test - Data Book No. 2, Questionnaire Comments," (BDM) Rpt BDM/A-86-70-TR, 18 Aug 1970.

26. Braddock, Dunn and McDonald, "USMC LADS Test - Data Book No. 3, Miscellaneous Data," BDM/A-90-70-TR, 21 Aug 1970.

27. Braddock, Dunn and McDonald, "USMC LADS Test - Data Book No. 4, Preliminary Questionnaire Data," BDM Rpt. BDM/A-91-70-TR, 27 Aug 1970.

28. Braddock, Dunn and McDonald, "USMC LADS Test - Data Analysis Working Papers - Event Data," BDM Rpt BDM/A-7-71TR, 7 Jan 1971 (Confidential).

29. Braddock, Dunn and McDonald, "USMC LADS Test - Data Analysis Working Papers - Graphical Data," BDM Rpt. BDM/A-9-71-TR, 7 Jan 1971 (Confidential).