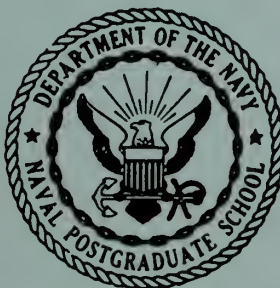# UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

VISUAL DETECTION OF VEHICULAR TARGETS FROM
ATTACK AIRCRAFT

by

C. H. Brown

VISUAL DETECTION OF VEHICULAR TARGETS

FROM ATTACK AIRCRAFT

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Charles H. Brown

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FROM ATTACK AIRCRAFT

by

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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

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Monterey, California
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ABSTRACT

Attack aircraft on interdiction or deep support missions are faced with the problem of detecting their targets by visual means. Much has been written about the general theory of computing detection probabilities associated with visual detection and some experiments have been performed to get estimates of the detection probabilities for small tactical targets observed from the air. Applying the theory to a special case involving the detection of a stationary tank by a relatively high speed aircraft, a lateral range curve of detection probabilities is computed in this paper. This is compared with (1) lateral range curves from an experiment conducted by the University of Michigan in the field and over a terrain simulator and (2) lateral range curves constructed from data taken in an operational experiment conducted with USNPGS personnel in conjunction with a CDEC tactical exercise.

The detection probabilities and maximum sighting ranges observed in the operational experiment are significantly below those predicted by the theory and the Michigan experiment described in this paper. It is recommended that further operational type experiments be conducted to provide accurate data for obtaining detection probabilities and maximum sighting ranges which can be used for operational planning purposes.

PREFACE

This thesis is concerned with the probability of visual detection occurring in the process of search for vehicular tactical targets by attack aircraft. It offers a comparison of the probability predicted by a theory, probabilities predicted and observed in an experiment conducted by the University of Michigan Vision Research Laboratories and probabilities observed in an operational experiment conducted by the writer.

The operational experiment was conducted with the cooperation of the Combat Development Experimental Center of the Army located at Fort Ord, California, the Aviation Department of the U. S. Naval Postgraduate School and the Naval Aviators of the Postgraduate School who volunteered to act as pilot observers for the experimental flights.

I wish to express my appreciation for the encouragement offered by Mr. Norman L. Thoburn of Project Michigan, Mr. Laurier E. Parent, of Stanford Research Institute who are presently working with the research staff of CDEC. I am indebted to Professors W. P. Cunningham and F. F. Sheehan for their guidance and encouragement while acting as faculty advisors.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd)

GLOSSARY

B_t Target luminance(brightness)--Intensity of light per unit area from target

B_t^i Background luminance(brightness)--Intensity of light per unit area from background

B_m Sky luminance(brightness)--Intensity of light per unit area from sky

B_m/B_t^i Sky-ground ratio--Ratio of sky and background luminances

C_o Inherent contrast--Defined as: $C_o = \dfrac{B_t - B_t^i}{B_t^i}$, a comparison of target and background luminance

C_r Apparent contrast--Contrast of target observed at some range from the target where inherent contrast has been reduced by atmospheric effects

C^1 Adjusted inherent contrast--Defined as: $C^1 = C_o/B_m/B_t^i$

C_t Threshold contrast of the eye--Minimum contrast which can be distinguished by the eye. Varies for individuals

$\ominus$ Target's angle off the visual axis(Percention angle)--Angular measurement in degrees of the target's location with respect to the visual axis

     Visual axis--The axis of the line of sight.

$\ominus_f$ Foveal off axis angle--Maximum angle off the visual axis at which a target may be detected at maximum range

A Target area

$\overline{A}$ Effective target area--Target area reduced by atmospheric effects

$\propto$ Solid angle subtended by the target at the eye

V   Meterological visibility--Generally the maximum distance at
             which large targets such as mountains
             or high coastlines can be seen against
             the sky (Koopman, p. 53)

R   Slant range

$\overline{R}$ Maximum optical slant range--Slant range reduced by atmos-
             pheric effects

R_h Horizontal range

R_m Maximum horizontal range

h   Observer height

h_o Atmospheric constant--10^4 is the accepted value at the height
             where the ratio of air molecules to the
             number at sea level is 1/e.

H   Height factor--Defined as: $H = h_o/h \, \overline{\underline{[} 1 - e^{-h/ho} \underline{]}}$

$\ominus_e$ Observer elevation angle relative to the target

τ Glimpse time--Time required for an observer to become aware of
             a target that he "sees"

$\textcircled{H}$ Search arc possible to an observer

1.   Introduction.

This thesis is a comparison of estimates of detection probabilities associated with the process of visually detecting a stationary vehicle from an attack aircraft. The methods of estimating the probabilities differ widely as do the resulting values determined. It is hoped that this paper will indicate an effective approach for arriving at values of detection probabilities which are accurate enough to be used as operational planning factors.

The weapons system of interest in this paper is the manned attack aircraft. It is presently the main component of the striking force of the navy. With the introduction of Polaris into the fleet the importance of the manned aircraft in a general war will be reduced, but it will remain of prime importance in conducting the strike missions required in limited war.

Assume that in a limited war manned attack aircraft missions will be:

1. Counter air--Attack and destroy or neutralize enemy airfields and associated aircraft

2. Interdiction--a. Attack and destroy points of concentration in the enemy supply and communication network
b. Locate, attack and destroy vehicular traffic along the routes of the above network

3. Direct support of ground forces--a. Close air support with direct control of air strikes by the supported ground forces
b. Deep support--Locate, attack and destroy tactical targets capable of directly affecting friendly forces but with which our forces do not have contact

In conducting the missions of (1) interdicting traffic and (2) deep support, which will be classed together as armed reconnaissance, the attack aircraft must be capable of detecting the targets, vehicles and other tactical targets, as well as destroying them. In both situations it is likely that the targets will be stationary, for the enemy will know of the threat of air strikes and will tend to cease movement during daylight hours.

In order to locate targets various sensing devices are available or are in the process of design, evaluation and installation in aircraft. These include infrared devices, high resolution radar, television, photography and visual detection by the eye. All of these systems are capable of detecting the targets of interest in armed reconnaissance missions with different degrees of effectiveness. However, at present, visual detection of the target by the pilot of an attack aircraft is the only operational system which is of value in locating targets which are capable of motion even though they are stationary at the time of detection. It is the only means which enables the pilot of the attack aircraft to attack immediately after detection, thereby giving the target no chance to move and create a new search problem. However unsophisticated visual detection may be, it is still important.

This paper describes a theoretical method of computing visual detection probabilities, presents a description of a University of Michigan visual experiment which determined detection probabilities and offers data and conclusions obtained from an operational experiment conducted

2

by the writer to obtain values of visual detection probabilities for tactical targets.

The paper does not include the evaluation of the problem of detection when it is necessary for the observer to report the target positions after returning to base.

2. Visual Detection Theory.

The study of the theory of visual detection must consider the process by which the eye sees objects. Details of the physiology of detection by the eye are presented in references (c) and (d) with a brief sketch of the process being given in Appendix I of this paper. The eye's ability to see an object, the target of interest, is affected by several variables. Laboratory experiments have led to the belief that the primary variables are: [d]

1. Target-background contrast[2]

2. The solid angle subtended by the target

3. The off-axis angle of the target and the eye's perception angle

4. Target shape

Determining the Maximum Horizontal Range of Detection

There is a minimum value of the threshold contrast of the eye necessary for the eye to detect the target. [g] The inherent contrast of the target is the contrast of the target with its background when it is viewed at extreme range, with very little atmosphere between the observer and the target. As the distance between the target and observer is increased the inherent contrast is reduced, due to the reduction of light from the target transmitted through the atmosphere. At some extreme maximum range the contrast of the target reduces to the minimum or threshold contrast of the eye and that range is the maximum range of detection for the target.

An equation may be set up involving the essential variables of the

visual detection process presented above. (c) This equation may be
solved for the maximum visual range. This equation considers these
variables:

1. Atmospheric conditions

2. Meterological visibility range

3. Luminance levels

4. Size and inherent contrast of the target

5. Height of the observer

The solution of the equation is based on these assumptions: (c)

1. The atmosphere is composed of optically standard stratified layers

2. There is uniform sky illumination

3. The sun's directional effect is ignored

4. All observers are giving optimum performance while searching

      Appendix I describes a method of using a nomograph giving solu-
tions of the equation under various conditions. (c) An example is set
up for calculations of R_h, which have been made and are presented in
Figure 1. The inputs of the calculations of the example were:

1. Assumed targets: Tank and jeep

2. Sky-ground ratio: 2.5 (Forest on a bright day) (c)

3. Inherent target contrast: .125, .25, and .50(a reasonable range
                        of values)

4. Meterological visibility: 30 miles

      Figure 1 indicates that the range of detection is reduced as the
target inherent contrast becomes smaller in absolute magnitude. Opti-
mum altitudes for search are also indicated by this theoretical approach

MAXIMUM HORIZONTAL RANGE OF DETECTION

FIGURE 5

ALT., h (ft)

HORIZONTAL RANGE, R_h (yds)
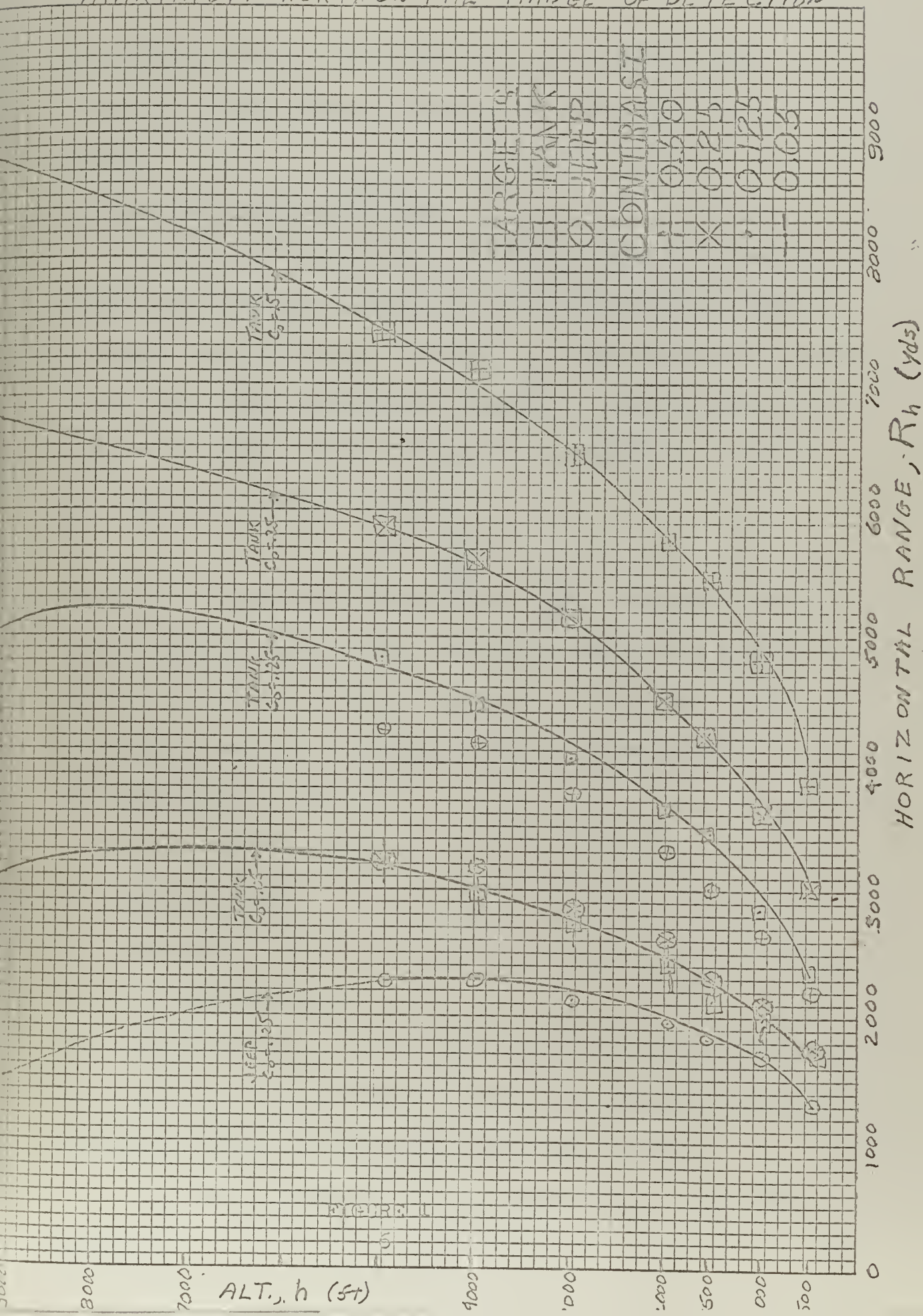
for obtaining maximum range of detection. For the target of large

contrast value, this maximum falls at heights greater than those

plotted.

Determining Detection Probabilities

The visual perception angle of the eye is defined as the maximum

angle off the visual axis of the eye at which the eye can see a target. [a]

This angle varies with range. Generally, the greater the range the smaller

is the angle. This is established in Appendix I. The relationship of the

angle and the range is shown in Figure 2. The probability of detection

of a target in one glimpse is defined as:

$$g_i = \frac{\partial \zeta}{\textcircled{H}}$$

where, g_i, is the glimpse probability and, $\textcircled{H}$, is the arc of the ob-

server's possible circle of vision. Using this quantity as a basis, it is

possible to derive, as is shown in Appendix I, an expression for the

probability of detection of a target at any given lateral range. [b]

The expression is in terms of:

1. Maximum horizontal range

2. Observer's speed

3. Glimpse time

4. Visual perception angle

The maximum horizontal range was affected by the height of the observer,

the target size, the ratio of range to meterological visibility and the tar-

get contrast so these parameters also affect this expression.

The example presented previously is extended to include these

conditions:

1. Target: Tank

2. Inherent contrast: -.125

3. Observer height: 1500 and 5000 feet

4. Observer speed: 200 and 400 knots

Figure 2 presents the lateral range curves computed by the method of Appendix I for the above conditions. It is the representation of the final results of the theory showing the probability of detection of a target and indicating the maximum possible range of detection.

THEORETICAL LATERAL RANGE CURVES

FIGURE 2

TGT AREA: 150 S·ɣ²

C_o = .125

200 kts
h = 5000'
n = 1500'

100 kts
5000'
1500'

LATERAL HORIZONTAL RANGE (yds)

700   1400   2100   2800   3500   4200   4900

9
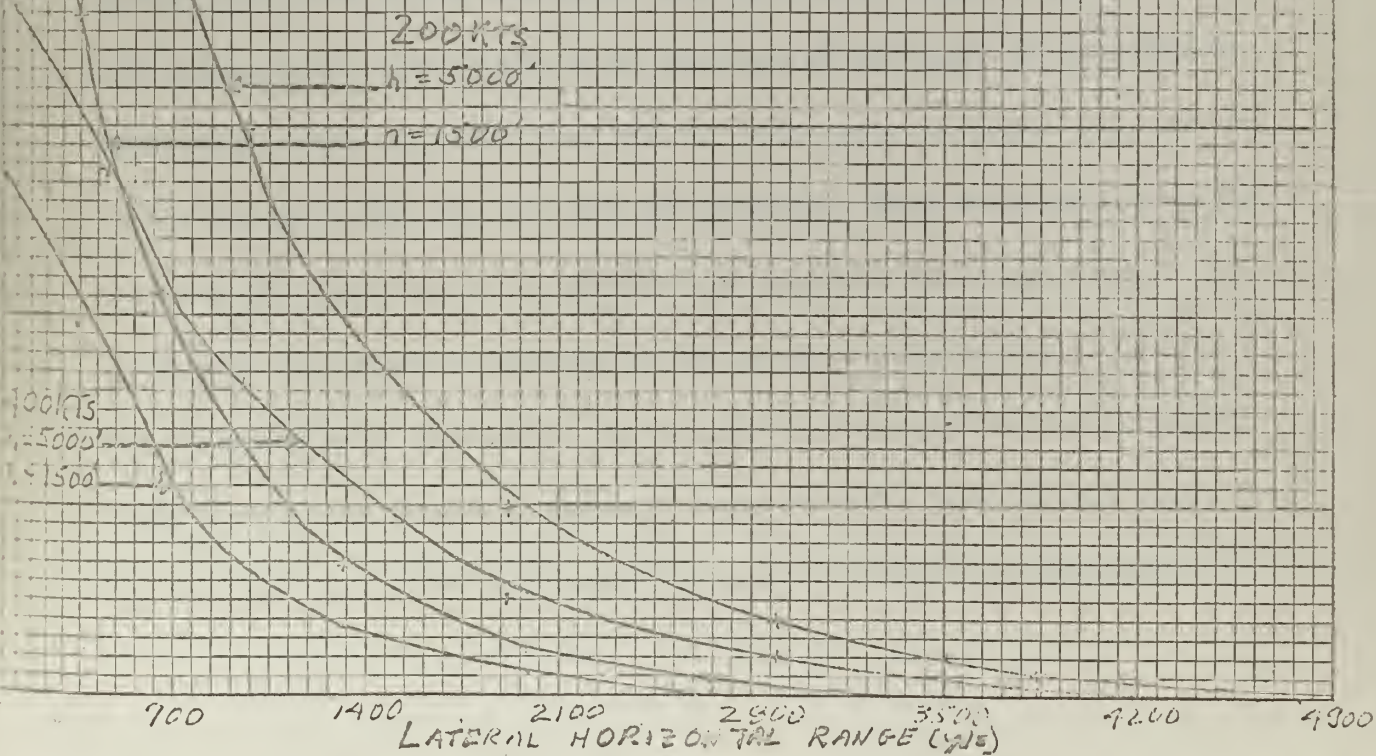
3.   The Michigan Experiment [i]

The University of Michigan Research Institute Vision Research
Laboratories conducted field and simulator studies of air-to-ground
visibility distances and detection probabilities. These studies were
reported in December, 1958. This project was conducted for the Navy
Bureau of Aeronautics to provide quantitative information on visibility
ranges of a vehicular target complex viewed against asphalt, grass and
dirt backgrounds from an aircraft, for varying flight altitudes and air-
craft flight path attitudes with respect to the sun.

Naval aviators flying SNB-5P aircraft acted as observers in the
field tests. The same aviators acted as observers in the later simu-
lator tests. The target in the tests was a vehicle convoy composed of
a 1/4 ton jeep, a 1/2 ton pickup truck and a 2 1/2 ton stake truck, all
painted standard Navy grey. Before each run the convoy was positioned
in a small state park, an area about one mile on a side. The target was
parked alongside one of the roads with no attempt made to conceal it.
109 flight passes were made at an airspeed of 130 knots at altitudes of
2000,4000,5700, and 7500 feet and for flight path attitudes with respect
to the sun of 3, 45, 90, 122 and 177 degrees. After each run the target
was moved to another of ten possible positions in the search area. On
each pass the observer reported to the target convoy by radio when he
felt he recognized the target. At the time of the radio report the pilots
photographed the terrain underneath their aircraft. Also at that time, a
transit elevation angle was marked making possible the computation of

the slant range of the aircraft from the target. This was checked against the range determined by photo interpretation of the terrain photographs taken at the time of recognition from the aircraft.

Simulation of the experiment was attempted. A model of the search area was produced with which it was possible to duplicate search altitudes and sun position as well as the terrain features and target position. There were 840 simulated passes made at the same altitudes and most of the attitudes as were used in the field tests.

In both the field and simulator passes the observers were briefed on the probable targets and the probable target positions. In fact, it was especially apparent in the simulator tests that the observers searched the known probable target locations almost exclusively.

The recognition ranges and recognition probabilities obtained in the field tests were not as great as those obtained in the simulator. This is shown in Figure 3. This difference is felt to be due to factors existing in the field tests which could not be duplicated in the simulator. One factor was the lack of distractions in the simulator which would occur to the pilot-observer in the aircraft.

By methods described in Appendix II theoretical curves of the detection probabilities as a function of slant range for various flight altitudes and flight path attitudes with respect to the sun were constructed and are shown in Figures 4 and 5.

Conclusions

For a search altitude of 2000 feet the maximum horizontal range for
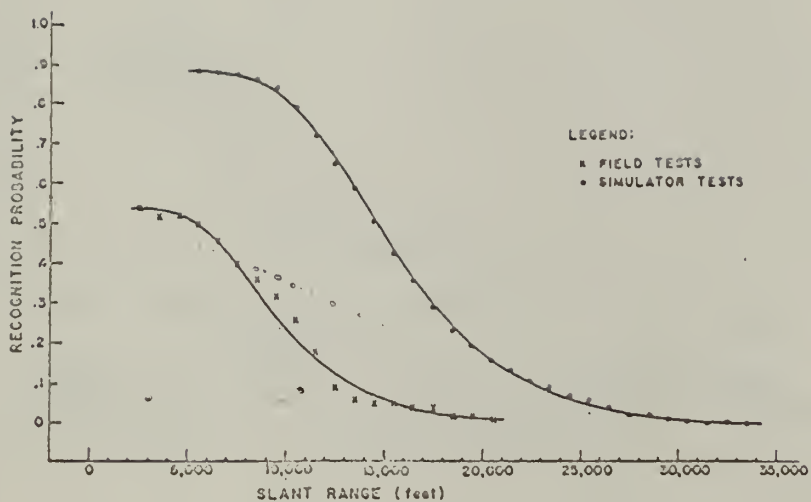
Data: Recognition probability as
a function of slant range: field and
simulator data

FIGURE 3

ALL VALUES OF FLIGHT ALTITUDE

Fig: 4 . Theoretical curves: Recognition
probability as a function of slant range:
All values of flight altitude.

ALL VALUES OF FLIGHT ATTITUDE
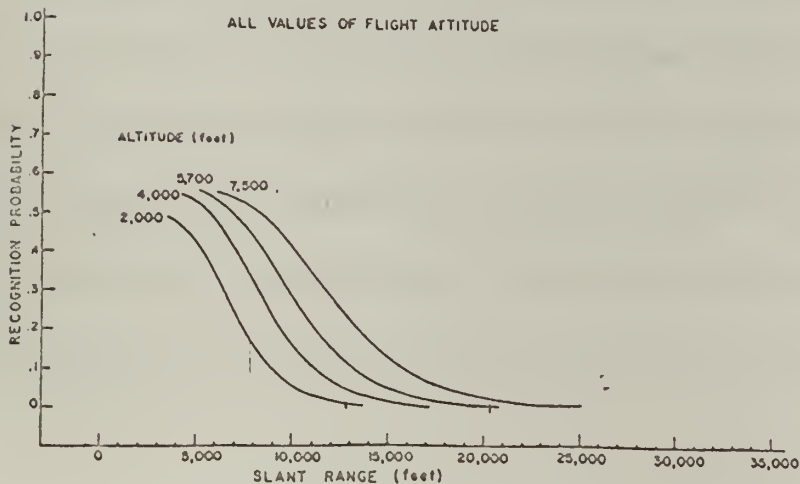
Fig: 5 . Theoretical curves: Recognition
probability as a function of slant range:
All values of flight attitude.
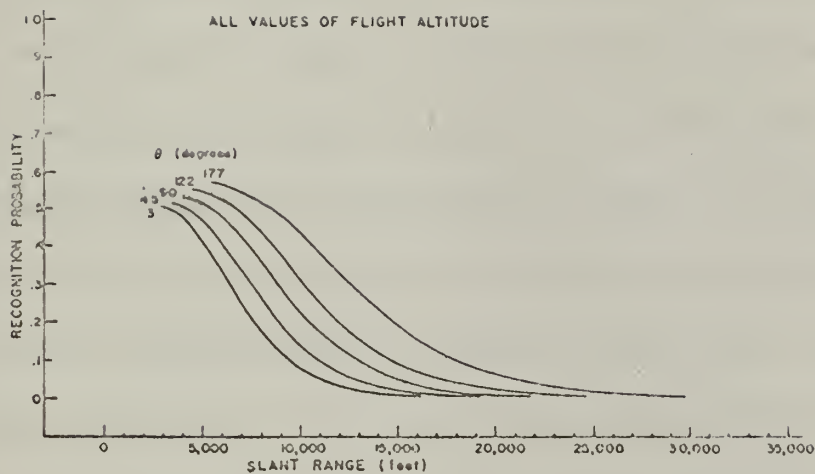
recognition was found to be 4280 yards. The detection range was somewhat longer. (See Appendix II for explanation of the difference of detection and recognition ranges). For an altitude of 5700 feet the maximum horizontal detection range was slightly over 4170 yards. These ranges are shorter than those predicted by the theory. The detection probability at the search altitude of 2000 feet was 0.49 and at an altitude of 5700 feet the maximum detection probability was 0.58. These probabilities were approximately the same as those predicted by the theory for search airspeed of 200 knots. The probabilities predicted by the theory for a search speed of 130 knots would be approximately 0.70. The effects of the variables which are not accounted for in the theory may be the cause of these differences; however, it is not possible to single out the ones responsible. Note that as the process used to predict detection probabilities approaches the conditions faced by an aviator in an operational situation, the detection probabilities are reduced; field tests results are smaller than simulator, simulator tests results are smaller than theory. It is important to note also that this experiment did not match operational conditions since it was performed with slow aircraft and with observers well briefed on possible target positions.

4. The Operational Experiment

Since there was so little data on detection probabilities of tactical
targets by visual search in a tactical environment, it was hoped that an
operational experiment could be performed using the men and aircraft
available in the Postgraduate School vicinity. Permission was obtained
from the Combat Development Experimental Center of the Army for Navy
aircraft to overfly the area where an operational field experiment simu-
lating a land battle was being conducted. Data was to be obtained on
the number of targets observed from the aircraft. Permission was also
obtained to use the ground vehicle position reports which were made for
the CDEC experiment so that a comparison could be made of the number
of vehicles sighted from the air and the number of vehicles which were
actually there.

The flights simulated the mission of a single seat attack aircraft
searching an area for vehicular targets such as tanks, personnel carriers
and trucks, which would appear as targets of opportunity to an aircraft
on an armed reconnaissance mission. The flights were made in T-28
aircraft. The flights were conducted at 200 knots airspeed. The effect
of the wind was neglected. An altitude of 1500 feet was maintained by
the search aircraft for the first phase flights and 5000 feet was main-
tained during the second phase. The pilots were assigned to fly the
tracks of course I or II as shown on Chart 1 depending on the army's
area of activity.

The pilots were not briefed on the possible target locations.

15

Flight paths were planned to cover the area of army operations. No familiarization flights were flown by the pilots. The pilot of the aircraft was responsible for the search as well as flying the aircraft. The rear seat passenger assisted in data recording. Target's position and observer's position at the time of sighting a target as well as the time and target type were recorded.

The army's field problem placed about 250 vehicles of varying types in the area. Position reports were made by each vehicle in the battle problem area at frequent intervals. These reports were collected and checked for validity through a cross check system in the reporting procedure. The data was assumed to be reasonably accurate. Estimates of the number of vehicles not concealed were made by the field commanders and from photo interpretation of aerial photography coverage of the battle area.

No effort was made to obtain information on the attitude of the flight paths with respect to the sun, the sun elevation angle or the contrast of the targets. Flights were made in both morning and afternoon periods so that a sample of all conditions are probably present in the data.

Analysis

Taking eight flights at random from the first phase and six from the second phase, the vehicle position reports for the time periods of these flights were reconstructed on target position overlays. (See Chart II) A comparison was made of the pilots' reported target positions and the

plotted position reports. It was decided to use the pilots' estimate of distance to the target at time of sighting as the target detection range. These ranges varied from 200 yards to 2000 yards.

Lateral range bands of widths of 500 yards centered on the track line of the aircraft were measured on the overlay. (Chart II) In each range band the probability of detection, p , was computed where $\hat{p}$ is:

$$\hat{p} = \frac{\text{number of targets detected}}{\text{number of targets in the range band}} .$$

In order to get a detection probability not affected by the particular battle tactics which place a percentage of targets under cover hence unavailable for visual detection, the estimate of the percentage of targets concealed was used to arrive at a figure for the number of targets observable. The estimate of the probability of detection now became, $\hat{p}_1$

$$\hat{p}_1 = \frac{\text{number of targets detected}}{\text{number of targets observable in each range band}} .$$

A lateral range curve based on these probabilities is shown in Figure 6. Note that the maximum range of detection and the detection probabilities were less in this operational experiment than in those computed by theory or those obtained in the Michigan experiment.

This experiment indicates that there is a significant amount of degradation of theoretical detection probabilities in the conduct of visual reconnaissance searching for ground vehicle targets from high speed attack aircraft.

17

OPERATIONAL LATERAL RANGE CURVES

FIGURE 6

h = 1500 FT

h = 5000 FT

0   500   1000   1500   2000

HORIZONTAL LATERAL RANGE (Yds)

18
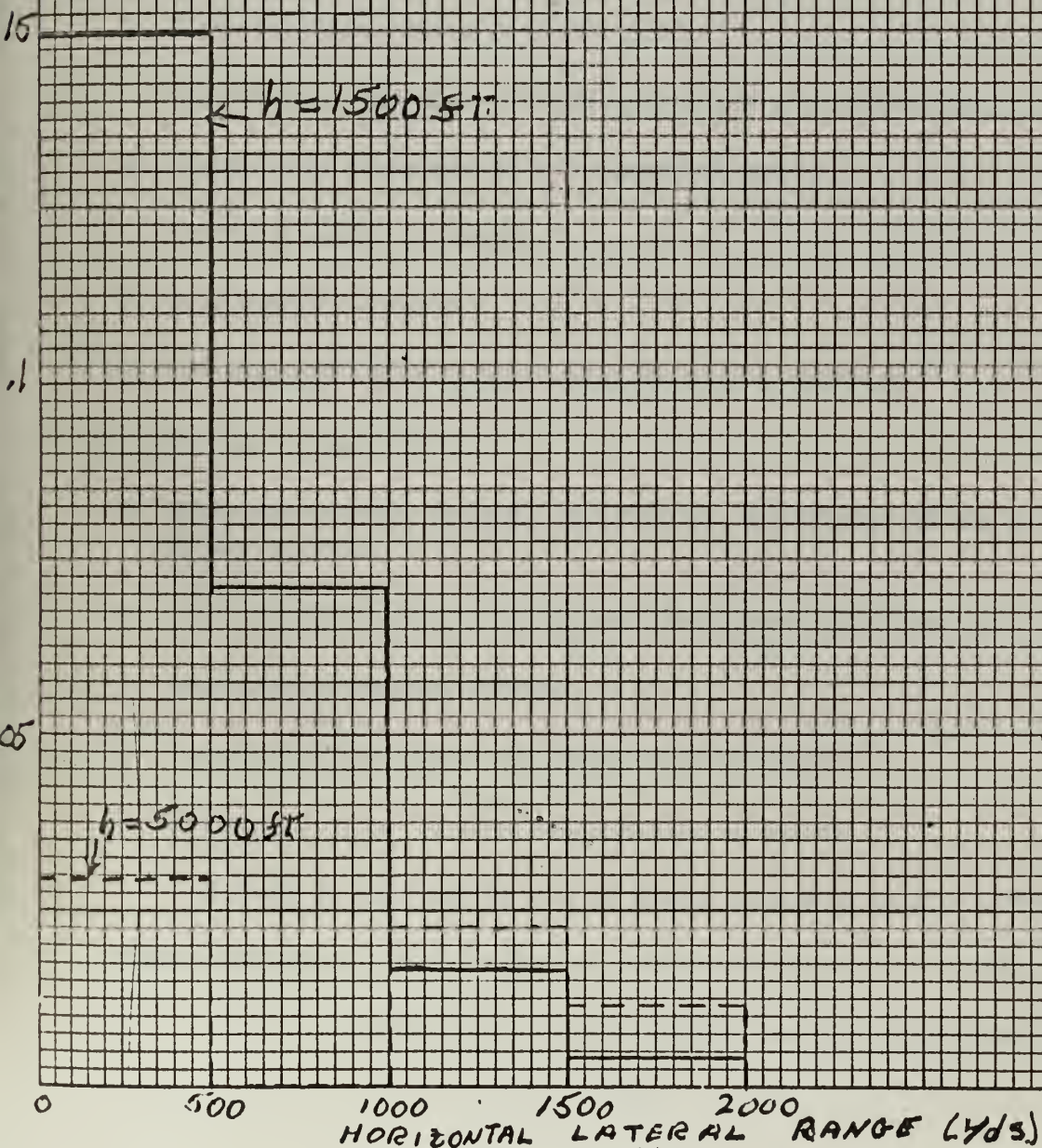
5.	Effects of Variables

Determining detection probabilities either by theory or experiment is difficult because of the number of variables which are involved in the detection process. In addition to those variables which are accounted for in the theory described in this paper, D. A. Gordon of the University of Michigan has enumerated many others. [j] The list of detection probability parameters below includes most of the variables which are recognizable. Those marked * are not measurable.

1. Laboratory threshold contrast of the eye

2. Data handling capacity of the mind *

3. Continuous variation of background and sky luminance *

4. Continuous variation of sun elevation angle

5. Target inherent contrast

6. Atmospheric effects

7. Variation of target aspect relative to the observer *

8. Target movement *

9. Observer acuity, fatigue, motivation, knowledge of the probable target location *

10. Time available to make judgment (airspeed, glimpse time)

11. Background textural effects *

12. Target internal contrasts (glints off the target) *

13. Secondary clues leading to detection of target *

Failure to account for any of these variables in any theoretical model will cause errors in the calculated detection probability.

Even the measurable variables of the visibility equation are difficult

to evaluate in any one situation. Dr. Duntley of the Visibility Laboratory of the Scripps Institution of Oceanography has conducted field measurements of the contrast of olive drab targets against various backgrounds. Examples of values obtained are shown in Figures 7 and 8. Contrast is shown as a function of the sun's zenith angle, observer bearing from the sun and the angle of the target with respect to the vertical and the observer. There is a large variation in contrast shown in these curves. It is easy to see that it would be extremely difficult to determine the target contrast applicable to the solution of probability curves for a single search mission.

Results of operational experiments, however, include the effects of all the variables because the actual detection process is carried out. Field experiments varying the operational parameters of observer height, airspeed, target type, aircraft type, overall light conditions and terrain would give information in terms of parameters known to operational commanders, another advantage in the use of operational experiments.

It is interesting to note that the lack of success in constructing a useful theory which can predict the results of trials in the field is not unique to the study of visual detection. It has recently been found that the radar detection theory is not sound because of variables not accounted for in the theory. Sonar detection processes contain an enormous number of variables, both caused by man in the system and those provided by nature. So far, it has been impossible to include all of these in the theories of detection in any of the types mentioned.

CONTRAST VALUES

Bearing from Sun $\phi = 180°$
Background: Dirt
Target: Olive drab

$N(95,0)$ $N(90,45)$

$N(90,0)$

$N(0,\phi)$

B_m/B_t

FIGURE 7

ZENITH ANGLE (θ_i)

CONTRAST VALUES

Bearing from sun 90°
Background: Dirt
Target: Olive drab

N(90, 225/315)

N(45, 20)

N(90, 90)

FIGURE 8

ZENITH ANGLE (Θ)
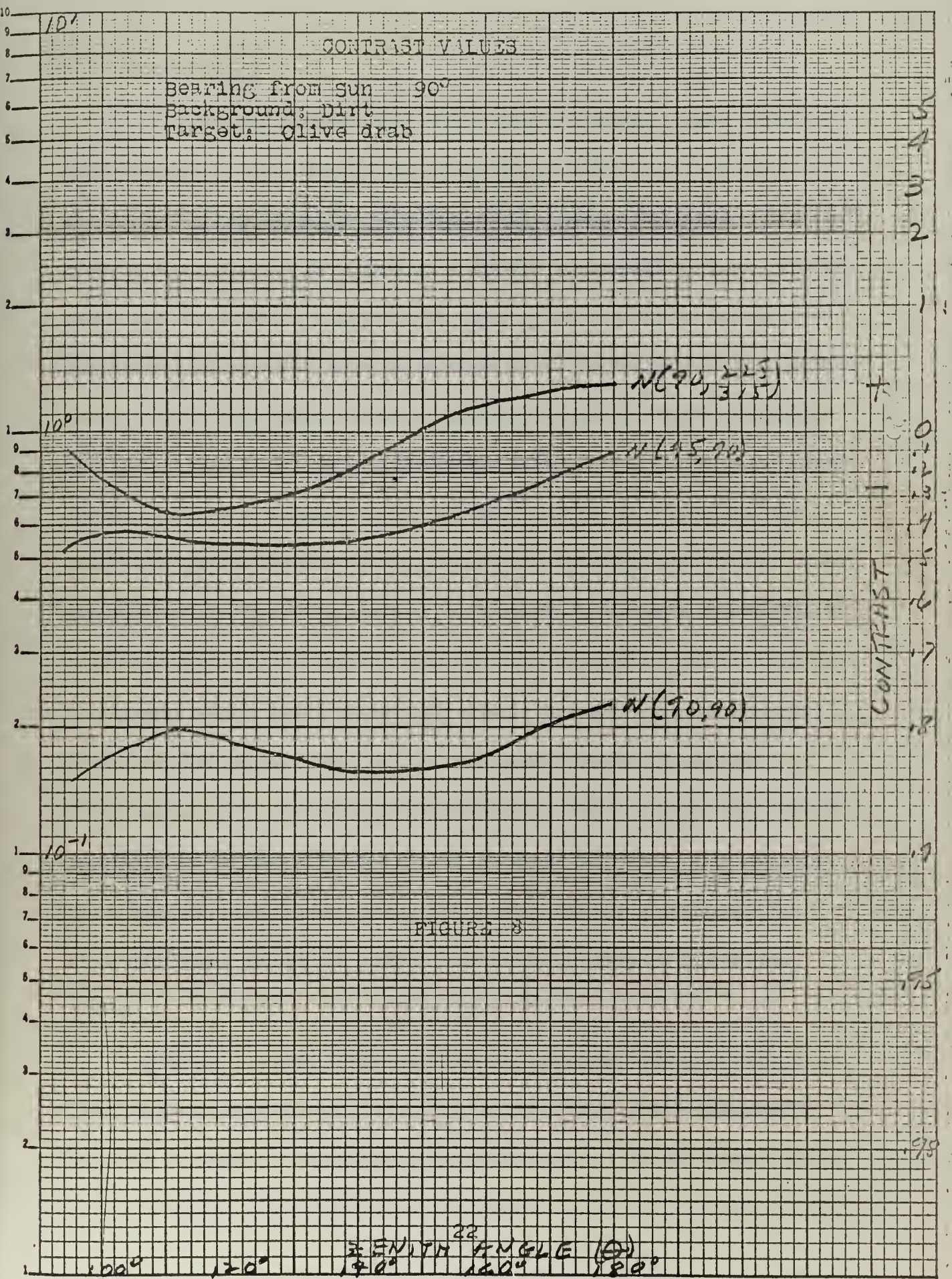
6.   Conclusions

The detection probabilities and maximum sighting ranges observed in the operational experiment are significantly below those predicted by the theory and the Michigan experiment described in this paper. Figure 9 gives a comparison of the maximum detection probabilities, i.e., at zero range, for the methods shown in the paper. The conditions acting in an operational environment have an extreme effect on the detection probabilities. In the Michigan experiment under less difficult search conditions and also probably with targets of greater contrast than those in the operational experiment, detection probabilities were not decreased as radically from the theoretical values. Also in the Michigan experiment some variables of the detection process, especially (1) observer knowledge of target position and (2) time available to make judgment, were considered in a manner which would allow their effects to raise the detection probabilities over those resulting from operational work. It appears that the conditions of the operational experiment greatly reduced the detection probabilities and the maximum ranges of target sighting. This reflects the effects of such things as no pilot briefing on possible target positions and higher airspeeds nearly comparable to those of operational aircraft.

Although the operational experiment presented here was conducted under inexact control conditions, the results obtained are sufficiently accurate to warrant comparisons with the results of the Michigan experiment and theory. The operational experiment indicates it is quite possible

23

Estimates of
Maximum Detection Probabilities

METHOD OF DETERMINATION

Figure 9

24
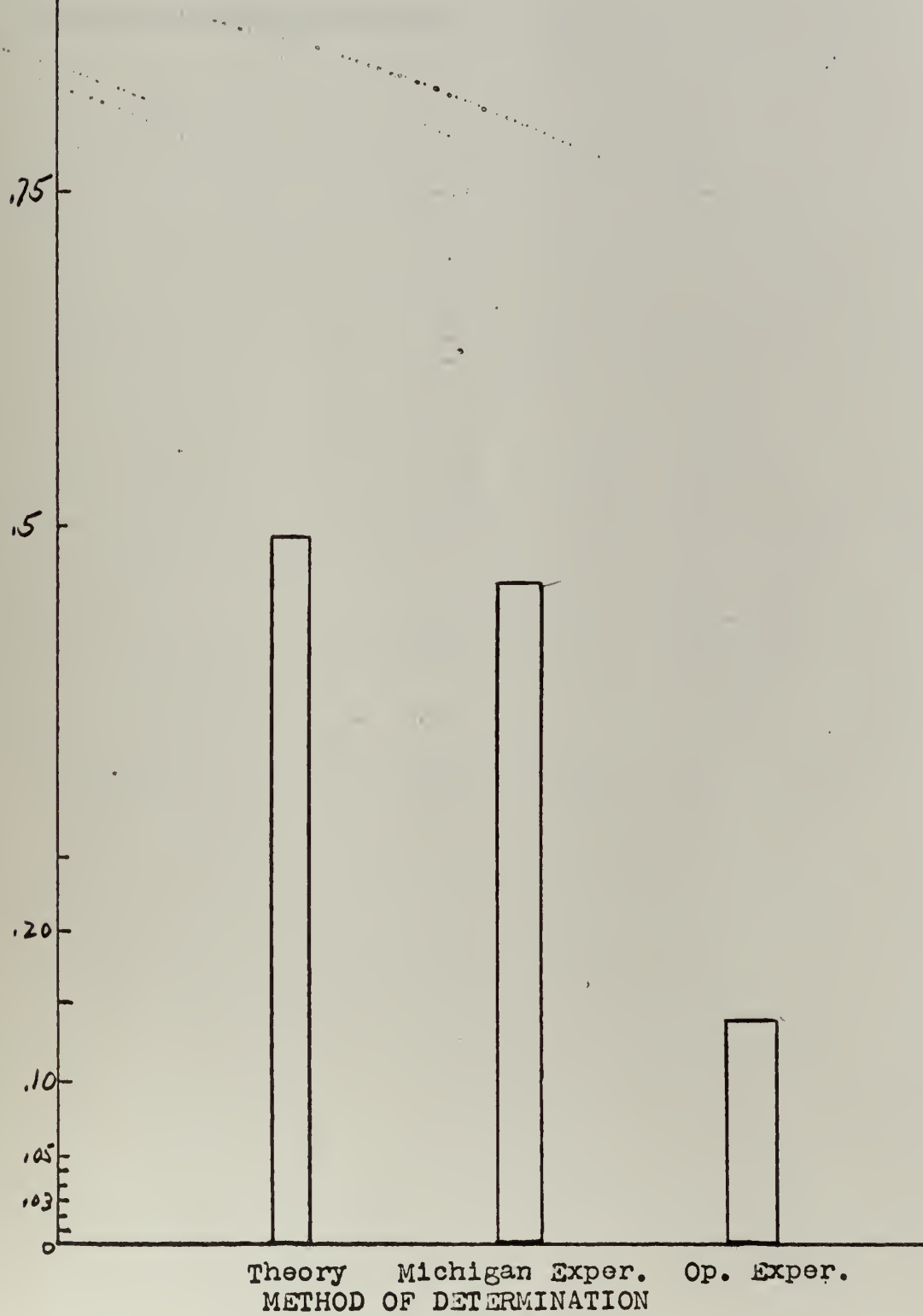
that the maximum sighting ranges and detection probabilities obtained

in a tactical environment are sufficiently different from Michigan results

to warrant further investigation of the problem before using their figures

in planning for attack missions.

7.   Recommendations

In order to provide accurate data for obtaining detection proba-
bilities and maximum sighting ranges of vehicular targets likely to be
encountered in a limited war, an operational experiment should be
designed and conducted utilizing operational attack aircraft, fleet
pilots and targets located in a tactical environment.

It would also be interesting to construct a Monte Carlo model
of the attack mission using detection probability as one parameter of
the model. Detection probability could then be studied for sensi-
tivity. Limits of the detection probability which would change the
success of an attack system could be found. Also the amount of
change in success for a difference in detection probability could be
determined. Then, an experiment of practical precision could be
designed to find detection probabilities. The construction of such
an attack system model is offered as an idea upon which to base
further work in establishing detection probabilities.

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APPENDIX I

VISUAL DETECTION THEORY

Before considering the theory of predicting detection probabilities,
an explanation of how the eye sees is necessary to introduce the phy-
sical concepts of the eye's detecting process. Details of the physiology
of detection by the eye are presented in references (c) and (d), however,
a brief sketch of the eye's detection process will be given in this paper.

Let a target be defined as an object of interest to the observer,
generally differing from the background of the area in which it is situated.
To start the detection process the target must generate or reflect some
amount of light. The intensity of light from the target per unit area is the
target brightness. [c] The intensity per unit area of light given off by the
background is background brightness. The eye is stimulated by the light
from the target. If the target brightness differs from the background bright-
ness sufficiently the eye will sense that the target is there; that is re-
solve the target from its background. In addition to the difference in
target and background brightness, the target's angle off the visual axis
of the eye affects the eye's ability to resolve the target. [a] The visual
axis is an imaginary line from the center of the retina of the eye through
the center of the lens of the eye and forms the center of the line of sight.
The angle off the visual axis of the target is the angular measure of the
target's distance from the line of sight. The retina contains the sensing
elements, the rods and cones, of the optic nerves. The fovea, which is
the small center portion of the retina, contains the densest collection of

these sensing elements. A target at extreme range must make an impression on the foveal sensing elements before it will be detected by the eye. Since the fovea is a small area in the center of the retina, targets must be near the line of sight before they will be detected at extreme ranges, that is, the target's angle off the visual axis must be no more than one or two degrees in magnitude for the target to be detected. This angle is the foveal off axis angle. At shorter ranges the target may be further off the visual axis and still be sensed by the eye. Here the off axis angle is described as the perception angle. The amount of time required for the eye to sense a target, assuming the target is in a position where it can be seen, is also of importance in studying visual detection probabilities. In searching an area the eye looks in a series of fixations of about 0.25 seconds apiece. It is believed that from six to eight of these fixations are needed to see a target. The glimpse time is the time required to make these six to eight fixations. It has been statistically determined that the average glimpse time is 1.63 seconds. [a]

Two different laboratory experiments have led to the conclusion that the eye detection capability is primarily affected by:

1. Target-background contrast

2. The solid angle subtended by the target

3. The off axis angle of the target and the eye's perception angle

4. Target shape

Blackwell in reference (g) has shown the relationship of the minimum target-background contrast (threshold contrast) to the angle subtended

by the target required in order for an observer to detect a target 50% of the time. K. J. W. Craik at Columbia University established a relationship between threshold contrast and the foveal off axis angle. Craik used a value of 0.8° for the foveal off axis angle, θ_f.

Determining the Maximum Horizontal Range of Detection

Contrast is required by the eye in order for the eye to detect a target. The minimum value of this contrast is the threshold contrast. The inherent contrast of the target is the contrast of the target with its background when it is viewed at extreme close range, with very little atmosphere between the observer and the target. As the distance between the target and observer is increased the inherent contrast is reduced, due to the reduction of light from the target transmitted through the atmosphere. At some extreme maximum range the contrast of the target reduces to the minimum or threshold contrast of the eye and that range is the maximum range of detection of the target.

An equation may be set up involving the essential parameters of the visual detection process. This equation may be solved for the maximum visual range. The parameters of the equation for determining maximum range of detection of targets from the air are:

1. Atmospheric conditions

2. Meterological range of visibility

3. Luminance level

4. Size and inherent contrast of the target

5. Height of the observer

The solution to the equation for determining the maximum range of detection is made with these assumptions:

1. The atmosphere is composed of optically standard stratified layers

2. There is uniform sky illumination

3. The sun's directional effect will be ignored

4. All observers are giving optimum performance in searching

References (e), (f) and (h) report on the method of construction of nomographs which can be used to determine the maximum range of detection. The nomographs were based on equations developed by Duntley and on the experimental work of Blackwell. Blackwell discovered that the threshold contrast of the eye depended on the angle subtended by the target, α.

Let: Range $\equiv$ R (yards)

Apparent target area $\equiv$ A (ft^2)

Apparent contrast $\equiv$ C_r

Inherent contrast $\equiv$ C_o

Inherent luminance of the background $\equiv$ B_t^i

Luminance of background sky $\equiv$ B_m

Sky-ground ratio $\equiv$ B_m / B_t^i

Meterological visibility $\equiv$ V

and let: $\alpha = \dfrac{129.3\sqrt{A}}{R}$

Duntley established that:

$$C_r = C_o \left[1 - B_m / B_t^i \left(1 - e^{-3.912\,\overline{R}/V} \right) \right]^{-1} \tag{1}$$

31

The nomograph of reference (h) which is used in this paper,
solves the equation formed by setting equation (1) equal to the minimum
threshold contrast. This equation is solved for the quantity, $\overline{AR}$, the
product of the maximum optical slant range, $\overline{R}$, and the effective target
Area, $\overline{A}$. The optical slant range is different from the true slant range,
R, because of the characteristics of the atmosphere. After allowing
assumption 1, the following equation is true:

$$\overline{R} = h_o \csc \theta_e \left[1 - e^{-\frac{R \sin \theta_e}{h_o}} \right] = \frac{R \, h_o}{h} \left[1 - e^{-h/h_o} \right] \quad (2)$$

where: Elevation angle $\equiv \theta_e$: $\sin \theta_e = h/R$

Observer height $= h$

Atmospheric constant $\equiv h_o$

Let: Height factor $\equiv H$

It has been shown that: $\overline{R} = HR$ [a].   (3)

Because the optical slant range is usually shorter than the true
slant range, the effective target area, $\overline{A}$, is also decreased as shown in
the figure below. In the solution for the maximum detection range which
follows the target will be assumed to have no vertical development.
This is the worst possible case for with observers at low altitudes the
effective target area becomes less for this case than for a target with
some vertical development. [a]
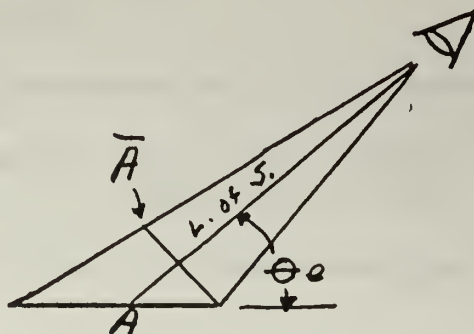
From the figure: $\bar{A} = A \sin \theta_e \, \bar{R}^2/R^2 = Ah \, R^2/R^3$

Then: $$\overline{AR} = Ah \, H^3 \qquad\qquad (4)$$

Where: $$H = h_o/h \left[1 - e^{-h/h_o} \right]$$

Values of the quantities H and hH^3 have been computed and are tabulated in Table I-1.

Using Table I-1, the nomograph and equations (3) and (4) the true slant range, R, may be found using the following procedure. (a)

1. From Table I-1 find H and hH^3.

2. Then from equation (4) solve for $\overline{AR}$.

3. Enter the nomograph with $\overline{AR}$, the meterological visibility and the adjusted inherent contrast.

4. From the nomograph find $\bar{R}$.

5. Solve equation (3) for R.

6. Solve for R_h in the equation: $R_h = R\cos \theta_e$.

Since the nomograph was constructed using the threshold contrast for a level of 50% detections, the maximum horizontal range computed by this method is the maximum range for detection of 50% of the targets.

In order to provide a basis for the comparison of visual detection theory and the operational experiment reported in this paper, an example was set up for calculations of R_h which have been made and are presented graphically in Figure I-2.

The inputs to the calculations of the example were:

1. Assumed targets: Tank with A = 450 ft^2
   Jeep with A = 75 ft^2

2. Sky-ground ratio: 2.5(Forest in daylight) (c)

3. Inherent target contrast: ± .125, ± .25, ± .50
   (For negative contrast, target is darker than background)

4. Meterological visibility: 30 miles

Craik used another approach to compute the maximum visual range
of detection. (d)

Let: Threshold contrast ≡ C_t

Angle off the visual axis (perception angle of the eye) ≡ θ

Angle subtended by the target ≡ α

Craik established that: $C_t = 1.75\,\theta^{1/2} + 19\,\theta/\alpha^2$ (5)

It is also demonstrated that for observations from aircraft along a slant-
ing line of sight, by making the proper substitutions:

$$C_t = 1.75\,\theta^{1/2} + 2.79(10^5)\,\theta\,\frac{R^3}{Ah} \qquad (6)\ (d)$$

With $\theta_f = 0.8°$, the foveal off axis angle, further

substitution shows:

$$V/h^{1/2} = 1.49\left(\frac{R_m}{h^{1/2}}\right)\Big/\log_{10}\left[\frac{C_o A}{2.26(10^5)(R_m^3/h)+1.57A}\right] \qquad (7)$$

This equation can be solved for the maximum slant range. The solutions

for the maximum slant range by Craik's method and by the nomograph

method are very nearly equal.

Determining Detection Probabilities

In the preceding section it was stated that, θ, the visual per-

ception angle varied with range. In the following development of detec-

tion probability it is first necessary to describe the relationship between

V and the range between the observer and the target.

The apparent contrast of the target when viewed at some range

through the intervening atmosphere is, C_r, the inherent contrast de-

creased by the affect of the atmosphere. [d] As the range to the target

increases the apparent contrast decreases.

$$C_r = C_o e^{-BR}$$

Where: Extinction coefficient $\equiv$ B

Range $\equiv$ R

Maximum Range $=$ R_m

Meterological Visibility $=$ V

Using R$=$V and experimental values of C_r and C_o for this condition, B

can be evaluated. B $=$ $3.44/V$

Then: $$C_r = C_o e^{-3.44 R/V} \tag{8} [d]$$

Again remembering that the threshold contrast must equal apparent con-

trast for the eye to detect the target at a maximum range form the equation: [d]

$$C_o e^{-3.44 R/V} = 1.75 \theta^{1/2} + 2.79(10^5) \theta \frac{R^3}{Ah} \tag{9}$$

(Apparent Contrast) = (Threshold contrast)

Solving for θ, as a function of range, visibility and inherent contrast:

$$\theta = F \left(\sqrt{\frac{G}{F} + 1} - 1 \right)^2 \tag{10}$$

where: $$F = \frac{0.49 (R_m/R)^6}{(C_o e^{-3.44(R_m/V)} - 1.565)^2}$$

and: $$G = \frac{0.8 C_o e^{-3.44(R_m/V)} (R/R_m) (R_m/R)^3}{C_o e^{-3.44(R_m/V)} - 1.565}$$

Equation (10) gives the relationships of the visual perception angle, the

range to the target, the visibility and the target contrast.

Continuing the example of the first section and adding these inputs:

1. $R_m/V = 0.09$, since, $0.0219 < R_m/V < 0.1605$

2. Inherent contrast, $C_o = \pm .125, \pm .25, \pm .50$

After solving equation (10) for θ using the inputs above and those given in section preceding, θ was plotted in Figure I-3 as a function of R/R_m for various values of C_o.

Note that the size of the target area does not affect θ.

To show the detection pattern of the eye in a more descriptive manner Figure I-4 was plotted on polar graph paper with θ again a function of R/R_m. This shows the two dimensional intercept of the cylinder of revolution within which the eye can detect targets. Target detection will occur 50% of the time on the surface of this surface of revolution.

It is next necessary to consider the type of search process which is followed by pilots of attack aircraft in carrying out an armed reconnaissance mission. Air to ground search from an attack aircraft will be assumed to be conducted by the pilot scanning along arcs on the ground at distances out to a maximum visual range from the aircraft. The arc, (H), is the foward 180° arc of the pilot's possible circle of vision. There is no search conducted abaft the beam of the pilot's aircraft. In flight it is very difficult for a pilot to maintain a uniform air-ground scan since his attention is split between the ground search, his flight instruments and an air search for possible enemy aircraft. It will be assumed that the pilot's search of the ground is random. It is equally likely that the pilot will observe any spot in the possible area inside the maximum

36

range and the arc, $\widehat{H}$, on each glimpse.

For each range from the aircraft there is an angle, θ, for which the pilot has a .50 probability of detecting the target. Figure I-3 gives the relationship between the angle off the axis and the range. Using the basic definition of probability define the probability of detecting a target in one glimpse as, g_1, where: (b)

$$g_1 = \theta_s / \widehat{H}$$

Let: $\quad g_i = 1 - g_i$

be the probability of failing to see the target in a glimpse. Assume g_i to be constant over any search path increment of length, L. Then the probability of not seeing the target in path length, L, becomes:

$$g_L = (1 - g_i)^{L/v T}$$

where: Airplane speed $= v$ (yd/sec)

Glimpse time $= T = 1.63$ sec.

Considering the total number of search paths of length, L, in the search area the probability of not seeing the target in the search area becomes:

$$Q_x = \prod_{i=1}^{n} (1 - g_i)^{L/v T}$$

Making appropriate approximations and substitutions:
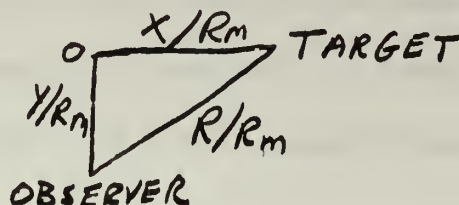
$$Q_x = e^{-\frac{L}{2 v T \widehat{H}} \sum_{i=1}^{n} \theta}$$

Let, y, be the distance along the line of flight with $y = 0$ when the target is at range R_m from the search aircraft, then:

$$Q_x = e^{-\frac{1}{2 v T \widehat{H}} \int_0^y \theta \, dy}$$

with y in units of R_m:

$$Q_x = e^{-\frac{1}{2 v T \widehat{H}} \int_0^{y/R_m} \theta \, d\left(y/R_m\right)}$$

37

Let x/R_m be the closest distance that the search aircraft comes to the

target. Integrating, Θ, graphically from $R/R_m = 1$ to $R/R_m = x/R_m$ on

Figure I-3 evaluates the exponential integral. The values of the integral

are plotted in Figure I-5.

The probability of detecting the target in the search area is:

$$P_x = 1 - Q_x$$

Lateral range curves showing P_x as a function of x may now be

constructed using Figures I-2 and I-5. These curves are for targets of

the two sizes in the example, with observer heights from 0 to 10,000

feet and contrast values of $-.125, -.25, -.50$. Any airspeed desired

may be used in the final computation for P_x. R/V remains 0.09.

Figure I-6 is a lateral range curve determined for the following

conditions:

1. R/V: 0.09

2. Target: Tank with area of 450 ft^2

3. Inherent contrast, C_o: $-.125$

4. Observer height: 1500 and 5000 feet

5. Aircraft speed: 200 and 400 knots.

In this problem the airspeed, 200 knots, was selected for two

reasons (1) it was the airspeed flown in the operational experiment to be

descirbed and (2) it can be considered a lower limit of jet aircraft search

speeds in an operational environment.

Several assumptions of this model of the search process detection

probabilities have already been mentioned. In order to remind the reader

of these assumptions which led to the probability curves presented in

in Figure I-6 all assumptions will be repeated here.

1. The model is based on a random search.

2. The position of the sun relative to the flight line and the sun elevation angle have been ignored.

3. A sky-ground ratio of 2.5 has been used. Scripps Visibility Institute warns against using a sky-ground ratio of much larger than one with the nomograph. Some error has been introduced with the assumed sky-ground ratio.

4. Contrast values for vehicle and other ground targets are not known accurately. However, the values determined experimently by Dr. Duntley and given in Figures 7 and 8 are close to the assumed values of contrast in the paper.

5. The target is assumed to have no vertical development.

SAMPLE CALCULATIONS

1. For Table I-1

   H = Height factor

   $h_o = 10^4$

   h = height of observer in yards

   $$H = h_o/h \left[1 - e^{-h/h_o} \right]$$

   Let: $h = 3333$ yards

   $H = 10^4/3333 \left[1 - e^{-.333} \right] = 3 \left[1 - .714 \right] = 0.858$

   $hH^3 = (3333)(.632) = 2106$

2. For Figure I-2

   $A = 450$ ft^2

   $B_m/B_t^1 = 2.5$

   $C_o = -.125$

   $V = 30$ miles

   $h = 3333$ yards and 500 yards

   $c^1 = .05$

   Then:

   $H = 0.858$ and 0.975

   $hH^3 = 2106$ and 464

   $\overline{AR} = 948,000$ and $208,000$

   $\overline{R} = 5100$ yards and 3350 yards

   $R = 5950$ yards and 3440 yards

   $R_h = 4980$ yards and 3400 yards

3. Calculation of the range of values for C_o

   $B_m = 1000$ ft. lamberts

   $B_t^1 = 400$ ft. lamberts

   Assume $B_m/B_t^1 = 2.5$

   $$C_o = \frac{B_t - B_t^1}{B_t^1} = \frac{B_t - 400}{400}$$

B_t	C_o
800	1.0
700	0.75
600	0.50
500	0.25
450	0.125
400	0.0
300	-0.25
200	-0.50
100	-0.75
0	-1.0

4. For Figure I-3 with the same inputs as calculation 2.

   Let: $R_m/V = 0.09$

   $$\theta = F\left(\sqrt{\frac{G}{F}+1} - 1\right)^2$$

   $$F = \frac{(.49)\left(R_m/R\right)^6}{\left(C_o\, e^{-3.44\,(R_m/V)} - 1.565\right)^2}$$

   $$G = \frac{0.8\, C_o\, e^{-3.44\,(R_m/V)(R/R_m)}\left(R_m/R\right)^3}{C_o\, e^{-3.44\,(R_m/V)} - 1.565}$$

   $$R/R_m = .2 \;;\; R_m/R = 5$$

   $$F = \frac{(.49)(1.563)(10^4)}{\left(12.5\, e^{-.22} - 1.565\right)^2} = \frac{7.65 \times 10^3}{8.473^2}$$

   $$F = 106.6$$

41

$$G = \frac{(.8)(12.5)(.98)(125)}{8,973} = 144.8$$

$$\sqrt{\tfrac{G}{F}+1} = \sqrt{\tfrac{144.8}{106.6}+1} = 1.539$$

$$\sqrt{\tfrac{G}{F}+1} -1 = 0.539$$

$$\theta = F\left(\sqrt{\tfrac{G}{F}+1} -1\right)^2 = (106.6)(.291) = 30.7$$

Table of θ Values

C_o | R/R_m	.2	.4	.6	.8	1.0	0
.125	29.5	9.4	3.49	1.55	.796	51.4
.25	59.8	11.9	3.85	1.62	.801	
.50	87.5	13.3	4.04	1.64	.803	
-.125	30.7	6.56	2.62	1.14	.583	
-.25	54.6	10.3	3.29	1.37	.670	
-.50	81.6	13.0	3.35	1.51	.733	

5. Table for Figure I-5; $\int_0^{Y/R_m} \theta \, d(Y/R_m)$

From the graphical integration of Figure I-3

x/R_m | C_o	-.125	-.25	-.50
0	.227	.402	.496
.2	.086	.138	.185
.4	.025	.029	.037
.6	.009	.010	.012
.8	.003	.003	.004
1.0	0	0	0

6. For Figure I-6

$$P_x = 1 - e^{\frac{-R_n}{2v\gamma \circledast}} \int_0^{Y/R_m} \circleddash \, d(Y/R_m)$$

$\circledast = \pi$ RADIANS

$\gamma = 1.63$ SEC

$v = 200$ KT $= 112.3$ '/sec, 400 KTS $= 224.6$ '/sec

$h = 1500$ FT, 5000 FT

$R_h = 3300$ yd, 4800 yds

$$P_x = 1 - e^{2.85 \int \circleddash \, dY/R_m}, \quad 1 - e^{-4.08 \int \circleddash \, dY/R_m}$$

Let: v = 200 knots

x/R_m	x	$2.8 \int \circleddash \, d(Y/R_m)$	$e^{-\phi}$	P_x	
.1	3300	.443	.642	.358	h = 1500
.1	4800	.645	.525	.475	h = 5000

Let: v = 400 knots
$4.08 \int \circleddash \, d(Y/R_m)$

| .1 | 3300 | .221 | .803 | .197 | h = 1500 |
| .1 | 4800 | .322 | .724 | .276 | h = 5000 |

8. Calculation with target of size used in Michigan

experiment

A = 975 ft^2

h = 5000 ft

$C_0 = -.05, -.25, -.50$

$hH^3 = 1304$

$AhH^3 = 127,200$

R = 5100 yds, 10,720 yds, 10,850 yds

$R_h = 4830$ yds, 8,650 yds, 8,800 yds

FIGURE I-1

AR NOMOGRAPH

MAXIMUM HORIZONTAL RANGE OF DETECTION

TARGETS
□ TANK
○ JEEP

CONTRAST
+ 0.50
× 0.25
• 0.125
— 0.05

HORIZONTAL RANGE, R_h (yds)

ALT., h (ft)

FIGURE I-2

45
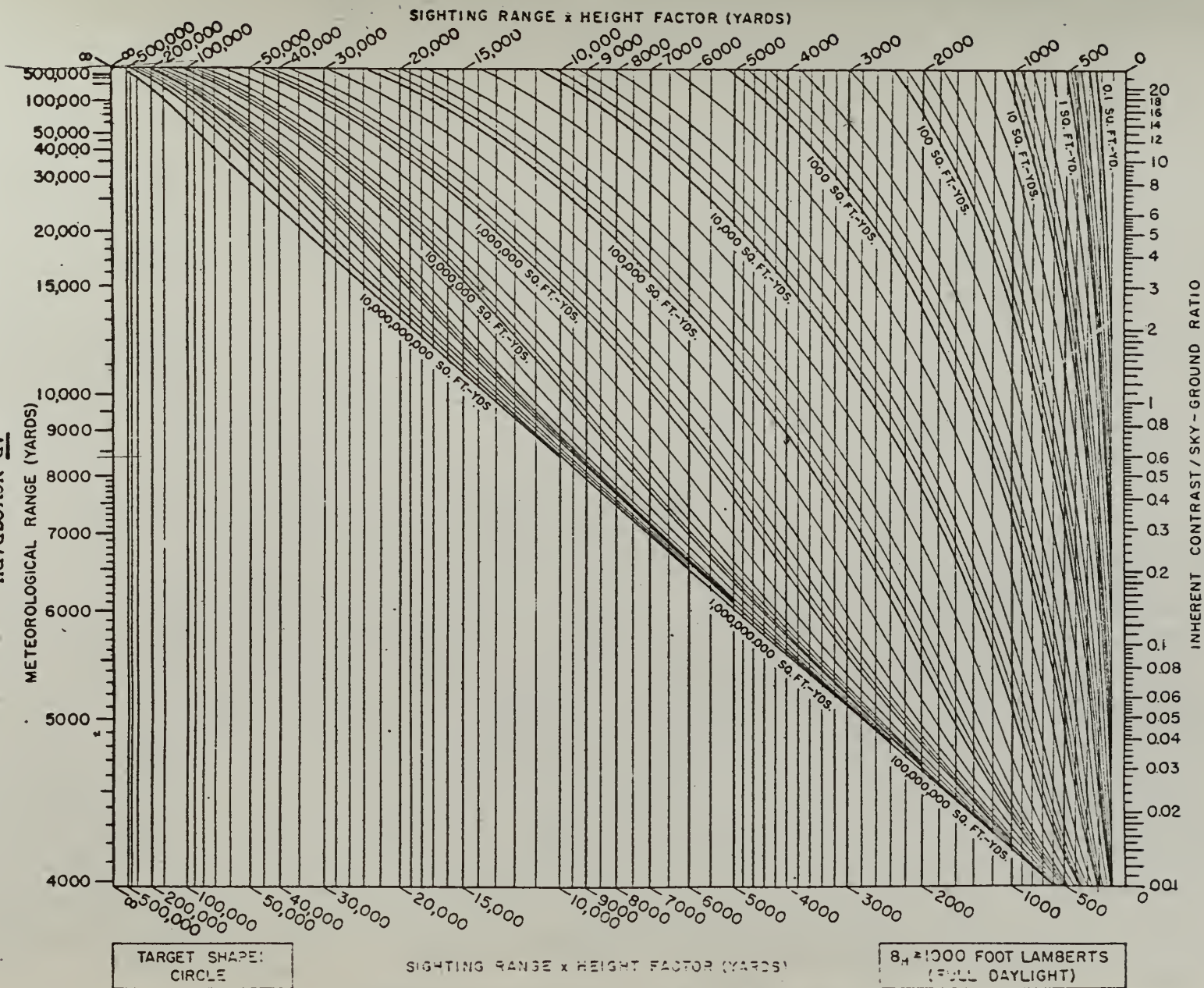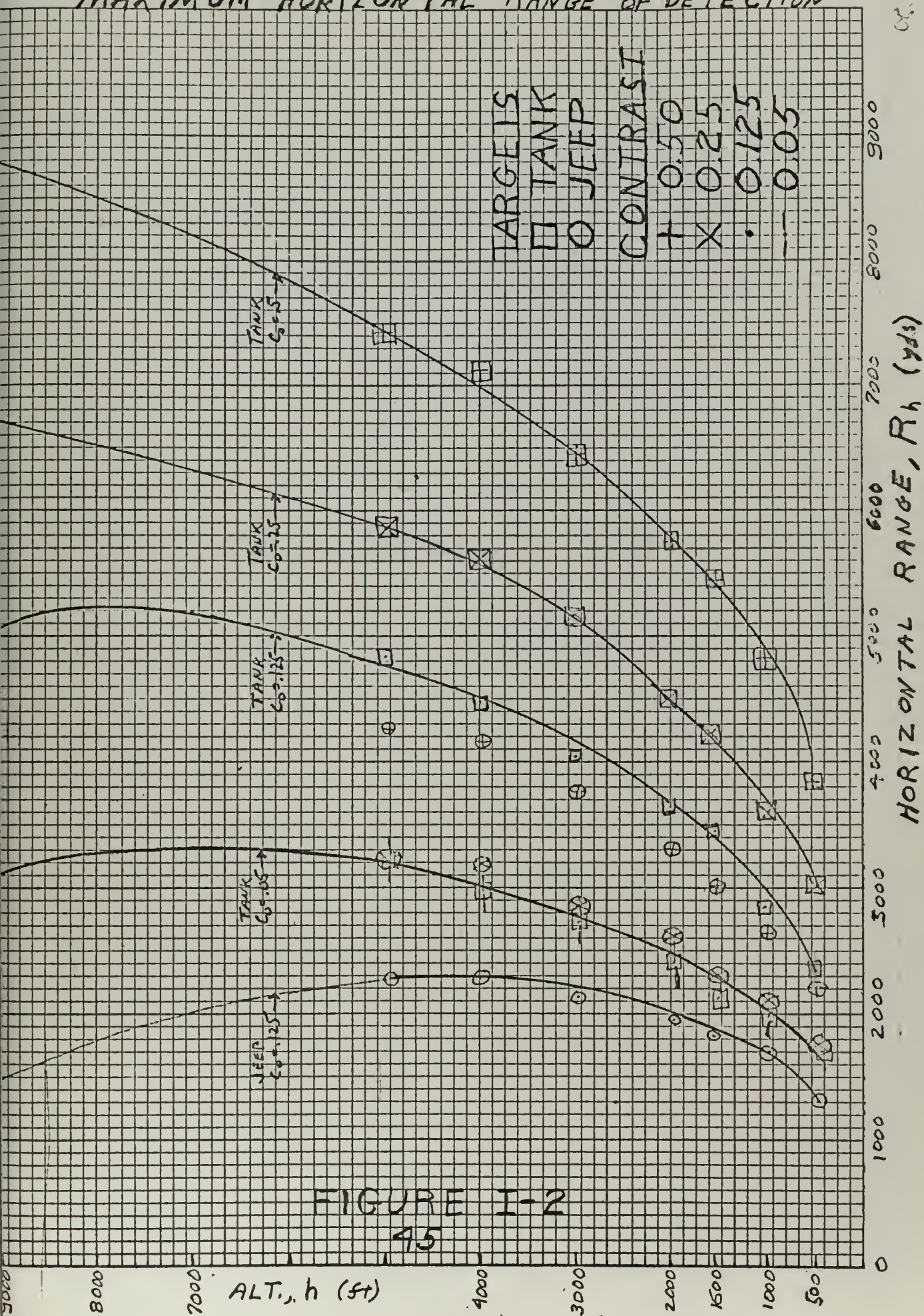
THRESHOLD OFF AXIS ANGLE Θ

FIGURE I-3

$C_0 = +.5$

$C_0 = +.25$

$C_0 = -.25$

R/R_M

FIGURE 1-4

DETECTION CYLINDER OF REVOLUTION
$c_0 = -1.25$

EYE

R/Rm

0.1 0.2 0.3 0.4 0.5 0.6
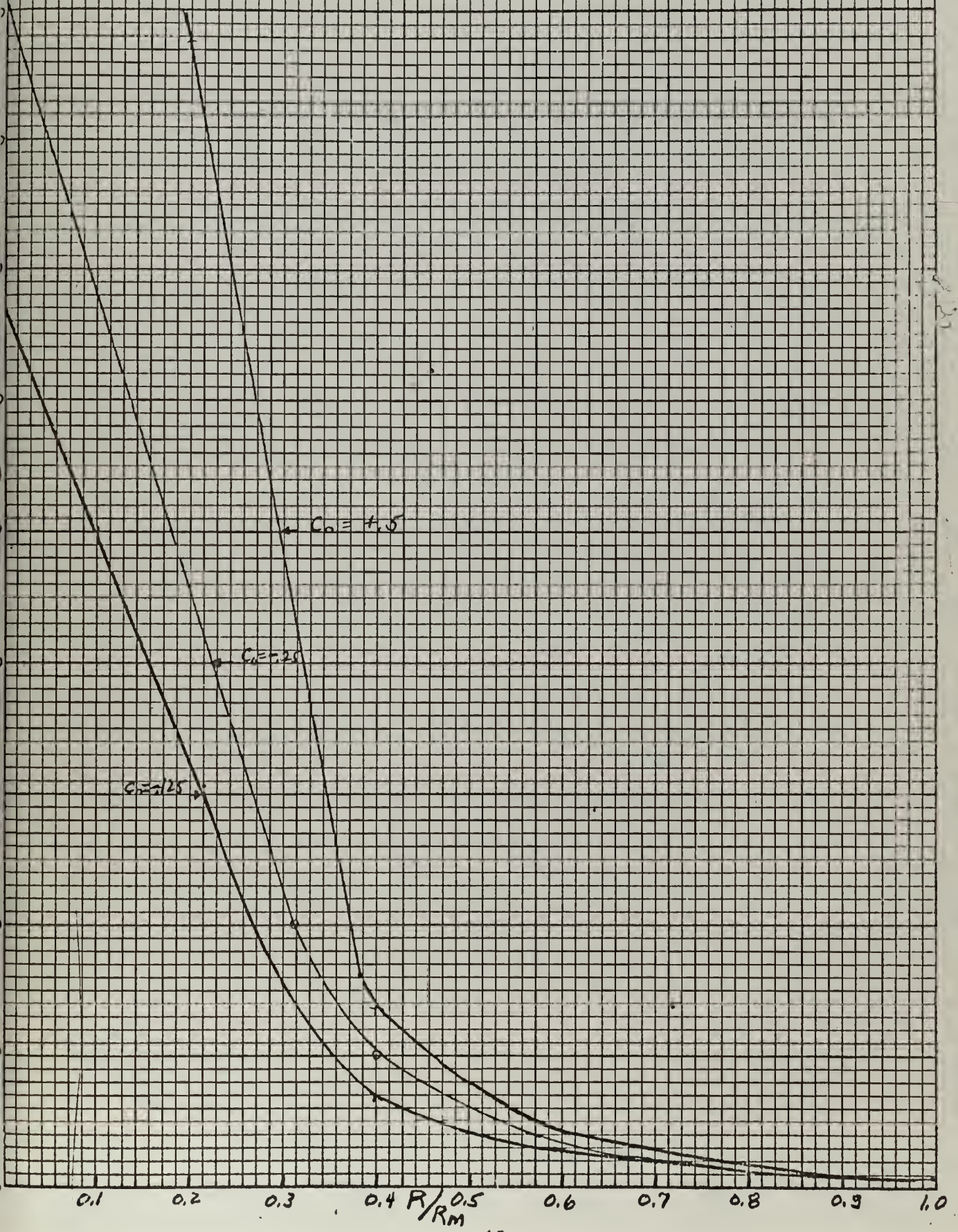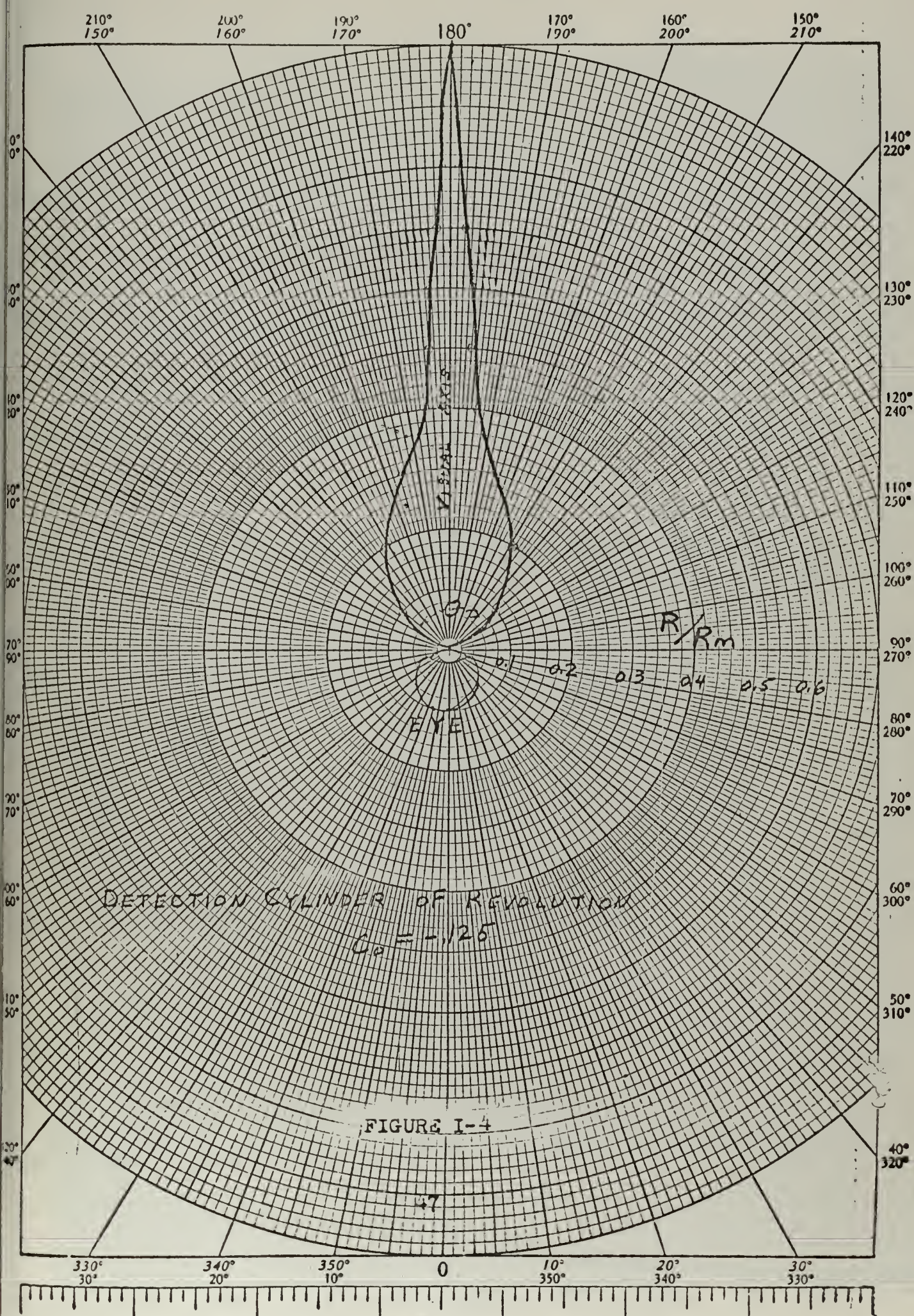
VALUE OF EXPONENTIAL INTEGRAL

FIGURE II-5

48

THEORETICAL LATERAL RANGE CURVES

FIGURE 1-6

TGT. AREA: 450 ft²
C_D : .125

200 KTS
h = 5000'
h = 1500'

400 KTS
h = 5000'
h = 1500'

LATERAL HORIZONTAL RANGE (yds)
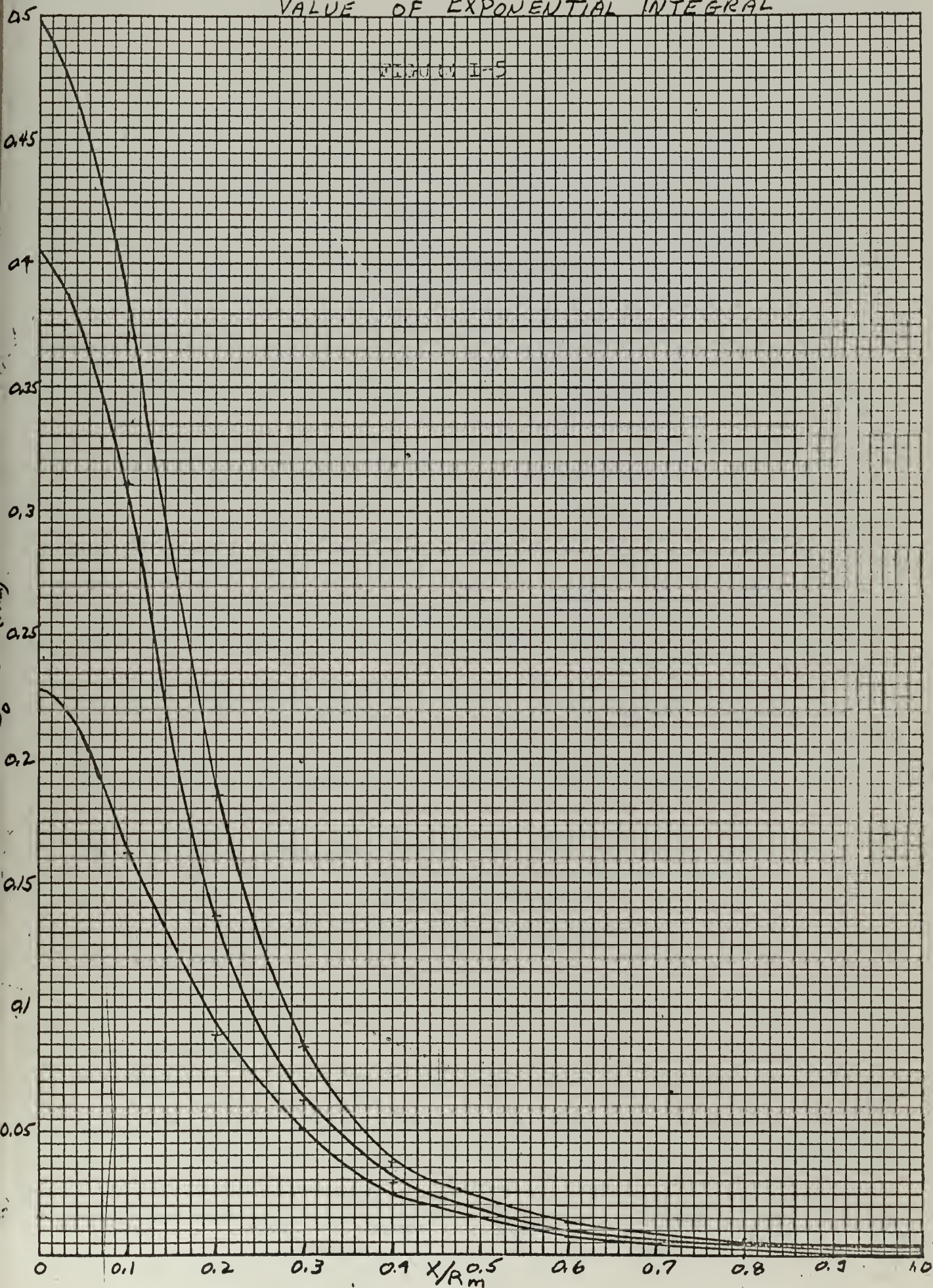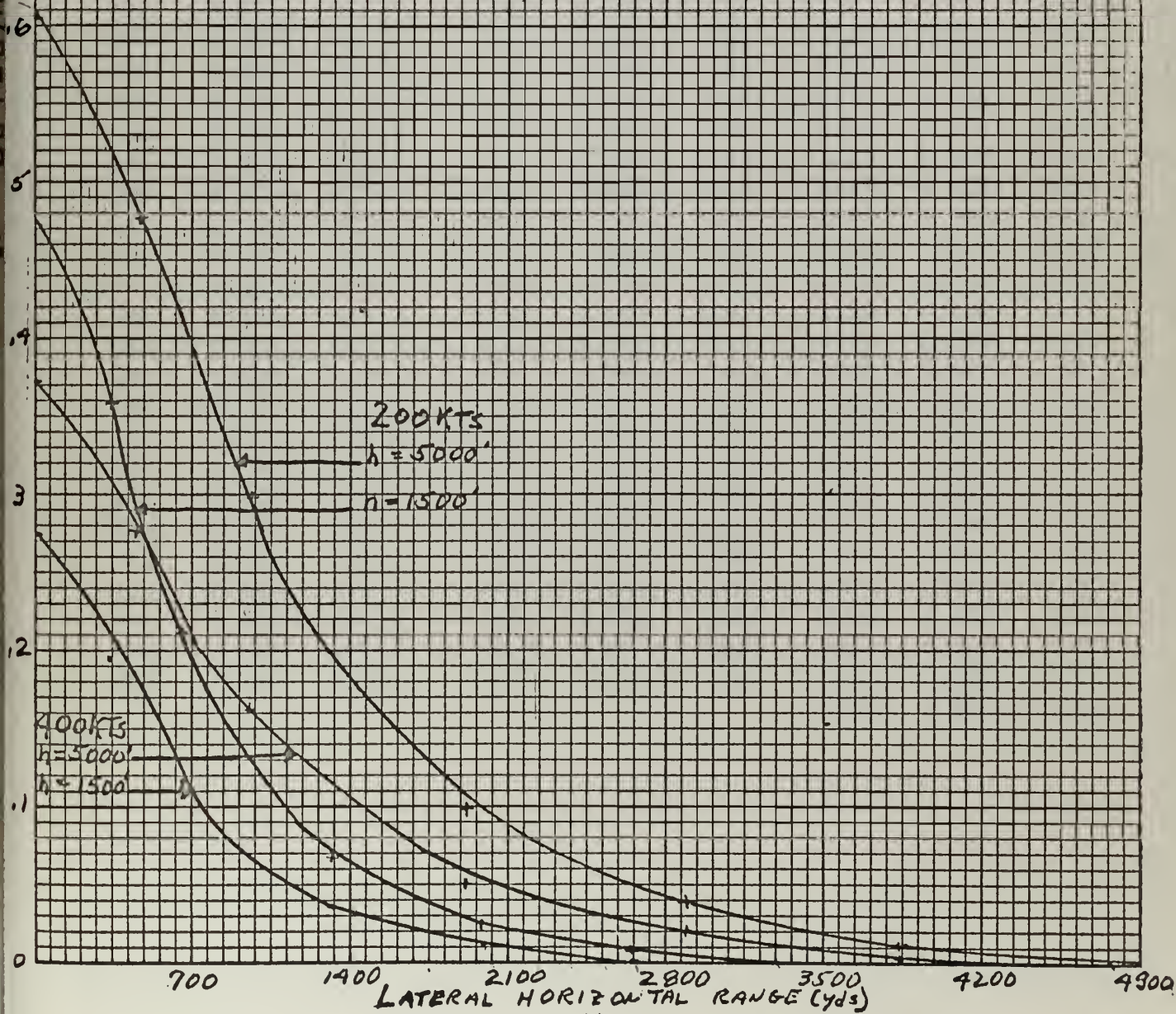
Table I-1

VALUES OF HEIGHT FACTOR (h in yards)

h	H	hH^3	h	H	hH^3	h	H	hH^3
0	1.00	0	825	0.960	730	1650	0.922	1290
25	0.999	24.9	850	0.959	749	1675	0.921	1310
50	0.998	49.6	875	0.958	768	1700	0.919	1320
75	0.996	74.2	900	0.956	787	1725	0.918	1340
100	0.995	98.5	925	0.955	806	1750	0.917	1350
125	0.994	123.0	950	0.954	825	1775	0.916	1370
150	0.993	147.0	975	0.953	843	1800	0.915	1380
175	0.991	171.0	1000	0.952	862	1825	0.914	1390
200	0.990	194.0	1025	0.950	880	1850	0.913	1410
225	0.989	218.0	1050	0.949	898	1875	0.912	1420
250	0.988	241.0	1075	0.948	916	1900	0.911	1430
275	0.987	264.0	1100	0.947	935	1925	0.910	1450
300	0.985	287.0	1125	0.946	952	1950	0.909	1460
325	0.984	310.0	1150	0.945	968	1975	0.908	1480
350	0.983	332.0	1175	0.944	988	2000	0.907	1490
375	0.982	355.0	1200	0.943	1010	2025	0.905	1500
400	0.980	377.0	1225	0.941	1020	2050	0.904	1520
425	0.979	399.0	1250	0.940	1040	2075	0.903	1530
450	0.978	421.0	1275	0.939	1060	2100	0.902	1540
475	0.977	442.0	1300	0.938	1070	2125	0.901	1550
500	0.975	464.0	1325	0.937	1090	2150	0.900	1570
525	0.974	486.0	1350	0.936	1110	2175	0.899	1580
550	0.973	507.0	1375	0.935	1120	2200	0.898	1590
575	0.972	528.0	1400	0.933	1140	2225	0.897	1600
600	0.971	549.0	1425	0.932	1150	2250	0.896	1620
625	0.969	569.0	1450	0.931	1170	2275	0.895	1630
650	0.968	590.0	1475	0.929	1180	2300	0.894	1640
675	0.967	610.0	1500	0.928	1200	2325	0.893	1650
700	0.966	631.0	1525	0.927	1220	2350	0.891	1660
725	0.965	651.0	1550	0.926	1230	2375	0.890	1680
750	0.964	671.0	1575	0.925	1250	2400	0.889	1690
775	0.962	690.0	1600	0.924	1260	2425	0.888	1700
800	0.961	710.0	1625	0.923	1280	2450	0.887	1710
						3333	0.858	2106

APPENDIX II

THE MICHIGAN EXPERIMENT

This appendix is a summary of a report entitled Field and Simu-
lator Studies of Air-to-Ground Visibility Distances by H. Richard
Blackwell, James G. Ohmart and E. Rae Harcum of the University of
Michigan Research Institute Vision Research Laboratories. This was the
final report on a coordinated program of inflight and simulator measure-
ments of target recognition distances and target detection probabilities.
This project was conducted for the Navy Bureau of Aeronautics to pro-
vide quantitative information on visibility ranges of a vehicular target
complex viewed against asphalt, grass and dirt backgrounds from an
aircraft for varying flight altitudes and attitudes of the flight path with
respect to the sun.

In Flight Measurements

The field search flights were conducted under controlled condi-
tions. The aircraft searched an area for a target while flying at varying
altitudes and varying angles of the flight path with respect to the sun.
The target was a convoy composed of a 1/4 ton jeep, a 2 1/2 ton stake
truck, and a 1/2 ton pickup truck, all painted navy grey.

The target was to be detected in an area of one square mile in a
county park located near the Michigan facilities. The terrain was flat
and had houses, outbuildings and such features as trees, grass and
planted fields. There were several roads in the area. Normal traffic
was permitted to continue on the roads during the experimental flight

periods. There was some air traffic over the park. Ten different target positions were selected. Each was in the open alongside a road in the search area. The target vehicles were parked in one of the selected positions with about two to three vehicle lengths between each of them.

The search flights were flown by nine naval aviators in an SNB-5P aircraft. The pilot of the aircraft searched for the target and flew the aircraft. The nine pilots participating in the experimental flights were given considerable pre-briefing on the type of target and the target's probable location. They were permitted to make low level target recognition passes over the search area before conducting a series of search runs for record.

The search flights were flown at an airspeed of 130 knots. The effect of wind on the search pattern was neglected. The flights were flown at altitudes of 2000, 4000, 5700, and 7500 feet.

A clover leaf pattern as shown below was flown over the area on each run. After each pass made on a cardinal heading during the pattern, the target was moved to another position, allowing four different possible detections during the execution of one pattern.
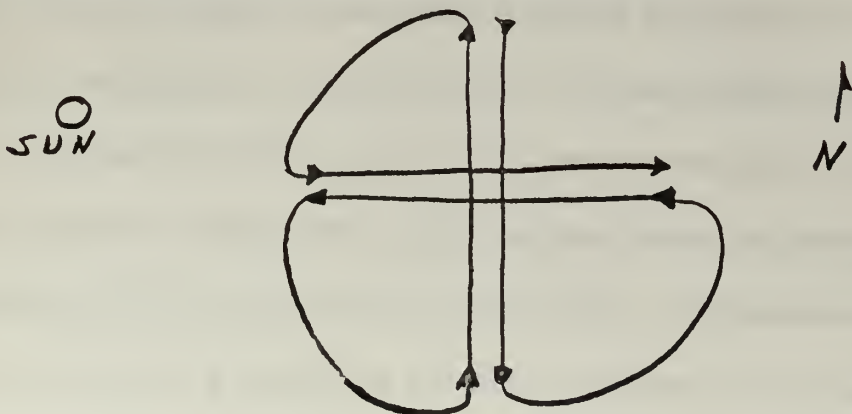
On each pass, at the time he felt that he had recognized the target, the pilot reported by radio to a control station located with the target convoy. In the report, target location and relative position of the vehicles in the convoy were given. At the time of reporting the pilot photographed the terrain beneath his position with a K-17 camera, belly mounted on the SNB. Also at the time of the report personnel with the convoy marked the elevation angle of a transit with which they had been tracking the aircraft. The photographs and the transit elevation angle data were used to compute the slant range of the target from the aircraft at the time of target recognition by the pilot observer.

All flights were made with a meterological visibility equal to or greater than 15 miles. The average sun elevation angle was 45° and the average sun azimuth angle was 267°.

There were 109 flights flown in the experiment.

Simulator Measurements

Simulation of the experiment was attempted. A model of the terrain of the county park was made with a scale of 1:600. The terrain features, target and non-target vehicles and a simulated sun were included in the model. This provided a reasonably accurate duplication of the terrain and light conditions of the field tests. An observation platform mounted on a track leading to the terrain model was constructed. The eye level of the observer when seated on the platform could be adjusted to scale altitudes of 2000, 4000, 5700, or 7500 feet. The platform was moved along the track at a simulated speed of 134 knots. For a simulated search

53

pass the observer was seated on the platform with the eye level at the proper altitude. The platform was drawn toward the target area. When he detected the target he pressed a button which lighted a light over a floor distance measuring scale which indicated the distance to the target from the observer. This distance was recorded. Again moving toward the target, when he recognized the target another button was pushed turning on a second light over the scale and this recognition distance was recorded. The platform dolly was then returned to the opposite end of the track. The passes were made in groups of 20 with a change of sun position made between each group to provide different angles of flight path attitude with respect to the sun.

There were 840 simulator passes made.

Detection and Recognition

The process of target detection implied a discrimination between the target and its background while recognition of a target was to mean that the observer could correctly identify the target. The detection distances were hard to determine since different people had a different concept of detection. Detection might occur when the observer decided something he had previously noticed was a target or detection might occur when the observer just noticed a target which was clearly well within the range required to see the target judging by visibility factors alone. Experimenters noticed that every case of failure to see a target on a pass was a failure of search rather than a condition of the target being below the detection threshold of the observer during the entire pass. Since

54

it seemed that the recognition distance could be checked when the proper vehicle positions in the convoy were reported, this distance was used as the distance to be determined in the experiment.

Limitations of the Experiment

1. The observers knew where the targets might be located and searched those areas almost exclusively.

2. In the simulator the sunlight was not collimated nor was it of high enough intensity.

Comparison of Field and Simulator Data

A. General

Averages of the slant recognition ranges and detection probabilities for field and simulator data are tabulated for the different altitudes and attitudes with respect to the sun. A study of Tables II-1 and II-3 will show:

1. A difference in results of field and simulator trials for both range and detection probabilities.

2. Detection probabilities depend both on altitude and attitude with respect to the sun.

An investigation of these differences with the possibility of determining similarity of field and simulator data was conducted in order to allow the more extensive simulator data to be used properly.

B. Some Causes for Differences Between Field and Simulator Data

1. The process of flying the aircraft caused some diversion from searching. Other physical distractions such as radio transmissions, distortions

of the windscreen, and approach of other aircraft also caused diversion
from the search.

2. In the SNB aircraft it was almost impossible to see out of the aircraft
except on the pilot's side. This limited the field of view. The field of
view was unlimited in the simulator.

C. Analysis of the Effect of Flight Altitude Upon Slant Range

Using the averages of slant recognition ranges and detection pro-
babilities shown in Table II-1 as a basis, the relative slant range was
defined as the ratio of each average value tabulated for altitudes and the
grand average computed for all altitudes and attitudes. This was done
for both the field and simulator data. The relative slant ranges of the
field data and the simulator data were shown to be similar. See Table
II-2.

D. Analysis of the Effect of Attitude With Respect to the Sun Upon Slant
Range

Again the relative slant ranges were computed for the field and
simulator tests, this time for each angle, θ, for all altitudes. θ is
the angle of the flight path with respect to the sun. In Figure II-1 a plot
of θ as a function of the log of the relative slant range showed a linear
relation between the two quantities. This relation held for both field and
simulator data.

E. Analysis of Detection Probabilities

The computing procedure for determining detection probabilities
gave the probability of the target being detected at a slant range equal

to or greater than a given value of slant range. A summary of the probability data for the field and simulator measurements was presented in Table II-3 and Figure II-2. These summary curves should be used when the sun's position relative to the flight path and/or the flight altitude cannot be specified in describing the conditions of detection in planning for an operational situation.

The values of the detection probabilities determined varied between the field and simulator tests and also between various altitudes and attitudes with respect to the sun within the field data and simulator data. In Figure II-2 the difference between the field and simulator data can be seen.

This difference was broken into three classes:

1. Differences in detection probabilities for the same slant range

2. Difference in the maximum detection probability determined in the field and simulator tests

3. Difference in shape of the probability curves of the field and simulator tests.

An analytical model describing the quantitative characteristics of both the field and simulator probability curves was desired in order to explain the differences between the curves.

It was assumed that the probability data represented two processes acting concurrently. The first process depended only on the value of the slant range; the greater the range, the less the detection probability. The second process affecting detection probability was caused by lack

of attention, improper search, or any other factor which could cause a complete failure to see the target on a pass. The second process was assumed to be statistically independent of the first process.

These quantities were defined:

P is the probability obtained from the data

P' is the probability obtained in the absence of the second process

ϕ is the upper asymptotic value of P

Using proper values of ϕ in the equation:

$$P' = P/\phi$$

made it possible to correct out the effect of the second process. Using a value of $\phi = .54$ values of P' for the field test data were computed. With a value of $\phi = .89$ values of P' for the simulator data were also computed. For each set of the data P' was plotted as a function of the log of the slant range. Smooth curves as shown in Figure II-2 were fitted to these plots. The differences in the values of ϕ required for a fit of the field data and the simulator data show the greater weight of the second process felt in the field test.

Conclusions

Based on the similarity of the slant range data of the field and simulator tests, the decision was made to pool the data from the two sources. By using the proper values of ϕ determined for the field and simulator data the theoretical curves in Figure II-3 and II-4 were constructed from the pooled data.

In a supplementary experiment olive drab painted targets were used.

58

The median slant range increased 7.5% and detection probability in-
creased 2.5%. Against backgrounds of grass and dirt as compared to
the asphalt background used initially with grey painted targets the slant
range increased 1.2 and 1.34 times. The detection probability differences
were negligible. It is interesting to note that the pilots reported that the
color of the target made no difference in their ability to see the target but
that luminance conditions were different in the two experiments possibly
causing the difference in ranges and probabilities obtained.

In order to provide a basis of comparison of the results of this
experiment and the theory described in this paper, Figure II-3 was used
to determine the maximum slant range. This was about 13,000 feet for a
search altitude of 2000 feet and 21,000 feet for an altitude of 5700 feet.
Computing the horizontal ranges for each altitude we have

R_h = 4280 yards and

R_h = 4170 yards.

The maximum detection probabilities were 0.49 and 0.58 for 2000 feet
and 5700 feet respectively.

These ranges are for conditions:

1. Target size: Approximately 975 ft^2

2. Observer altitudes: 2000 ft. and 5700 ft.

3. Search airspeed: 134 knots

4. Aircraft: SNB

5. Target contrast: Approximately -.5

TABLE II-1

MEAN SLANT RECOGNITION RANGES: FIELD DATA

Altitude (feet)	θ 3°	θ 90°	θ 177°	Average	N
2,000	6,677	6,832	10,980	8,160	44
4,000	7,376	9,767	11,014	9,390	50
5,700	8,273	12,901	16,292	12,490	12
7,500		10,380	17,600	13,990	3
Averages	7,442	9,970	13,972		

Grand Average   11,008 feet

MEAN SLANT RECOGNITION RANGES: SIMULATOR DATA

Altitude (feet)	θ 45°	θ 122°	Average	N
2,000	11,430	12,210	11,820	180
4,000	13,390	15,610	14,500	240
5,700	16,030	17,160	16,600	240
7,500	18,710	22,610	20,600	180
Averages	14,890	16,897		

Grand Average   15,895 feet

RECOGNITION PROBABILITIES: SIMULATOR DATA

Altitude (feet)	θ 45°	θ 122°	Average
2,000	.75	.90	.825
4,000	.91	.94	.925
5,700	.89	.90	.895
7,500	.91	.93	.920
Averages	.865	.918	

Grand Average   .891

RECOGNITION PROBABILITIES: FIELD DATA

Altitude (feet)	θ 3°	θ 90°	θ 177°	Average
2,000	.45	.54	.64	.543
4,000	.54	.46	.54	.513
5,700	.67	.67	.67	.670
7,500	.00	1.00	1.00	.670
Average	.415	.668	.712	

Grand Average   .599

TABLE II-2

VALUES OF RELATIVE SLANT RANGE: ATTITUDE VARIATION

Field	Simulator	Field	Simulator	Field
θ 3°	θ 45°	θ 90°	θ 122°	θ 177°
.75	.94	.97	1.06	1.37

VALUES OF RELATIVE SLANT RANGE: ALTITUDE VARIATION

| Altitude (feet)	Field Tests	Simulator Measurements
2,000	.74	.74
4,000	.85	.91
5,700	1.13	1.04
7,500	1.27	1.30

TABLE II-3

RECOGNITION PROBABILITY AS A FUNCTION OF SLANT RANGE:
ALL ALTITUDES AND ATTITUDES COMBINED

| Slant Range (feet)	Field Data	Simulation Data
2,500	.54	.89
3,500	.52	.89
4,500	.52	.89
5,500	.50	.89
6,500	.46	.88
7,500	.40	.88
8,500	.36	.87
9,500	.32	.84
10,500	.26	.80
11,500	.18	.73
12,500	.09	.65
13,500	.06	.59
14,500	.05	.51
15,500	.05	.43
16,500	.04	.36
17,500	.04	.29
18,500	.02	.24
19,500	.02	.20
20,500	.01	.16
21,500	.00	.14
22,500	.00	.11
23,500	.00	.10
24,500	.00	.07
25,500	.00	.06
26,500	.00	.04
27,500	.00	.03
28,500	.00	.03
29,500	.00	.02
30,500	.00	.01
31,500	.00	.01
32,500	.00	.01
33,500	.00	.00
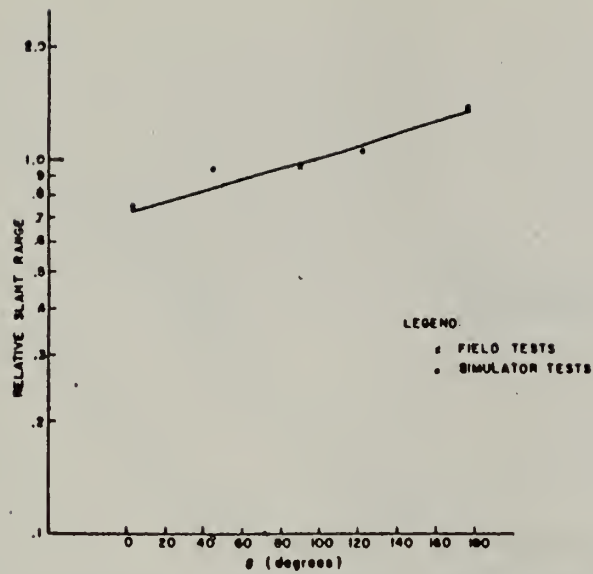
Log relative slant range as
a function of flight attitude
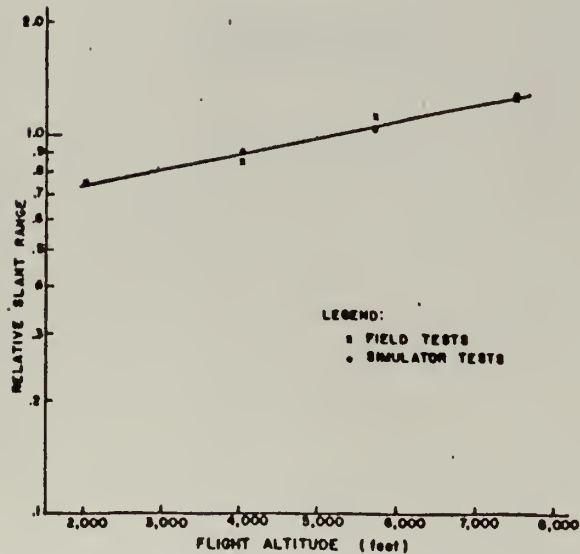
Log relative slant range as
a function of flight altitude

FIGURE II-1
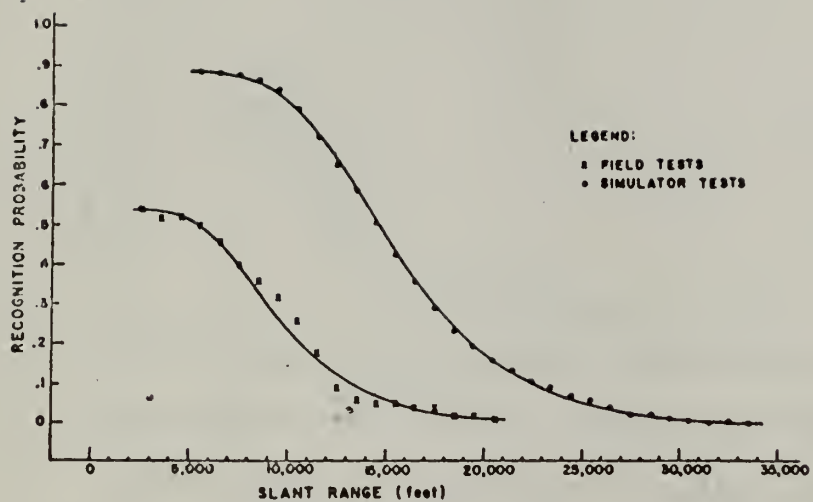
Data: Recognition probability as
a function of slant range: field and
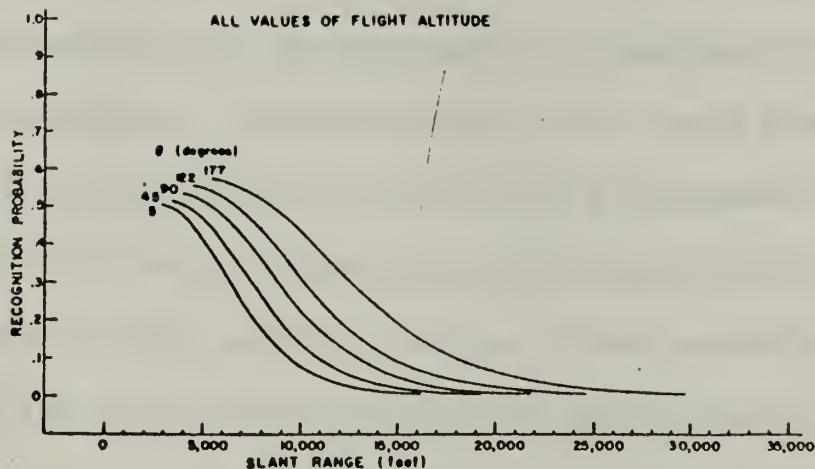simulator data

FIGURE II-2

Fig. II-3. Theoretical curves: Recognition
probability as a function of slant range:
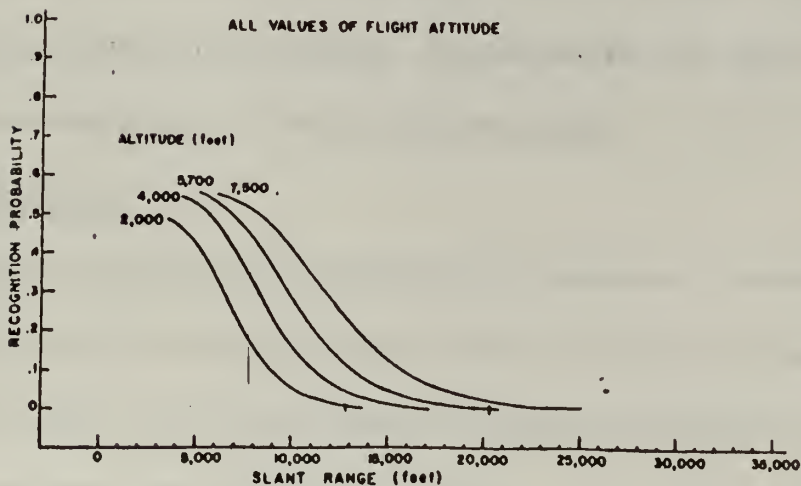All values of flight altitude

Fig. II-4. Theoretical curves: Recognition
probability as a function of slant range:
All values of flight attitude

65

THE OPERATIONAL EXPERIMENT

Stimulated by the fact that there was little experimental data on detection probabilities of tactical targets by visual search from the air in an operational environment it was hoped that an experiment to gather such data utilizing the men, material and time already available in the Postgraduate School area would be possible. It was learned during September, 1959 that the Combat Development Experimentation Center at Fort Ord, California would be doing an operational field experiment simulating a land battle in order to evaluate new army tactics. Permission was received from the Commanding General, CDEC, to conduct an air visual reconnaissance experiment in conjunction with their battle problem. The Aviation Department of the Postgraduate School authorized naval aviators to participate in the reconnaissance flights during their scheduled flight proficiency periods. The response to a call for aviator volunteers was adequate to conduct the experiment.

General Description

The flights simulated the mission of a single seat, attack aircraft searching an area for vehicular targets such as tanks, personnel carriers, trucks, etc. which would appear as targets of opportunity to an aircraft on an armed reconnaissance mission.

During the experiment pilots on reconnaissance flights over the CDEC battle area reported (1) the positions of targets observed and (2) their own position at the time of target observation. A comparison of

this data with vehicle position reports taken in the field and compiled by the Project Michigan group at CDEC provided an estimation of the probability of detection of these targets. An analysis of the data was done to construct lateral range detection curves.

The Area

The battle problem was conducted at Hunter Liggett Military Reservation, Jolon, California. Two separate areas each covering about 144 mi^2. and offering similar terrain features were used at different time periods in the experiment. The terrain was predominantly rolling hills cut by two dry river beds. About three-quarters of the area was covered by sparse woods. The area was very dry causing the terrain to be brown in color. There were three asphalt roads through the area with many "tank trails" cutting across the area. Moving vehicles left dust trails but stationary vehicles painted army olive drab generally blended very well with the terrain. Terrain height varied from 2500 feet at the northern end of the search area to 1200 feet at the southern end. The area of operation is depicted in Chart 1.

Targets

The army's field problem placed about 250 vehicles of varying types, i.e., medium tanks, armored personnel carriers, etc., all of a similar size, in the area. These were the targets for the reconnaissance aircraft.

Flight Conditions

The reconnaissance flights were flown during three two week periods.

Flights were made during both morning and afternoon hours. The sun elevation angle varied for different flights. No effort was made to establish its position. The surface visibility was estimated to be 30 miles on each of the flying days. The pilots reported the same visibility condition. Haze or dust from moving vehicles was not a factor reducing the detection range to a great extent. In fact, dust trails were the cause of many moving target detections. Data was not obtainable on target contrast in the field nor was data taken on sighting direction of targets relative to sun position.

The flights were made in T-28 aircraft, the closest approximation to a single seat operational aircraft available. The cockpit conformation and canopy design are very similar to operational jet aircraft. Downward visibility and handling characteristics are also reasonably comparable to operational aircraft. The second person carried in the T-28 served as a recorder noting information which was required by the experiment but which would not be required by a pilot of an armed reconnaissance aircraft.

Flight Instructions

The reconnaissance searchs were flown at 200 knots true air speed. Wind effect was considered negligible. An altitude of 1500 feet above the terrain was maintained by the search aircraft for the first phase of the experiment and an altitude of 5000 feet above the terrain was maintained during the second phase. The pilots were assigned to fly the tracks of Course I or II as shown on Chart 1 depending on the army's area of activity. The pilots were instructed to fly a slight weave about the track

68

line as is done in operational aircraft to increase the area visible forward of the nose of the aircraft. The pilot of the search aircraft was required to fly the airplane, make target detections and at the time of detection note the position of the target and his own position on a 1:50,000 scale chart which he carried. At the time of a detection he would commence to circle his position until he was through making the required notations. This prevented him from overlooking the area along the track which would have been covered while recording information about the detected target if he had continued on course. At the time of detection he also told the rear seat recorder to note the time of detection and told him the type of target, the target's condition of motion (stopped or moving), and the target's cover (in open or not). Each aircraft flew an individual search, remaining in the search area about 30 minutes. All charts and navigation data were furnished the pilots.

Pilot Background

The pilots flying the reconnaissance search flights had from three to ten years experience in attack squadrons. Five of the eight pilots had Korean combat experience flying the type of mission this experiment attempted to simulate. However, the pilots were currently flying only four to eight hours a month in the T-28. They were not given a refresher course in search procedures and target recognition. Neither were they given familiarization flights over the search area before conducting a reconnaissance flight.

Vehicle Position Reports

The field reports of vehicle position were given by each vehicle in the battle problem area every five minutes. These reports were collected by Project Michigan's representative to CDEC and checked for validity through a cross check system in the reporting procedure. It was found that there were many obvious discrepancies in the vehicle position reports which were easily corrected. It was suspected that other errors might be in the position report data which could not be caught and corrected. However, the data was assumed to be reasonably accurate. No data was available on the concealment status of the vehicles but estimates of the number of vehicles under cover at any one time were obtained from the field commanders and from interpretation of the photographic coverage of some phases of the battle problem done by the CDEC photo interpreters.

Analysis

There were thirteen flights conducted during the first phase of the experiment and six flights conducted during the last phase. Vehicle position reports for the time periods of the flights were constructed on overlays, target position overlays, of the area. The target position overlays were laid over the chart and targets were counted in range bands. The range bands were centered on the track lines and measured 0-500 from the tracks, 500-1000 yards from the tracks, 1000-1500 yards from the tracks and 1500-2000 yards from the tracks. Both stationary and moving target positions were plotted without regard to target size. Table III-1

indicates the number of targets in each range band for each flight studied. The pilot's reported targets were also plotted and a comparison was made of the pilot's reported target positions and the ground vehicle positions. Unfortunately, the match of pilot's position reports and the vehicle position reports was not good. Possible errors from the field vehicle position reports have already been noted. Pilot reporting errors could have stemmed from the fact that without prior familiarization flights over the area position reporting would have been difficult. However, it is felt that the landmarks defining the planned flight tracks were recognized by the pilots. They all reported that they stayed on the planned search tracks.

Using the assumption that the pilots did stay on track, it was decided to use the pilot's estimate of distance, determined from his plotted target position and his plotted position at the time of detection, as the target detection range. The targets detected by the pilots were also sorted into range bands using the pilot's estimate of range of detection to place the target in the range band from the track. It is assumed that pilots did not report targets not actually seen. These results are tabulated in Table III-2.

Assume that each target in a range band can be detected or not detected independently on each pass of the search aircraft along the tracks defining the range bands. The detection or failure of detection of each target, therefore, can be considered to be one sample drawn from a binomial distribution. To get an estimate of the parameter, p, the detection

probability, let us use the ratio:

$$\hat{p} = \frac{\text{number of targets observed in each band}}{\text{number of targets available in each band}}$$

The plotting and counting process was done for eight flights taken at random from the first phase and for four flights taken at random from the second phase. At that time the average number of targets available in each range band was 275. For sample sizes of this order the binomial distribution approaches the normal distribution. The interval estimate for p, the detection probability, was formed in the following manner:

$$\hat{p} - 1.96 \sqrt{\frac{\hat{p}(1-\hat{p})}{275}} < p < \hat{p} + 1.96 \sqrt{\frac{\hat{p}(1-\hat{p})}{275}}$$

where p is the estimated value of p.

Intervals computed in this manner have a .95 probability of including the value of p. These intervals are tabulated below.

First Phase--Altitude 1500 feet

Range Band	Estimate	Confidence Interval
0-500	$\hat{p} = .118$	$.080 < p < .156$
500-1000	$\hat{p} = .036$	$.025 < p < .047$
1000-1500	$\hat{p} = .014$	$.007 < p < .021$
1500-2000	$\hat{p} = .004$	$.000 < p < .007$

Second Phase--Altitude 5000 feet

Range Band	Estimate	Confidence Interval
0-500	$\hat{p} = .023$	$.012 < p < .034$
500-1000	$\hat{p} = .000$	$p = 0$
1000-1500	$\hat{p} = .018$	$.008 < p < .028$
1500-2000	$\hat{p} = .010$	$.003 < p < .017$

It was considered that these confidence intervals were small enough, so the remaining flights were not analyzed.

The probabilities of detection for each range band for each flight are shown in Table III-3.

In order to get a detection probability not affected by the particular battle tactics which placed some percentage of targets under cover, hense unavailable for visual detection, the estimate of the percentage of targets under cover was used to arrive at a figure for the number of targets observable. Then the estimate of the probability of detection, $\hat{p}_1$, was defined as:

$$\hat{p}_1 = \frac{\text{number of targets observed in each band}}{\text{number of targets observable in each band}}$$

These probabilities are shown in Table III-4.

At this point in the analysis conversations with pilots revealed that some pilots had found so many moving targets in the area that they ignored them and searched for and reported only stationary targets. It is felt that this experiment indicates that moving targets have a much higher probability detection than stationary targets but that no quantitative basis for this statement can be made from the data collected in the experiment.

Using the range band detection probabilities, a lateral range curve for visual detection of stationary army vehicles in the open in an operational environment observed from altitudes of 1500 and 5000 feet above the terrain from a single seat aircraft at an airspeed of 200 knots was constructed and is shown in Figure 6, p. 18.

It can be seen from the lateral range curves that:

1. No targets were detected at ranges over 2000 yards from the track of the aircraft.

2. The probability of detection near the track decreased when the search altitude was raised to 5000 feet.

Both of these conclusions are contradictory to the detection probabilities predicted in the visual search theory presented previously. It is felt that this is caused by factors in the operational situation which are not considered in the theory. These are principally (1) lack of familiarity with the terrain (2) necessity for the pilot to divide his time between search and aircraft control (3) obstruction or distortion of vision by the construction of the aircraft and the pilot's helmet. The second factor is felt to be the biggest contributor to the difference in experimental and theoretical results. The theory has been found good for determining detection probabilities for targets at sea with observers who were not required to fly the aircraft as well as conduct the search.

Detection ranges also differed from those reported in the Michigan experiment. There the target was a vehicle convoy, larger than the single targets which were of interest in the battle problem. Also the Michigan pilots were familiar with the terrain and the expected target positions. There was no data on target contrast given in either experiment, but it seems likely that the contrast of olive drab army vehicles against natural terrain would be less than the contrast of Navy grey vehicles against natural terrain. If this condition did exist, the smaller

74

contrast value in the battle problem would partially explain the shorter detection ranges of the operational experiment.

This experiment indicates that there is a significant amount of degradation of theoretical detection probabilities in the conduct of visual reconnaissance for ground vehicle targets from high speed aircraft. It is felt that the lateral range curves constructed, despite the assumptions of the analysis, give a better estimate of the actual detection probabilities obtained by armed reconnaissance aircraft than the theoretical curves previously computed.

TABLE III-1

NUMBER OF TARGET VEHICLES/RANGE BAND/RUN

All Targets Stationary

First Phase, Altitude of Search 1500 ft.

Range	0-500	500-1000	1000-1500	1500-2000	Total
Run 1	44	84	85	65	358
Run 2 & 3	34	43	62	41	180
Run 4	34	46	75	70	225
Run 5 & 6	62	12	0	20	94
Run 7	9	2	16	4	31
Run 8	88	60	57	87	292
Total	271	247	295	287	1100

Second Phase, Altitude of Search 5000 ft.

Range	0-500	500-1000	1000-1500	1500-2000	Total
Run 9	64	32	53	2	151
Run 10	17	71	54	77	219
Run 11	51	27	48	43	169
Run 12	42	55	67	72	236
Total	174	185	222	194	775

TABLE III-2

NUMBER OF TARGETS OBSERVED/RANGE BAND/RUN

All Targets Stationary

First Phase, Altitude of Search 1500 ft.

Range	0-500	500-1000	1000-1500	1500-2000	Total
Run 1	3	2	0	1	6
Run 2	3	1	2	0	6
Run 3	0	0	1	0	1
Run 4	4	1	1	0	6
Run 5	8	2	0	0	10
Run 6	3	1	0	0	4
Run 7	2	2	0	0	4
Run 8	9	0	0	0	9
Total	32	9	4	1	

Second Phase, Altitude of Search 5000 ft.

Run 9	1	0	0	0	1
Run 10	1	0	0	0	1
Run 11	1	0	4	0	5
Run 12	1	0	0	2	3
Total	4	0	4	2	

TABLE III-3

DETECTION PROBABILITIES

All Targets Stationary; in Open and Concealed

First Phase, Altitude of Search 1500 ft.

Range	0-500	500-100	1000-1500	1500-2000
Run	.068	.0238	.0	.0154
Run 2	.0883	.0232	.0323	.0
Run 3	.0	.0	.0162	.0
Run 4	.1175	.0218	.0133	.0
Run 5	.129	.1665	.0	.0
Run 6	.33	.5	.0	.0
Run 7	.222	1.0	.0	.0
Run 8	.102	.0	.0	.0
Total	.118	.0364	.0135	.0035

Second Phase, Altitude of Search 5000 ft.

	0-500	500-100	1000-1500	1500-2000
Run 9	.0156	.0	.0	.0
Run 10	.0588	.0	.0	.0
Run 11	.0196	.0	.0	.0465
Run 12	.0238	.0	.0596	.0
Total	.023	.0	.018	.0103

TABLE III-4

DETECTION PROBABILITIES

All Targets Stationary; in Open Only

First Phase, Altitude of Search 1500 ft.

Range	0-500	500-1000	1000-1500	1500-2000
Run 1	.085	.0298	.0	.0193
Run 2	.1105	.029	.0403	.0
Run 3	.0	.0	.0202	.0
Run 4	.147	.0273	.01416	.0
Run 5	.161	.208	.0	.0
Run 6	.413	.625	.0	.0
Run 7	.278	1.0	.0	.0
Run 8	.1275	.0	.0	.0
Total	.149	.0455	.0168	.00438

Second Phase, Altitude of Search 5000ft.

Range	0-500	500-1000	1000-1500	1500-2000
Run 9	.0195	.0	.0	.0
Run 10	.0738	.0	.0	.0
Run 11	.0245	.0	.0	.0581
Run 12	.0298	.0	.0746	.0
Total	.0288	.0	.0225	.01288
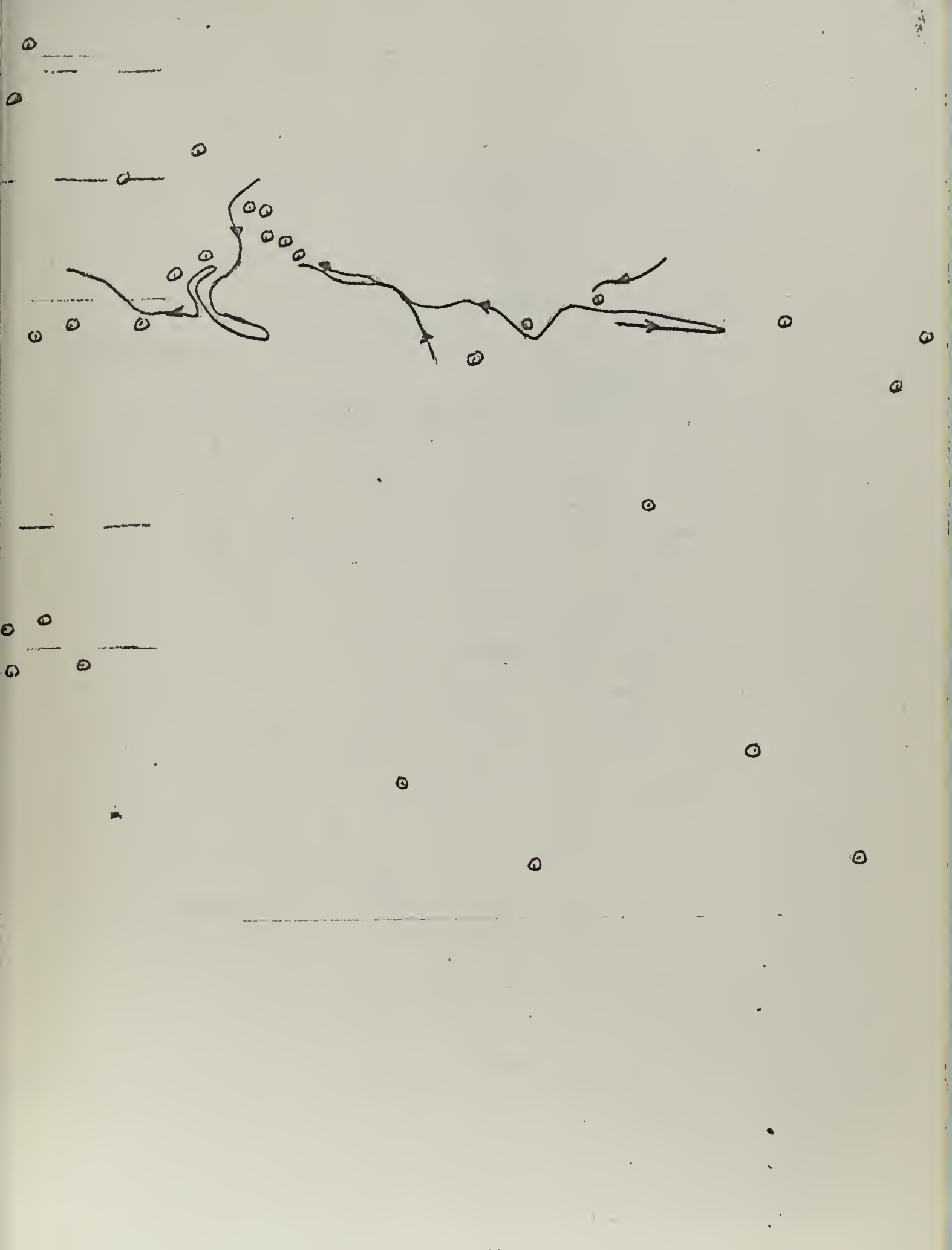
FLIGHT PATH
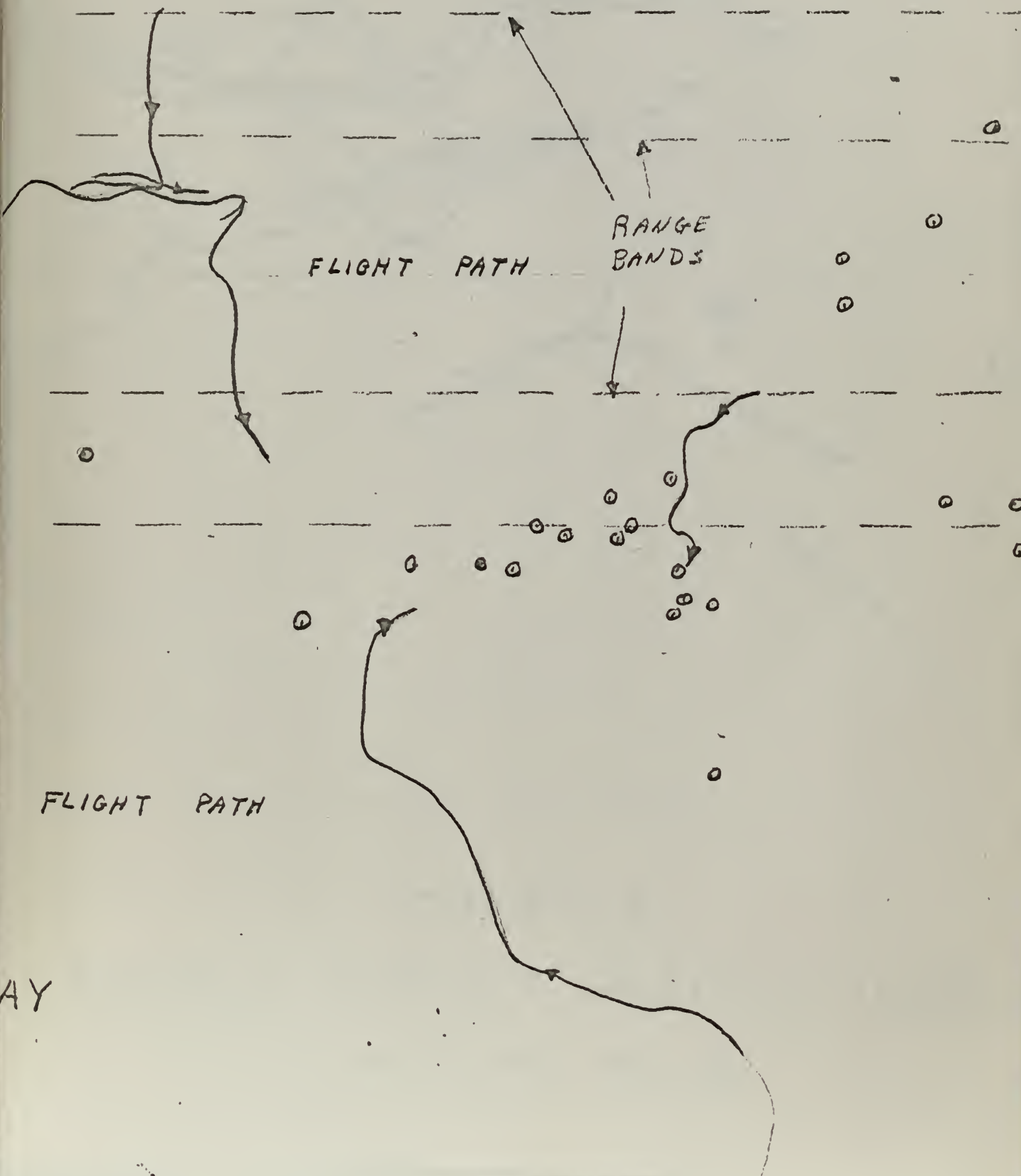
FLIGHT PATH

RANGE
BANDS

FLIGHT PATH

FLIGHT PATH

AY
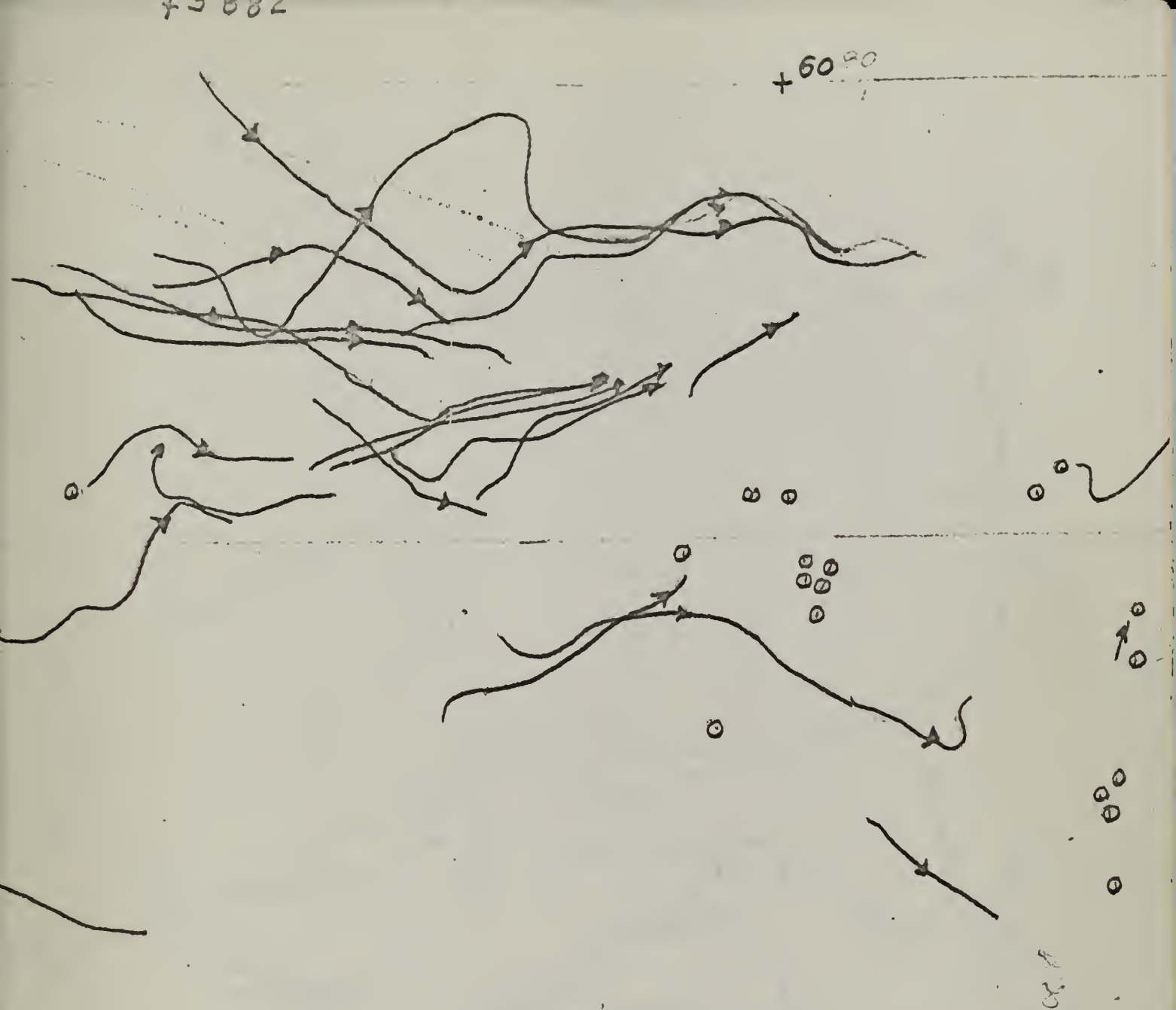
CHART 2

SAMPLE TARGET POSITION OVERLA
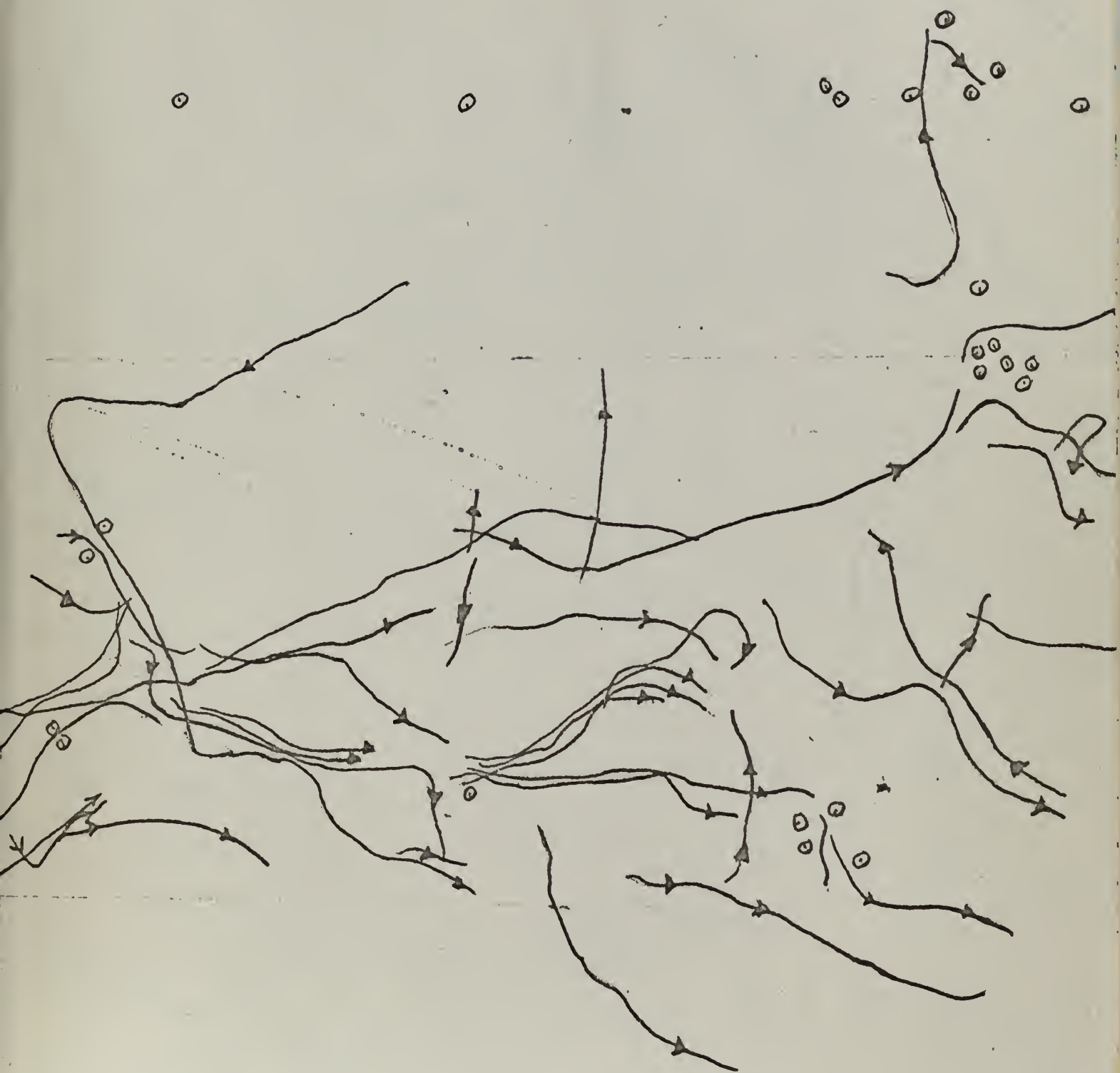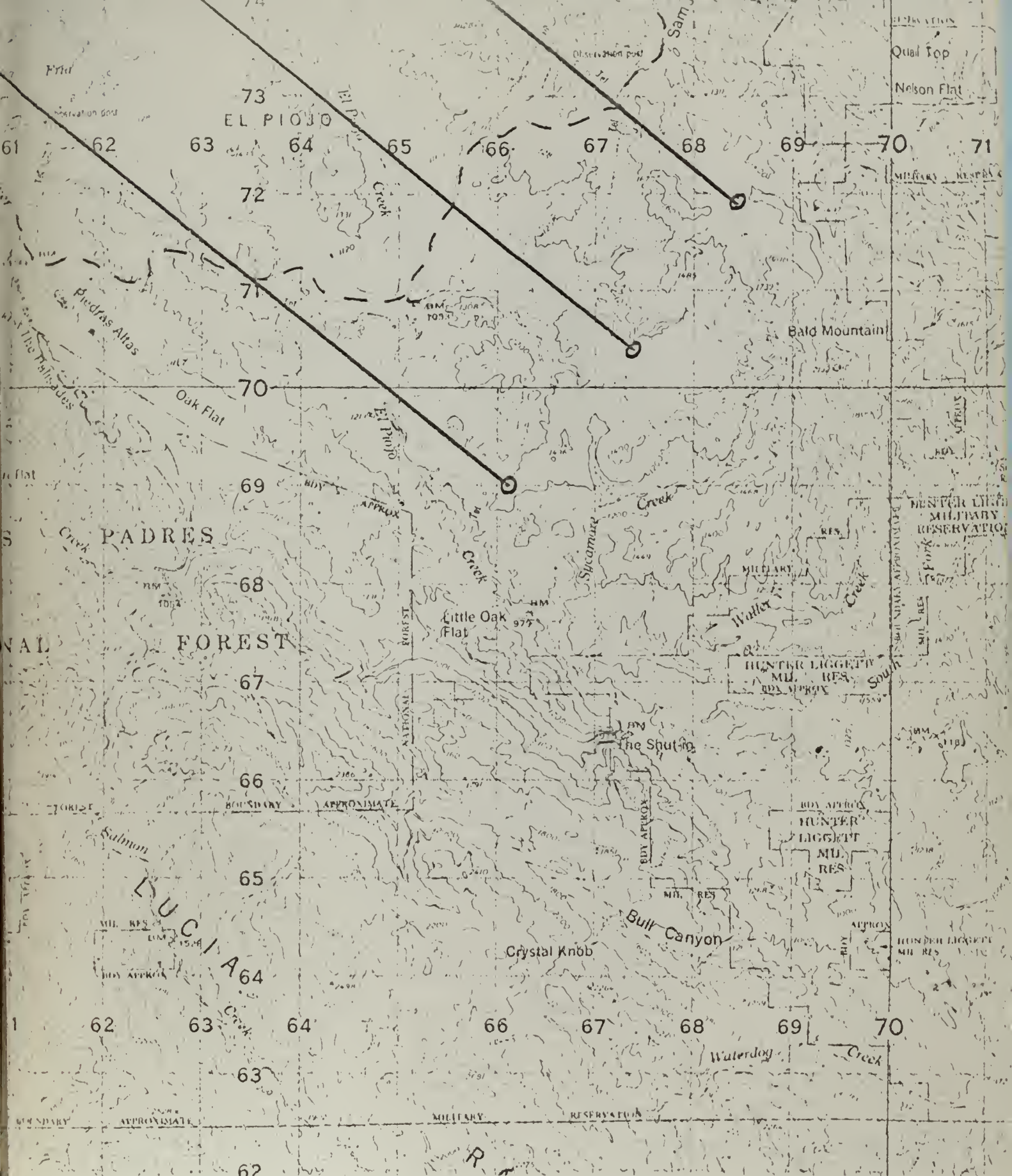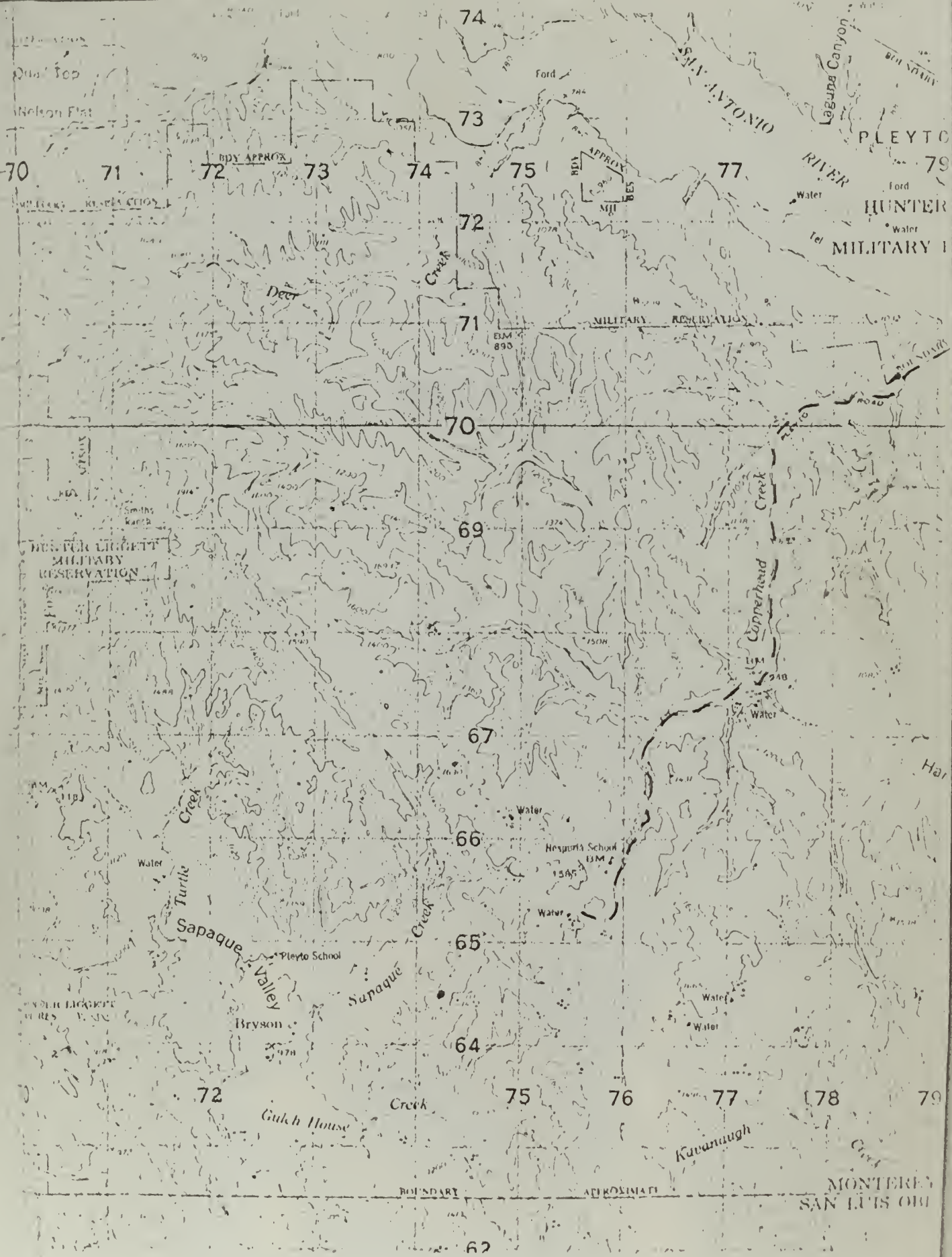
20 OCT. 1959; 1400-1430

SERVATION

74

73

72

71

70

69

68

67

65

63

62

53 54 56 57 60 61 62

Nacimiento

EL PIOJO

Ford

servation post

Frio

Los Burros Creek Burros

ADI APPROX

Los

Creek

Piedras Altas

River

NATIONAL FOREST The Palisades

Burro Mountain

Burros Creek

NAL FOREST

Burros Creek

Little Fork

Three Peaks

Rangey lookout

Taco Hondo

Pozo

Hondo

Italian Flat

Steve Creek

LOS PA

S NATIONAL

SANTA

ERVATION Davis Canyon

Wagner Creek

NATIONAL FOREST

MILITARY RESERVATION

NATIONAL FOREST

Salmo

San Carpofo Creek

BDY APPROX
HUNTER
LIGGETT
MIL RES

HUNTER LIGGETT
MIL RES

MIL RES

Jones Mtn

MONTEREY COUNTY
SAN LUIS OBISPO COUNTY

MONTEREY COUNTY
SAN LUIS OBISPO COUNTY

RANGE

Dutra Creek

53 54 59 60 61 62

CHART I : HUNTER LI

74

73
EL PIOJO

Frd

Quail Top

Nelson Flat

61 62 63 64 65 66 67 68 69 70 71

72

71

Piedras Altas

Oak Flat

70

69

PADRES

Creek

68

FOREST

67

66

BOUNDARY   APPROXIMATE

Salmon

65

LUCIA

64

62 63 64 66 67 68 69 70

63

62

Little Oak
Flat

Sycamore   Creek

Bald Mountain

HUNTER LIGGETT
MILITARY
RESERVATION

HUNTER LIGGETT
MIL   RES
BDY APPROX

HUNTER
LIGGETT
MIL
RES

The Shut In

Bull Canyon

Crystal Knob

Waterdog   Creek

MILITARY   RESERVATION

ER LIGGETT AREA